SEPs

NOAA SPACE WEATHER SCALES

https://www.swpc.noaa.gov/noaa-scales-explanation

Solar cycle 25 SEP Events Catalog

https://data.serpentine-h2020.eu/catalogs/sep-sc25/

This catalog contains multi-spacecraft solar energetic particle (SEP) events, which were observed with the new spacecraft fleet in solar cycle 25.

More information can be found in

Dresing et al. 2024

A&A 687, A72 **2024**

https://arxiv.org/pdf/2403.00658.pdf

https://data.serpentine-h2020.eu/catalogs/sep-sc25/ **catalog**

https://www.aanda.org/articles/aa/pdf/2024/07/aa49831-24.pdf

STEREO REleASE SEP forecasting system now publicly available!

It provides real-time forecasts of hazardous solar proton events in the inner heliosphere from STEREO's location with the use of relativistic or near-relativistic electrons.

STEREO REleASE: https://hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/stereo-release

Data Retrieval Tool (DRT): https://hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/data-retrieval-tool

See Olga E. **Malandraki** and N. **Crosby 2024**

NOAA Space Weather Prediction Center
Solar Proton Events Affecting the Earth Environment
1976 - Present

https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/SEP%20page%20code.html

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The Astrophysical Journal, 966:165 (15pp), 2024 May 10 Rotti, Aydin, & Martens

Table 5
List of Existing SEP Event Prediction Models That Consider Solar Protons, X-Ray Flare Fluxes, and Their Properties as Input

Model	Period	Type	HSS	TSS
Balch (2008)	1986–2004	Empirical	0.48 ± 0.04	⋯
Laurenza et al. (2009)	1995–2005	Empirical	0.58	⋯
Winter & Ledbetter (2015)	1995–2005	Empirical	0.60	⋯
Alberti et al. (2017)	2004–2014	Empirical	0.55	⋯
Anastasiadis et al. (2017)	1984–2013	Empirical	0.37 ± 0.011	0.5
Engell et al. (2017)	1986–2018	ML	0.58	⋯
Papaioannou et al. (2018)	1997–2013	Empirical	0.65	⋯
Lavasa et al. (2021)	1988–2013	ML	0.69 ± 0.04	0.75 ± 0.05
Aminalragia-Giamini et al. (2021)	1988–2013	ML	⋯	0.79
Sadykov et al. (2021)	2010–2019	ML	0.434 ± 0.046	0.821 ± 0.003

Note. HSS—Heidke skill score; TSS—true skill statistics; ML—machine learning.

38th International Cosmic Ray Conference

26 July - 3 August, 2023 Nagoya, Japan

https://pos.sissa.it/444/

Review of solar energetic particle models. **Review**

Whitman, K., Egeland, R., Richardson, I. G., Allison, C., Quinn, P., Barzilla, J., et al.

Adv. Space Res. Volume 72, Issue 12, 15 December **2023**, Pages 5161-5242, 82 p. **File**

doi:10.1016/j.asr.2022.08.006

https://reader.elsevier.com/reader/sd/pii/S0273117722007244

Space Weather Live

https://www.spaceweatherlive.com/en.html

The solar cycle 25 multi-spacecraft solar energetic particle event catalog of the SERPENTINE project

N. **Dresing**, A. Yli-Laurila, S. Valkila, J. Gieseler, D. E. Morosan, G. U. Farwa, +++

A&A **2024**

https://arxiv.org/pdf/2403.00658.pdf

https://data.serpentine-h2020.eu/catalogs/sep-sc25/ **catalog**

A Living Catalog of Parker Solar Probe IS⊙IS Energetic Particle Enhancements

J. G. **Mitchell**7,1, C. M. S. Cohen2, T. J. Eddy3, C. J. Joyce4, J. S. Rankin3, M. M. Shen3, G. A. de Nolfo1, E. R. Christian1, D. J. McComas3, R. L. McNutt Jr.5 +++

2023 ApJS 264 31

https://iopscience.iop.org/article/10.3847/1538-4365/aca4c8/pdf

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Cliver et al. (2022)

Table 8 Largest SEP events during the space age, rank ordered for F_{30}, F_{200}, and F_{GLE}

Rank	Date	F_{30} (10^9 cm^{-2}) (a)	Rank	Date	F_{200} (10^7 cm^{-2}) (b)	Rank	Date	F_{GLE} (%*h) (c)
(1)	2, 4, & 7 Aug 72	8.4	(1)	23 Feb 56	14.0	(1)	23 Feb 56	5202 ± 104
(2)	12, 15, & 20 Nov 60	6–9.8	(2)	12 Nov 60	6.4	(2)	29 Sep 89	1189 ± 60
(3)	Aug–Oct 89(d)	7.2	(3)	19 Oct 89	5.5	(3)	12 Nov 60	677 ± 25
(4)	Sep–Nov 01(e)	5.5	(4)	14 Jul 00	3.4	(4)	24 Oct 89	576 ± 27
(5)	14 Jul 00	4.3	(5)	29 Sep 89	3.1	(5)	15 Nov 60	552 ± 106
(6)	10, 14, & 16 Jul 59	4.0	(6)	15 Nov 60	3.0	(6)	19 Oct 89	411 ± 15
(7)	Oct-Nov 03(f)	3.8	(7)	24 Oct 89	2.2	(7)	20 Jan 05	385 ± 55
(8)	08 Nov 00	3.1	(8)	20 Jan 05	2.2	(8)	15 Apr 01	170 ± 15
(9)	23 July 12(g)	2.1	(9)	17 Jul 59	1.6	(9)	28 Oct 03	110 ± 7
(10)	23 Feb 56	1.4	(10)	22 Oct 89	1.6	(10)	28 Jan 67	110 ± 3

References: (a) (F_{30}) (1) Jiggens et al. (2014); (2) Webber et al. (2007; low), Shea and Smart (1990; high); (3) Smart et al. (2006b); cf. Jiggens et al. (2014) for October 1989; (4) Smart et al. (2006b) and NGDC (https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html); (5) Smart et al. (2006b); (6) Usoskin et al. (2020b); (7,8) NGDC; (9) Gopalswamy et al. (2016); (10) Usoskin et al. (2020b)

(b) (F_{200}) Usoskin et al. (2020b) for 1956; Kovaltsov et al. (2014)

(c) (F_{GLE}) Asvestari et al. (2017a); integral of the excess above the galactic cosmic ray background over the entire duration of the event

(d) SEP events on 12 and 16 Aug, 29 Sep, and 19, 22, and 24 Oct 89

(e) events on 24 Sep and 4 and 22 Nov 01

(f) events on 28 and 29 Oct and 2 Nov 03

(g) Backside solar event observed by STEREO-A (Gopalswamy et al. 2016)

Extreme Solar Particle Storms **Book**

The hostile Sun
Ed. by Miyake, Fusa; Usoskin, Ilya; Poluianov, Stepan. ISBN: 978-0-7503-2230-0. IOP ebooks. Bristol, UK: IOP Publishing, **2019**, https://iopscience.iop.org/book/978-0-7503-2232-4

Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond – New Book Review
Olga E. **Malandraki** and Norma B. Crosby (Eds.)
Astrophysics and Space Science Library No. 444 **2018 File**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf

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The recording of the third webinar on the ISWI, Pertti **Mäkelä** – Large Solar Energetic Particle Events, which took place on 29 June 2022 https://youtu.be/2R11hXAf0-Q

Catalogs of Solar Energetic Particles and Related Phenomena

© SRTI-BAS 2022 Last modified 09/17/2018 13:56:05

Wind/EPACT proton event catalog

SOHO/ERNE proton event catalog

Radio emission signatures catalog

Supported by **Space Climate Group** Space Research and Technology Institute Bulgarian Academy of Sciences Contact: R. Miteva Web-support: D. Danov

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Integrated Geostationary Solar Energetic Particle Events Catalog: GSEP
Sumanth **Rotti**, Berkay Aydin, Manolis K. Georgoulis, Petrus C. Martens
ApJS **262** 29 **2022**
https://arxiv.org/ftp/arxiv/papers/2204/2204.12021.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/ac87ac/pdf **File**
GSEP Dataset
https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/DZYLHK

STEREO Data
4. List of Solar Energetic Proton (SEP) Events Observed by both STA and STB
SEP list in pdf format
SEP list in the SPASE HPEvent list format
Plots of SEP events
5. List of PLASTIC Suprathermal Proton Events from University of New Hampshire
Suprathermal Lists
SEP Events from STEREO A **There is a list of >25 MeV proton events**
https://stereo-ssc.nascom.nasa.gov/data/ins_data/impact/level3/SEPs.pdf

Energetic storm particles (near shock) ESP
SEP intensities often peak as a shock wave passes, indicating a local source from which particles diverge. These peaks were called "energetic storm particle" or "ESP events."

Solar Energetic Electron (SEE) events

SEP Event List (http://sepem.eu/help/ event_ref.html) 1988–2013

Major SEP Events_CMEs_Flares (1997-2017) https://cdaw.gsfc.nasa.gov/CME_list/sepe/

Topical issue, "Ground Level Enhancement Events of Solar Cycle 23" GLEs
Ed. by N. Gopalswamy & N. V. Nitta
Space Science Reviews Volume 171, issue 1-4, October **2012**
https://link.springer.com/journal/11214/volumes-and-issues/171-1

Solar Orbiter First Results (Cruise Phase): many papers on ^{3}He-rich SEPs, near-relativistic electrons, stealth CME, ICMEs, GCR flux, Forbush
Astronomy & Astrophysics Volume 656 (December **2021**)
https://www.aanda.org/articles/aa/abs/2021/12/contents/contents.html

SEP Event lists are available:
for impulsive (Reames, Cliver, and Kahler, Solar Phys., Volume 289, pp 3817-3841, **2014**);
Table 2 Properties of the Fe-rich SEP events and associated CMEs (1995-2013);
https://link.springer.com/article/10.1007/s11207-014-0547-1/tables/2
https://link.springer.com/content/pdf/10.1007/s11207-014-0547-1.pdf;
and gradual (Reames Solar Phys., 291 911, **2016**) events
Table 2 Source plasma temperatures of gradual SEP events (1997-2014)
https://link.springer.com/content/pdf/10.1007/s11207-016-0854-9.pdf

Free Access
https://link.springer.com/article/10.1007/s11207-016-0854-9/tables/2

We perform hindcasts Мы делаем ретроспективные прогнозы

THE RESEARCH TOPIC **Solar and Space Weather Radio Physics**
Front. Astron. Space Sci. Vol. 7, **2020**
https://www.frontiersin.org/research-topics/10360/solar-and-space-weather-radio-physics#articles
https://www.frontiersin.org/research-topics/10360/

From **Aminalragia-Giamini**_SEP Fluence and Peak flux spectra_**2020** J. Space Weather Space Clim. 2020, **10**, 1 (**File**):
***State of the art forecasting schemes** include* the University of Malaga Solar Energetic Particle (UMASEP) system (Núñez, 2011, 2015), the FORecasting Solar Particle Events and Flares (FORSPEF) system (Papaioannou et al., 2015, 2018), the Warning System for Aviation

Exposure to SEP (WASAVIES) (Kataoka et al., 2014) and WASAVIES – Earth Orbit (WASAVIES-EO) (Sato et al., 2019) systems, the Relativistic Electron Alert System for Exploration (RELeASE) (Posner, 2007; Malandraki & Crosby, 2018), the Empirical model for Solar Proton Events Real Time Alert (ESPERTA) (Laurenza et al., 2009; Alberti et al., 2017) and the Proton Prediction System (PPS) (Smart & Shea, 1989, 1992; Kahler et al., 2007). **...**

Earth-affecting Solar Transients: A Review of Progresses in Solar Cycle 24
Jie **Zhang**, Manuela Temmer, Nat Gopalswamy, +
https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf **File 2021**
2020 **https://arxiv.org/abs/2012.06116**

SEPs	--	Solar Proton Events from SWPC https://umbra.nascom.nasa.gov/SEP/	--
SEPs	--	> 25 MeV Proton Events Observed by the High Energy Telescopes on the STEREO A and B Spacecraft and/or at Earth	(I. Richardson et al. 2014)
SEPs	--	Catalogue of 55-80 MeV solar proton events extending through solar cycles 23 and 24	(Paassilta et al. 2017)
SEPs	--	STEREO/SEPT Solar Energetic Electron Event List http://www2.physik.uni-kiel.de/stereo/downloads/sept_electron_events.pdf	(Nina Dresing et al. 2020)

Секундные данные GOES по протонам

https://satdat.ngdc.noaa.gov/sem/goes/data/full/, ***файлы csv читаются Excel.***

Space Weather Database Of Notifications, Knowledge, Information (DONKI)
One-stop on-line **tool for space weather** researchers and forecasters.
https://ccmc.gsfc.nasa.gov/donki/

Data from the **GOES** (Geostationary Operational Environmental Satellite) energetic particle sensor (EPS) and high energy proton and alpha detector (HEPAD) datasets2 (Onsager et al. 1996; Sellers & Hanser 1996) https://www.ngdc.noaa.gov/stp/satellite/goes/index.html

Cosmic Ray DataBase (CRDB) https://tools.ssdc.asi.it/CosmicRays/
SEP spectrum measured by the PAMELA experiment

NMDB - Neutron Monitor Database [http://www01.nmdb.eu]

The GOES, PAMELA and STEREO data are available at
https://www.ngdc.noaa.gov/stp/satellite/goes/
https://www.ssdc.asi.it/pamela/ and
http://www.srl.caltech.edu/STEREO/, respectively.

Solar Energetic Particles (Second Edition) **Review Book**
A Modern Primer on Understanding Sources, Acceleration and Propagation
Donald V. **Reames**
Lecture Notes in Physics **2020 File**
https://arxiv.org/ftp/arxiv/papers/2010/2010.08517.pdf

The Astrophysical Journal Supplement Series

Volume 246, Number 2, 2020 February

Early Results from Parker Solar Probe: Ushering a New Frontier in Space Exploration

https://iopscience.iop.org/issue/0067-0049/246/2

Proc. of the 36th International Cosmic Ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A.
https://pos.sissa.it/358/

Real-time Forecasting Methods Validation: SEP Scoreboard Planning Page https://ccmc.gsfc.nasa.gov/challenges/sep.php

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Publications of the Athens Neutron Monitor Group
http://cosray.phys.uoa.gr/index.php/publications-menu/publications

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High EneRgy sOlar partICle events analysis (HEROIC)
http://www.issibern.ch/teams/heroic/
ISSI Team #441 led by Athanasios Papaioannou (GR)

GLEs **http://gle.oulu.fi**

Catalogue of >55 MeV Wide-longitude Solar Proton Events Observed by SOHO, ACE, and the STEREOs at ≈1≈1 AU During 2009 – 2016
Miikka **Paassilta**, Athanasios Papaioannou, Nina Dresing, Rami Vainio…
Solar Physics April **2018**, 293:70
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1284-7.pdf

Catalogue of 55 – 80 MeV solar proton events extending through Solar Cycles 23 and 24.
Paassilta, M., Raukunen, O., Vainio, R., Valtonen, E., Papaioannou, A., Siipola, R., Riihonen, E., Dierckxsens, M., Crosby, N., Malandraki, O., Heber, B., Klein, K.-L.:
2017, J. Space Weather Space Clim. 7, A14.
https://arxiv.org/pdf/1707.00498.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170003.pdf
Table 3. Proton fluxes, selected TSA and VDA parameters, ion fluences, and Fe/O ratios for 55–80 MeV proton events in 1996–2016. https://www.swsc-journal.org/articles/swsc/olm/2017/01/swsc170003/swsc170003-1-olm.pdf

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Catalog of Solar Proton Events in the 23rd Cycle of Solar Activity (1996 – 2008) edited by Logachev
http://www.wdcb.ru/stp/data/SPE/

Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration and Propagation **Book Review**
Donald V. **Reames**
Lecture Notes in Physics, Vol. 932
Springer International Publishing AG **2017**, 136 p. **File**
http://sci-hub.cc/10.1007/978-3-319-50871-9
https://link.springer.com/content/pdf/10.1007%2F978-3-319-50871-9.pdf

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Proceedings of 35th ICRC Conference, PoS(ICRC2017),
10-20 July, 2017 Bexco, Busan, Korea
https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=301
PDF файлы статей

Journal of Space Weather and Space Climate: Topical issues
https://www.swsc-journal.org/component/list/?task=topic

- **Developing New Space Weather Tools: Transitioning fundamental science to operational prediction systems**
- **Flares, coronal mass ejections and solar energetic particles and their space weather impacts**
- **Space weather effects on GNSS and their mitigation**
- **Measurement, Specification and Forecasting of the Solar Energetic Particle Environment and GLEs** **2017-2019**
- **Brightness Variations of the Sun and Sun-like Stars and Resulting Influences on their Environments**
- **Scientific Challenges in Thermosphere-Ionosphere Forecasting**
- **Statistical Challenges in Solar Information Processing**
- **Satellite mission concepts developed at the Alpbach 2013 Summer School on space weather**
- **Solar variability, solar forcing, and coupling mechanisms in the terrestrial atmosphere**
- **Space Weather and Challenges for Modern Society**
- **COST Action ES0803**
- **EU-FP7 funded space weather projects**
- **Space Climate**

See **Major SEP Events** starting from 1997
http://cdaw.gsfc.nasa.gov/CME_list/sepe/

http://onlinelibrary.wiley.com/doi/10.1002/2013JA019253/pdf
http://onlinelibrary.wiley.com/doi/10.1002/2013JA019253/abstract

Цифровые данные о протонных мониторов GOES доступны на сайте
http://satdat.ngdc.noaa.gov/sem/goes/data/new_avg/

Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration and Propagation **Book** **Review**
Donald V. **Reames**
Lecture Notes in Physics, Vol. 932
Springer International Publishing AG **2017**, 136 p. **File**
http://sci-hub.cc/10.1007/978-3-319-50871-9
https://link.springer.com/content/pdf/10.1007%2F978-3-319-50871-9.pdf

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Статьи по солнечным космическим лучам и др.
ИЗВЕСТИЯ РОССИЙСКОЙ АКАДЕМИИ НАУК. СЕРИЯ ФИЗИЧЕСКАЯ
Том: 81Номер: 2 Год: **2017**

The Wind/EPACT proton event catalog (1996-2016)
Rositsa **Miteva**, Susan W. Samwel, Marcus V. Costa-Duarte
Solar Phys. **2018**
https://arxiv.org/pdf/1801.00469.pdf **File**

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Solar flares, coronal mass ejections and solar energetic particle event characteristics
Athanasios **Papaioannou**1*, Ingmar Sandberg1, Anastasios Anastasiadis1, Athanasios Kouloumvakos2, Manolis K. Georgoulis3, Kostas Tziotziou1,3, Georgia Tsiropoula1, Piers Jiggens4 and Alain Hilgers
J. Space Weather Space Clim., 6, A42 (**2016**) **File**
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf
A new catalogue of 314 solar energetic particle (SEP) events extending over a large time span from 1984 to 2013 has been compiled.
Table 2 SEP events, recorded onboard GOES from 1984 to 2013, and associated solar features
https://www.swsc-journal.org/articles/swsc/olm/2016/01/swsc150076/swsc150076-tab2-olm.pdf
Table 3. Calculated characteristics (i.e. proton peak flux and fluence) of all 314 SEP events at E>10; 30; 60 and 100 MeV.
https://www.swsc-journal.org/articles/swsc/olm/2016/01/swsc150076/swsc150076-tab3-olm.pdf

Differential proton fluxes from the Energetic Particle Sensor (EPS) – one of the four instruments of the Space Environment Monitor (SEM) – onboard the Geostationary Operational Environmental Satellites (**GOES**) (Rodriguez et al. **2014**).
The European Space Agency (ESA) Solar Energetic Particle Environment Modelling (SEPEM) (http://dev.sepem.oma.be/) http://dev.sepem.oma.be/help/event_ref.html Team (Crosby et al. 2015)
The SEPEM reference event list 7.23 - 10.45 MeV
http://sepem.eu/help/event_ref.html http://sepem.eu/help/event_lists.html

The GOES/ SEM data by the SEPEM Team (see details on this procedure, here: http://dev.sepem.oma.be/help/data_pref.html)
http://ftp//ftp.estec.esa.int/private/pjiggens/anonymous/SEPEM_RDS_v2-00.zip
http://www.stce.be/esww11/contributions/public/Session5/S5-P-4-SandbergI/poster_ESWW_GOES.pdf
Currently freely available from ESA through
http://ftp//ftp.estec.esa.int/private/pjiggens/anonymous/SEPEM_RDS_v2-00.zip

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Каталоги Логачёва

http://www.wdcb.ru/stp/data/SPE/

List of Solar Proton Events in the 24 Cycle of Solar Activity (2009 – 2019)
Logachev Yu.I.1 , Bazilevskaya G.A.2 , Daibog E.I.1 , Ginzburg E.A.3, Ishkov V.N.4,5, Lazutin L.L.1 , Nguyen M.D.1 , Surova G.M.1 , Vlasova N.A.1 , Yakovchuk O.S.1
2020
http://www.wdcb.ru/stp/data/SPE/List_SPE_24_Cycle_SA.pdf
http://www.wdcb.ru/stp/data/SPE/List_SPE_24_Cycle_SA.ru.pdf

CATALOG of Solar Proton Events in the 23rd Cycle of Solar Activity (1996 – 2008)
Yu. I. **Logachev**, G. A. Bazilevskaya, E. V. Vashenyuk, E. I. Daibog, V. N. Ishkov, L. L. Lazutin, L. I. Miroshnichenko, M. N. Nazarova, I. E. Petrenko, A. G. Stupishin, G. M. Surova, O. S. Yakovchuk
2016
http://www.wdcb.ru/stp/data/SPE/Catalog_SPE_23_cycle_SA.pdf
Каталог солнечных протонных событий 23-го цикла солнечной активности (1996 – 2008 гг.)
http://www.wdcb.ru/stp/data/SPE/katalog_SPS_23_cikla_SA.pdf

Каталог Ишкова M1 - X>17.5 вспышек за 2009-2017
http://www.wdcb.ru/stp/data/Solar_Flare_Events/Fl_XXIV.pdf

СОВРЕМЕННОЕ ПРЕДСТАВЛЕНИЕ БАЗ ДАННЫХ НА ПРИМЕРЕ КАТАЛОГА СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ 23-ГО ЦИКЛА СОЛНЕЧНОЙ АКТИВНОСТИ
Ишков В.Н., Забаринская Л.П., Сергеева Н.А.
ГЕОМАГНЕТИЗМ И АЭРОНОМИЯ Том: 57Номер: 6 Год: **2017** Страницы: 736-743

Solar Cosmic Rays **Book**
Fundamentals and Applications
Series: Astrophysics and Space Science Library, Vol. 405
Miroshnichenko, Leonty
2nd ed. **2015**, XV, 521 p. 162 illus., 17 illus. in color.
http://link.springer.com/book/10.1007%2F978-3-319-09429-8

Table 1 >25 MeV proton events at 1 AU during the STEREO mission. **Catalog**
> 25 MeV Proton Events Observed by the High Energy Telescopes on the STEREO A and B Spacecraft and/or at Earth During the First ~ Seven Years of the STEREO Mission
I. G. **Richardson**, T. T. von Rosenvinge, H. V. Cane, E. R. Christian, C. M. S. Cohen, A. W. Labrador, R. A. Leske, R. A. Mewaldt, M. E. Wiedenbeck, E. C. Stone
Solar Phys., **2014; File**

Solar Eruptions and Energetic Particles: An Introduction **Review**
N. **Gopalswamy**1 , R. Mewaldt2 , and J. Torsti3
Book Series:Geophysical Monograph Series Volume 165, **2013**
https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/GM165

Journal of Physics: Conference Series, Volume 409, **2013**
http://iopscience.iop.org/1742-6596/409/1
23rd European Cosmic Ray Symposium (and 32nd Russian Cosmic Ray Conference)
3–7 July 2012, Moscow, Russia

Ground Level Enhancement Events of Solar Cycle 23 **Topical issue**
Guest Editors: Natchimuthuk **Gopalswamy** and Nariaki Nitta
Space Science Reviews, Volume 171, Numbers 1-4 / October **2012**
http://www.springerlink.com/content/0038-6308/171/1-4/

Particle Acceleration and Transport in the Heliosphere and Beyond
7th Annual International Astrophysics Conference
Kauai, HI, 7-13 March 2008
Series: AIP Conference Proceedings
Subseries: Astronomy and Astrophysics , Vol. 1039
Li, G.; Hu, Q.; Verkhoglyadova, O.; Zank, G.; Lin, R.P.; Luhmann, J. (Eds.)
2008, Approx. 455 p.,

Our star is a very effective particle accelerator. Energies up to GeVs have been observed in Solar energetic particle events. These events are often associated with solar flares and/or Coronal Mass Ejections. Understanding how particles are accelerated in these phenomena has been an outstanding problem in space plasma physics for a long time. Part of the reason is its practical (e.g. Space weather) and fundamental (cosmic ray origin) importance. In this conference we review recent progresses on this problem, with a balance between observations, theories and numerical simulations. Specific topics include 1) particle acceleration at flare site, 2) turbulence properties of the solar wind, 3) particle acceleration and transport in the inner heliosphere, 4) particle acceleration at the termination shock and heliosheath, and 5) particle acceleration at supernova remnant shocks.

Energetic Particles and Magnetic Reconnection on the Sun and in the Heliosphere
Advances in Space Research, Volume 41, Issue 6, Pages 829-1002 **(2008)**

Space Science Reviews, Volume 130 Number 1-4, 2007
Many papers **on SEP composition**

Advances in Space Research, Volume 38, Issue 3, pp. 389-560 (2006)
Many papers on Coronal Mass Ejections and Solar Particle Events in Solar Cycle 23

Solar Eruptions and Energetic Particles
AGU Monograph, Vol. 165, **2006**, ed. N. Gopalswamy, R. Mewaldt, & Torsti, J. (Washington DC: American Geophysical Union)
http://onlinelibrary.wiley.com/book/10.1029/GM165

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Detection of the Temporal Variation of the Sun's Cosmic Ray Shadow with the IceCube Detector
M. G. **Aartsen**1, M. Ackermann2, J. Adams1, J. A. Aguilar3, M. Ahlers4, M. Ahrens5, D. Altmann6, K. Andeen7, T. Anderson8, I. Ansseau3Show full author list
2019 ApJ 872 133
https://doi.org/10.3847/1538-4357/aaffd1
We report on the observation of a deficit in the cosmic ray flux from the directions of the Moon and Sun with five years of data taken by the IceCube Neutrino Observatory. Between 2010 May and 2011 May the IceCube detector operated with 79 strings deployed in the glacial ice at the South Pole, and with 86 strings between 2011 May and

2015 May. A binned analysis is used to measure the relative deficit and significance of the cosmic ray shadows. Both the cosmic ray Moon and Sun shadows are detected with high statistical significance (>10σ) for each year. The results for the Moon shadow are consistent with previous analyses and verify the stability of the IceCube detector over time. This work represents the first observation of the Sun shadow with the IceCube detector. We show that the cosmic ray shadow of the Sun varies with time. These results make it possible to study cosmic ray transport near the Sun with future data from IceCube.

Search for Large-scale Anisotropy on Arrival Directions of Ultra-high-energy Cosmic Rays Observed with the Telescope Array Experiment

R. U. **Abbasi**, M. Abe, T. Abu-Zayyad, M. Allen, R. Azuma, E. Barcikowski, at al.

2020 ApJL 898 L28

https://doi.org/10.3847/2041-8213/aba0bc

Motivated by the detection of a significant dipole structure in the arrival directions of ultra-high-energy cosmic rays above 8 EeV reported by the Pierre Auger Observatory (Auger), we search for a large-scale anisotropy using data collected with the surface detector array of the Telescope Array Experiment (TA). With 11 yr of TA data, a dipole structure in a projection of the R.A. is fitted with an amplitude of 3.3% ± 1.9% and a phase of 131° ± 33°. The corresponding 99% confidence-level upper limit on the amplitude is 7.3%. At the current level of statistics, the fitted result is compatible with both an isotropic distribution and the dipole structure reported by Auger.

SOLAR ENERGETIC PARTICLE SPECTRUM ON *2006 DECEMBER 13* DETERMINED BY IceTop

R. **Abbasi** et al.

The Astrophysical Journal, 689: L65–L68, 2008

On 2006 December 13 the IceTop air shower array at the South Pole detected a major solar particle event. By numerically simulating the response of the IceTop tanks, which are thick Cerenkov detectors with multiple thresholds deployed at high altitude with no geomagnetic cutoff, we determined the particle energy spectrum in the energy range 0.6–7.6 GeV. This is the first such spectral measurement using a single instrument with a welldefined viewing direction. We compare the IceTop spectrum and its time evolution with previously published results and outline plans for improved resolution of future solar particle spectra.

Predicting Solar Energetic Particles Using SDO/HMI Vector Magnetic Data Products and a Bidirectional LSTM Network

Yasser **Abduallah**, Vania K. Jordanova, Hao Liu, Qin Li, Jason T. L. Wang, Haimin Wang

ApJS **260** 16 **2022**

https://arxiv.org/pdf/2203.14393.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/ac5f56/pdf

Solar energetic particles (SEPs) are an essential source of space radiation, which are hazards for humans in space, spacecraft, and technology in general. In this paper we propose a deep learning method, specifically a bidirectional long short-term memory (biLSTM) network, to predict if an active region (AR) would produce an SEP event given that (i) the AR will produce an M- or X-class flare and a coronal mass ejection (CME) associated with the flare, or (ii) the AR will produce an M- or X-class flare regardless of whether or not the flare is associated with a CME. The data samples used in this study are collected from the Geostationary Operational Environmental Satellite's X-ray flare catalogs provided by the National Centers for Environmental Information. We select M- and X-class flares with identified ARs in the catalogs for the period between 2010 and 2021, and find the associations of flares, CMEs and SEPs in the Space Weather Database of Notifications, Knowledge, Information during the same period. Each data sample contains physical parameters collected from the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory. Experimental results based on different performance metrics demonstrate that the proposed biLSTM network is better than related machine learning algorithms for the two SEP prediction tasks studied here. We also discuss extensions of our approach for probabilistic forecasting and calibration with empirical evaluation.

PAMELA's measurements of geomagnetic cutoff variations during the 14 December 2006 storm

O. **Adriani**, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, et al

Space Weather Volume 14, Issue 3 March **2016**

Space Weather Quarterly Vol. 13, Issue 2, **2016**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016SW001364

Data from the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment were used to measure the geomagnetic cutoff for high-energy (≳ 80MeV) protons during the 14 December 2006 geomagnetic storm. The variations of the cutoff latitude as a function of rigidity were studied on relatively short timescales, corresponding to spacecraft orbital periods (~94 min). Estimated cutoff values were compared with those obtained by means of a trajectory-tracing approach based on a dynamical empirical modeling of the Earth's magnetosphere. We found significant variations in the cutoff latitude, with a maximum suppression of ~7° at lowest rigidities during the main phase of the storm. The observed reduction in the geomagnetic shielding and its temporal evolution were related to the changes in the magnetospheric configuration, investigating the role of interplanetary magnetic field, solar wind, and geomagnetic parameters. PAMELA's results represent the first direct measurement of geomagnetic cutoffs for protons with kinetic energies in the sub-GeV and GeV region.

PAMELA's Measurements of Magnetospheric Effects on High Energy Solar Particles

O. **Adriani**, G. C. Barbarino, G. A. Bazilevskaya et al.
ApJL **801** L3 **2015**
http://arxiv.org/pdf/1502.00935v1.pdf
https://iopscience.iop.org/article/10.1088/2041-8205/801/1/L3/pdf
The nature of particle acceleration at the Sun, whether through flare reconnection processes or through shocks driven by coronal mass ejections (CMEs), is still under scrutiny despite decades of research. The measured properties of solar energetic particles (SEPs) have long been modeled in different particle-acceleration scenarios. The challenge has been to disentangle to the effects of transport from those of acceleration. The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) instrument, enables unique observations of SEPs including composition and the angular distribution of the particles about the magnetic field, i.e. pitch angle distribution, over a broad energy range (>80 MeV) -- bridging a critical gap between space-based measurements and ground-based. We present high-energy SEP data from PAMELA acquired during the **2012 May 17** SEP event. These data exhibit differential anisotropies and thus transport features over the instrument rigidity range. SEP protons exhibit two distinct pitch angle distributions; a low-energy population that extends to 90{\deg} and a population that is beamed at high energies (>1 GeV), consistent with neutron monitor measurements. To explain a low-energy SEP population that exhibits significant scattering or redistribution accompanied by a high-energy population that reaches the Earth relatively unaffected by dispersive transport effects, we postulate that the scattering or redistribution takes place locally. We believe these are the first comprehensive measurements of the effects of solar energetic particle transport in the Earth's magnetosheath.

The PAMELA Mission: Heralding a new era in precision cosmic ray physics

Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al.
2014, Physics Reports, 544, 4, 323-370.
https://reader.elsevier.com/reader/sd/pii/S0370157314002087?token=BF7FB0A7AB00D9A44C75447129E07D45347BCFFD982D71CDEBCE42020F38D8DA7A85DEF7D5698EC3C4F085A08C077B5C
On the 15th of June 2006, the PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) satellite-borne experiment was launched onboard the Russian Resurs-DK1 satellite by a Soyuz rocket from the Baikonur space centre. The satellite was placed in a quasi-polar 70°inclination orbit at an altitude varying between 350 km and 600 km.
New results on the antiparticle component of the cosmic radiation were obtained. The positron energy spectrum and positron fraction were measured from 400 MeV up to 200 GeV revealing a positron excess over the predictions of commonly used propagation models. This can be interpreted either as evidence that the propagation models should be revised or in terms of dark matter annihilation or a pulsar contribution. The antiproton spectrum was measured over the energy range from 60 MeV to 350 GeV. The antiproton spectrum is consistent with secondary production and significantly constrains dark matter models.
The energy spectra of protons and helium nuclei were measured up to 1.2 TV. The spectral shapes of these two species are different and cannot be described well by a single power law. For the first time the electron spectrum was measured up to 600 GeV complementing the information obtained from the positron data. Nuclear and isotopic composition was obtained with unprecedented precision.
The variation of the low energy proton, electron and positron energy spectra was measured from July 2006 until December 2009 accurately sampling the unusual conditions of the most recent solar minimum activity period (2006–2009). Low energy particle spectra were accurately measured also for various solar events that occurred during the PAMELA mission.
The Earth's magnetosphere was studied measuring the particle radiation in different regions of the magnetosphere. Energy spectra and composition of sub-cutoff and trapped particles were obtained. For the first time a belt of trapped antiprotons was detected in the South Atlantic Anomaly region. The flux was found to exceed that for galactic cosmic-ray antiprotons by three order of magnitude.

OBSERVATIONS OF THE 2006 DECEMBER 13 AND 14 SOLAR PARTICLE EVENTS IN THE 80 MeV n–1-3 GeV n–1 RANGE FROM SPACE WITH THE PAMELA DETECTOR

O. **Adriani,** G. C. Barbarino, G. A. Bazilevskaya, et al.
2011 ApJ 742 102

https://iopscience.iop.org/article/10.1088/0004-637X/742/2/102/pdf

We present the space spectrometer PAMELA observations of proton and helium fluxes during the **2006 December 13 and 14** solar particle events. This is the first direct measurement of the solar energetic particles in space with a single instrument in the energy range from ~80 MeV n–1 up to ~3 GeV n–1. For the December 13 event, measured energy spectra of solar protons and helium are compared with results obtained by neutron monitors and other detectors. Our measurements show a spectral behavior different from those derived from the neutron monitor network. No satisfactory analytical fitting was found for the energy spectra. During the first hours of the December 13 event, solar energetic particles spectra were close to the exponential form, demonstrating rather significant temporal evolution. Solar He with energy up to 1 GeV n–1 was recorded on December 13. For the December 14 event, energy of solar protons reached 600 MeV, whereas the maximum energy of He was below 100 MeV n–1. The spectra were slightly bent in the lower energy range and preserved their form during the second event. Differences in the particle flux appearance and temporal evolution of these two events may argue for special conditions leading to the acceleration of solar particles up to relativistic energies.

Towards advanced forecasting of solar energetic particle events with the PARASOL model

Alexandr **Afanasiev**, Nicolas Wijsen, Rami Vainio

Journal of Space Weather and Space Climate (JSWSC) **2024**

https://arxiv.org/pdf/2412.11852

Gradual solar energetic particle (SEP) events are generally attributed to the particle acceleration in shock waves driven by coronal mass ejections (CMEs). Space-weather effects of such events are important, so there has been continuous effort to develop models able to forecast their various characteristics. Here we present the first version of a new such model with the primary goal to address energetic storm particle (ESP) events. The model, PARASOL, is built upon the PArticle Radiation Asset Directed at Interplanetary Space Exploration (PARADISE) test-particle simulation model of SEP transport, but includes a semi-analytical description of an inner (i.e., near the shock) part of the foreshock region. The semi-analytical foreshock description is constructed using simulations with the SOLar Particle Acceleration in Coronal Shocks (SOLPACS) model, which simulates proton acceleration self-consistently coupled with Alfven wave generation upstream of the shock, and subsequent fitting of the simulation results with suitable analytical functions. PARASOL requires input of solar wind and shock magnetohydrodynamic (MHD) parameters. We evaluate the performance of PARASOL by simulating the **12 July 2012** SEP event, using the EUropean Heliospheric FORecasting Information Asset (EUHFORIA) MHD simulation of the solar wind and CME in this event. The PARASOL simulation has reproduced the observed ESP event (E≲5 MeV) in the close vicinity of the shock within one order of magnitude in intensity.

Self-consistent modeling of the *energetic storm particle event* of 10 November 2012

A. **Afanasiev**1 , R. Vainio1 , D. Trotta2 , S. Nyberg1 , N. Talebpour Sheshvan1 , H. Hietala3 , and N. Dresing1

A&A 679, A111 **2023**

https://arxiv.org/pdf/2310.00993.pdf

https://www.aanda.org/articles/aa/pdf/2023/11/aa46220-23.pdf

Context. It is thought that solar energetic ions associated with coronal/interplanetary shock waves are accelerated to high energies by the diffusive shock acceleration mechanism. In order to be efficient, this mechanism requires intense magnetic turbulence in the vicinity of the shock. The enhanced turbulence upstream of the shock can be produced self-consistently by the accelerated particles themselves via streaming instability. Comparisons of quasi-linear-theory-based particle acceleration models including this process with observations have not been fully successful so far, which has been a reason for the development of acceleration models of different nature. Aims. Our aim is to test how well our self-consistent quasi-linear SOLar Particle Acceleration in Coronal Shocks (SOLPACS) simulation code, developed earlier to simulate proton acceleration in coronal shocks, models the particle foreshock region. Methods. We apply SOLPACS to model the energetic storm particle (ESP) event observed by the STEREO A spacecraft on **November 10, 2012**. Results. All but one main input parameters of SOLPACS are fixed by the in-situ plasma measurements from the spacecraft. Comparison of a simulated proton energy spectrum at the shock with the observed one allows us to fix the last simulation input parameter related to efficiency of particle injection to the acceleration process. Subsequent comparison of simulated proton time-intensity profiles in a number of energy channels with the observed ones shows a very good correspondence throughout the upstream region. Conclusions. Our results strongly support the quasi-linear description of the foreshock region.

Modelling of proton acceleration in application to a ground level enhancement

A. **Afanasiev**, R. Vainio, A. P. Rouillard, M. Battarbee, A. Aran, P. Zucca

A&A 614, A4 **2018**

https://arxiv.org/pdf/1806.05497.pdf

https://www.aanda.org/articles/aa/pdf/2018/06/aa31343-17.pdf

Context The source of high-energy protons (>500 MeV) responsible for the so-called ground level enhancements (GLEs) remains an open question in solar physics. One of the candidates is a shock wave driven by a coronal mass ejection, which is thought to accelerate particles via diffusive-shock acceleration.
Aims We perform physics-based simulations of proton acceleration using information on the shock and ambient plasma parameters derived from the observation of a real GLE event. We analyse the simulation results with the aim to find out which of the parameters are significant in controlling the acceleration efficiency and to get a better understanding of the conditions under which the shock can produce relativistic protons.
Methods We use results of the recently developed technique to determine the shock and ambient plasma parameters, applied to the **17 May 2012** GLE event, and carry out proton acceleration simulations with the Coronal Shock Acceleration model.
Results We have performed proton acceleration simulations for nine individual magnetic field lines characterised by various plasma conditions. Analysis of the simulation results shows that the acceleration efficiency of the shock, i.e., its ability to accelerate particles to high energies, tends to be higher for those shock portions that are characterised by larger values of the scattering-centre compression ratio and/or the fast-mode Mach number. At the same time, the acceleration efficiency can be strengthened due to enhanced plasma density in the flux tube. Analysis of the delays between the flare onset and the production times of protons of 1 GV rigidity for different field lines in our simulations, and a subsequent comparison of those with the observed values indicate a possibility that quasi-perpendicular portions of the shock play the main role in producing relativistic protons.

Self-consistent Monte Carlo simulations of proton acceleration in coronal shocks: Effect of anisotropic pitch-angle scattering of particles

A. **Afanasiev**, M. Battarbee and R. Vainio
A&A 584, A81 (**2015**)
http://arxiv.org/pdf/1603.08857v1.pdf

Context. Solar energetic particles observed in association with coronal mass ejections (CMEs) are produced by the CME-driven shock waves. The acceleration of particles is considered to be due to diffusive shock acceleration (DSA).
Aims. We aim at a better understanding of DSA in the case of quasi-parallel shocks, in which self-generated turbulence in the shock vicinity plays a key role.
Methods. We have developed and applied a new Monte Carlo simulation code for acceleration of protons in parallel coronal shocks. The code performs a self-consistent calculation of resonant interactions of particles with Alfvén waves based on the quasi-linear theory. In contrast to the existing Monte Carlo codes of DSA, the new code features the full quasi-linear resonance condition of particle pitch-angle scattering. This allows us to take anisotropy of particle pitch-angle scattering into account, while the older codes implement an approximate resonance condition leading to isotropic scattering. We performed simulations with the new code and with an old code, applying the same initial and boundary conditions, and have compared the results provided by both codes with each other, and with the predictions of the steady-state theory.
Results. We have found that anisotropic pitch-angle scattering leads to less efficient acceleration of particles than isotropic. However, extrapolations to particle injection rates higher than those we were able to use suggest the capability of DSA to produce relativistic particles. The particle and wave distributions in the foreshock as well as their time evolution, provided by our new simulation code, are significantly different from the previous results and from the steady-state theory. Specifically, the mean free path in the simulations with the new code is increasing with energy, in contrast to the theoretical result.

The Effect of Stochastic Re-acceleration on the Energy Spectrum of Shock-accelerated Protons

Alexandr **Afanasiev**1,2, Rami Vainio1,2, and Leon Kocharov
2014 ApJ 790 36

The energy spectra of particles in gradual solar energetic particle (SEP) events do not always have a power-law form attributed to the diffusive shock acceleration mechanism. In particular, the observed spectra in major SEP events can take the form of a broken (double) power law. In this paper, we study the effect of a process that can modify the power-law spectral form produced by the diffusive shock acceleration: the stochastic re-acceleration of energetic protons by enhanced Alfvénic turbulence in the downstream region of a shock wave. There are arguments suggesting that this process can be important when the shock propagates in the corona. We consider a coronal magnetic loop traversed by a shock and perform Monte Carlo simulations of interactions of shock-accelerated protons with Alfvén waves in the loop. The wave-particle interactions are treated self-consistently, so the finiteness of the available turbulent energy is taken into account. The initial energy spectrum of particles is taken to be a power law. The simulations reveal that the stochastic re-acceleration leads either to the formation of a spectrum that is described in a wide energy range by a power law (although the resulting power-law index is different from the initial one) or to a broken power-law spectrum. The resulting spectral form is determined by the ratio of the energy density of shock-accelerated protons to the wave energy density in the shock's downstream region.

Release History and Transport Parameters of Relativistic Solar Electrons Inferred From Near-the-Sun In-situ Observations

Agueda N. & Lario D.

2016 ApJ 829 131

E-print, 22 Sept 2016

We study four consecutive 300-800 keV electron events observed on **1980 May 28** by Helios-1, when the spacecraft was located at 0.31 AU from the Sun. We use two different techniques to extract the release time history of electrons at the Sun: (1) a data-driven method based on the assumption that particles conserve their magnetic moment as they propagate between the Sun and the spacecraft and (2) an inversion method that utilizes particle transport simulation results. Both methods make use of the particle angular distributions measured relative to the local direction of the magnetic field. The general characteristics of the release time profiles obtained by these two techniques are similar, especially during their rising phases. We find indications that the strength of the interplanetary scattering varies with the size of the solar parent event, suggesting that scattering processes are not necessarily an inherent property of the medium but are related to the amount of released particles at the Sun. We use the inferred release profiles to compute the expected intensities at 1 AU. In contrast to simultaneous near-Earth observations by IMP-8, our simulations predict the observation of four separate events at 1 AU. Processes that could contribute to the observation of one single time-extended event at 1 AU include (1) distinct magnetic connections of the spacecraft to the particle sources, (2) the spatio-temporal evolution of the particle sources, and (3) different particle transport conditions, including a variation of λr with radial distance and/or heliolongitude, as well as the possibility that electrons reached IMP-8 by diffusion perpendicular to the interplanetary magnetic field.

CURRENT SHEET REGULATION OF SOLAR NEAR-RELATIVISTIC ELECTRON INJECTION HISTORIES

N**. Agueda**1, R. Vainio2, S. Dalla3, D. Lario4, and B. Sanahuja

2013 ApJ 765 83

We present a sample of three large near-relativistic (>50 keV) electron events observed in 2001 by both the ACE and the Ulysses spacecraft, when Ulysses was at high-northern latitudes (>60°) and close to 2 AU. Despite the large latitudinal distance between the two spacecraft, electrons injected near the Sun reached both heliospheric locations. All three events were associated with large solar flares, strong decametric type II radio bursts and accompanied by wide (>212°) and fast (>1400 km s–1) coronal mass ejections (CMEs). We use advanced interplanetary transport simulations and make use of the directional intensities observed in situ by the spacecraft to infer the electron injection profile close to the Sun and the interplanetary transport conditions at both low and high latitudes. For the three selected events, we find similar interplanetary transport conditions at different heliolatitudes for a given event, with values of the mean free path ranging from 0.04 AU to 0.27 AU. We find differences in the injection profiles inferred for each spacecraft. We investigate the role that sector boundaries of the heliospheric current sheet (HCS) have on determining the characteristics of the electron injection profiles. Extended injection profiles, associated with coronal shocks, are found if the magnetic footpoints of the spacecraft lay in the same magnetic sector as the associated flare, while intermittent sparse injection episodes appear when the spacecraft footpoints are in the opposite sector or a wrap in the HCS bounded the CME structure.

Multi-spacecraft Study of the 8 November 2000 SEP Event: Electron Injection Histories 100 Degrees Apart

N. **Agueda**, D. Lario, V. Ontiveros, E. Kilpua, B. Sanahuja and R. Vainio

E-print, 30 March **2012,** Solar Physics, November **2012**, Volume 281, Issue 1, pp 319-331

We present the analysis of a large solar near-relativistic electron event observed by the Ulysses and the ACE spacecraft on **8 November 2000**, when Ulysses was located at a heliocentric distance of 2.4 AU and at a heliographic latitude of ~80? S. We use a particle propagation model to infer the local interplanetary transport conditions and the injection histories of the near-relativistic electrons observed by both spacecraft. We find different local transport conditions for each set of observations. The inferred injection profiles for both spacecraft extend for several hours; but the injection at Ulysses was smaller and started later. The association with type II radio emission suggests that the heliospheric electrons were provided by coronal shock acceleration. An analysis of the in situ magnetic field and plasma measurements indicates that the global configuration of the heliosphere (disturbed by transient structures) could play a role in shaping the characteristics of solar energetic particle events observed from different locations.

Modeling solar near-relativistic electron events
Insights into solar injection and interplanetary transport conditions

N. **Agueda**[1], D. Lario[2], R. Vainio[1], B. Sanahuja[3, 4], E. Kilpua[1], and S. Pohjolainen[5]

A&A 507, 981-993 (**2009**)

Context. Solar near-relativistic electrons (>30 keV) are observed as discrete events in the inner heliosphere following different types of solar transient activity. Several mechanisms have been proposed for the production of these electrons. One candidate is related to solar flare activity. Other candidates include shocks driven by fast coronal mass ejections (CMEs) or processes of magnetic reconnection in the aftermath of CMEs.
Aims. We study eleven near-relativistic (NR) electron events observed by the *Advanced Composition Explorer* (*ACE*) between 1998 and 2005 with the aim of estimating the roles played by solar flares, CME-driven shocks, and processes of magnetic restructuring in the aftermath of the CMEs in the injection of NR electrons. The main goal is to infer the underlying injection profile from particle observations at 1 AU, as well as the interplanetary transport conditions.
Methods. We used Monte Carlo simulations to model the transport of particles along the interplanetary magnetic field. By taking the angular response of the LEFS60 telescope of the EPAM instrument onboard *ACE* into account, we were able to deconvolve the transport effects from the observed intensities, and thus infer the solar injection profile.
Results. In this set of events, we have identified two types of injection episodes: short (<15 min) and time-extended (>1 h). Short injection episodes seem to be associated with the flare processes and/or the reconnection phenomena in the aftermath of the CME, while time-extended episodes seem to be consistent with injection from CME-driven shocks.
Conclusions. We find that there is no single scenario that operates in all the events. The interplanetary propagation of NR electrons can occur both under strong scattering and under almost scatter-free propagation conditions and several injection phases (related to flares and/or CMEs) are possible.

Sunspot activity and cosmic ray modulation at 1 a.u. for 1900–2013

H.S. **Ahluwalia**

Advances in Space Research, Volume 54, Issue 8, 15 October **2014**, Pages 1704–1716

http://www.sciencedirect.com/science/article/pii/S0273117714004141

The descent of sunspot cycle 23 to an unprecedented minimum of long duration in 2006–2009 led to a prolonged galactic cosmic ray (GCR) recovery to the highest level observed in the instrumental era for a variety of energetic charged particle species on Earth, over a wide range of rigidities. The remarkable GCR increase measured by several ground-based, balloon-borne, and detectors on a satellite is described and discussed. It is accompanied by a decrease in solar wind velocity and interplanetary magnetic field at 1 a.u., reaching the lowest values since measurements of the solar wind began in October 1963; the solar polar field strength (μT) measured at the Wilcox Solar Observatory (WSO) is also significantly reduced compared to prior cycles since the start of the program in 1976, the polar field in the northern hemisphere reversed in June 2012 and again in February 2014, that in the southern hemisphere reversed in July 2013. If updates of WSO data confirm the second reversal in northern solar hemisphere, it would pose a serious challenge to the Dynamo Theory. The long-term change in solar behavior may have begun in 1992, perhaps earlier. The physical underpinnings of these solar changes need to be understood and their effect on GCR modulation processes clarified. The study discusses the recent phenomena in the context of GCR modulation since 1900. These happenings affected our empirical predictions for the key parameters for the next two sunspot cycles (they may be progressively less active than sunspot cycle 24) but it enhanced support for our prediction that solar activity is descending into a Dalton-like grand minimum in the middle of the twentyfirst century, reducing the frequency of the coronal mass ejections; they determine the space weather affecting the quality of life on Earth, radiation dose for hardware and human activities in space as well as the frequency of large Forbush decreases at 1 a.u.

Results of quantitative diagnostics of proton flares from data on radiobursts for the control interval of 1970 - 1977.

Akinian, S. T. ; Fomichev, V. V. ; Chertok, I. M.

Geomagnetizm i Aeronomiia, vol. 20, May-June **1980**, p. 385-390. In Russian

An attempt is made to check the accuracy of a method (and relations) for calculating the parameters of proton fluxes from burst data. The calculated peak intensity and time-dependent parameters of the proton fluxes are found to be in satisfactory agreement with ground-based observations.

Radio radiation as information source on proton fluxes from solar flares.

Akin'yan, S. T. ; Fomichev, V. V. ; Chertok, I. M.

Complex investigations of the sun, p. 119 – 130б **1982**

Dispersive Suprathermal Ion Events Observed by the Parker Solar Probe Mission

S. T. **Alnussirat**1, R. Livi1, D. E. Larson1, A. Rahmati1, P. L. Whittlesey +++

2023 ApJL 954 L32

https://iopscience.iop.org/article/10.3847/2041-8213/acf21c/pdf

During Encounter 11, Parker Solar Probe observed a low-energy dispersive ions event of solar origin. The event was observed in the SPAN-I and IS⨀IS EPI-Lo sensors. The event started at a few MeV energy in the EPI-Lo sensor and progressed down in energy to ≈1 keV and merged with the bulk of the solar wind. This event is substantially different from typical solar energetic particles because the energetic population shows a distinct peak in the energy spectrum that descends in energy (not a power-law tail). In this Letter, we explore this event's nature, origin, and characteristics. **2022 February 27**

Solar Cycle Variation of 0.3-1.29 MeV/nucleon Heavy Ion Composition during Quiet Times near 1 AU in Solar Cycles 23 and 24

B. L. **Alterman**, Mihir I. Desai, Maher A. Dayeh, G. M. Mason, George Ho

ApJ **2023**

https://arxiv.org/pdf/2305.05441.pdf

We report on the annual variation of quiet-time suprathermal ion composition for C through Fe using Advanced Composition Explorer (ACE)/Ultra-Low Energy Isotope Spectrometer (ULEIS) data over the energy range 0.3 MeV/nuc to 1.28 MeV/nuc from 1998 through 2019, covering solar cycle 23's rising phase through Solar Cycle 24's declining phase. Our findings are (1) quiet time suprathermal abundances resemble CIR-associated particles during solar minima; (2) quiet time suprathermals are M/Q fractionated in a manner that is consistent with M/Q fractionation in large gradual solar energetic particle events (GSEP) during solar maxima; and (3) variability within the quiet time suprathermal pool increases as a function of M/Q and is consistent with the analogous variability in GSEP events. From these observations, we infer that quiet time suprathermal ions are remnants of CIRs in solar minima and GSEP events in solar maxima. Coincident with these results, we also unexpectedly show that S behaves like a low FIP ion in the suprathermal regime and therefore drawn from low FIP solar sources.

Solar Activity from 2006 to 2014 and Short-term Forecasts of Solar Proton Events Using the ESPERTA Model

T. **Alberti**1, M. Laurenza2, E. W. Cliver3, M. Storini2, G. Consolini2, and F. Lepreti

2017 ApJ 838 59 **File**

http://sci-hub.cc/10.3847/1538-4357/aa5cb8

http://iopscience.iop.org/article/10.3847/1538-4357/aa5cb8/pdf

To evaluate the solar energetic proton (SEP) forecast model of Laurenza et al., here termed ESPERTA, we computed the input parameters (soft X-ray (SXR) fluence and ~1 MHz radio fluence) for all ≥M2 SXR flares from 2006 to 2014. This database is outside the 1995–2005 interval on which ESPERTA was developed. To assess the difference in the general level of activity between these two intervals, we compared the occurrence frequencies of SXR flares and SEP events for the first six years of cycles 23 (1996 September–2002 September) and 24 (2008 December–2014 December). We found a reduction of SXR flares and SEP events of 40% and 46%, respectively, in the latter period. Moreover, the numbers of ≥M2 flares with high values of SXR and ~1 MHz fluences (>0.1 J m−2 and >6 × 105 sfu × minute, respectively) are both reduced by ~30%. A somewhat larger percentage decrease of these two parameters (~40% versus ~30%) is obtained for the 2006–2014 interval in comparison with 1995–2005. Despite these differences, ESPERTA performance was comparable for the two intervals. For the 2006–2014 interval, ESPERTA had a probability of detection (POD) of 59% (19/32) and a false alarm rate (FAR) of 30% (8/27), versus a POD = 63% (47/75) and an FAR = 42% (34/81) for the original 1995–2005 data set. In addition, for the 2006–2014 interval the median (average) warning time was estimated to be ~2 hr (~7 hr), versus ~6 hr (~9 hr), for the 1995–2005 data set. **6 Dec 2006, 13 Dec 2006, 8 Mar 2011, 7 Aug 2011, 9 Aug 2011, 23-26 Sep 2011, 28 Jan 2012, 7-8 Mar 2012, 13 Mar 2012, 7 Jul 2012, 12 Jul 2012, 11 Apr 2013, 22-23 May 2013, 22-24 Jun 2013, 6-8 Jan 2014, 25-28 Feb 2014, 18-19 Apr 2014, 11-12 Sep 2014**

Table 1 SEP Flare List (2006–2014)

Хорошее Введение

Characterization of X-ray and Type III radio bursts during solar cycle 24 for short-term warning of solar energetic particle events

Alberti, Tommaso; Laurenza, Monica; Storini, Marisa; Lepreti, Fabio; Cliver, Edward W.

EGU General Assembly 2016, held 17-22 April, **2016** in Vienna Austria, p.14599

http://meetingorganizer.copernicus.org/EGU2016/EGU2016-14599-1.pdf

The empirical model developed by Laurenza et al. (2009), based on data from 1995 to 2005, can provide short-term warnings of solar energetic proton (SEP) events that meet or exceed the Space Weather Prediction Center threshold of J (≥ 10MeV) = 10 p cm-2 s-1 sr-1, within 10 minutes after the maximum of the associated soft X-ray flare. The ≥

M2 X-ray and type III bursts occurred in the period 2006 - 2014 were used to compute the parameters of the model, i.e. the time-integrated soft X-ray intensity and time-integrated intensity of type III radio emission at about 1 MHz. The probability distribution functions associated with both parameters were derived. It was found that both the occurrence and the fluence of X-ray bursts is noticeably reduced in solar cycle 24 (35% and 30%, respectively, compared to solar cycle 23). The radio fluence of type III bursts associated to the considered X-ray events was lower of about 30% as well. Moreover, in order to test the accuracy of the model, the probability of detection (POD) and the False Alarm Rate (FAR) were evaluated by using the new database. The obtained verification measures show a good performance of the model: POD= 59% and FAR= 30%, which are, respectively, comparable and even lower with respect to those obtained from the datset on which the model was developed. Moreover, the performance is very high when major SEP events, having a peak flux ≥ 100 pfu, are considered (POD=79%, FAR=5%), i. e., for the most hazardous Space Weather conditions. Finally, the median warning time (as computed by Nunez (2011)) was estimated to be of about 11 h, highly exceeding that obtained through other competing techniques. References [1] Laurenza, M., E. W. Cliver, J. Hewitt, M. Storini, A. Ling, C. C. Balch, and M. L. Kaiser (2009), Space Weather, 7, S04008, doi:10.1029/2007SW000379. [2] Núñez, M. (2011), Predicting solar energetic proton events (E > 10 MeV), Space Weather, 9, S07003, doi:10.1029/2010SW000640.

Predicting Solar Proton Events of Solar Cycles 22-24 using GOES Proton & Soft X-Ray Flux Statistics

Aatiya **Ali**, Viacheslav Sadykov, Alexander Kosovichev, Irina N. Kitiashvili, Vincent Oria, Gelu M. Nita, Egor Illarionov, Patrick M. O'Keefe, Fraila Francis, Chun-Jie Chong, Paul Kosovich, Russell D. Marroquin

2024 *ApJS* **270** 15

https://arxiv.org/pdf/2303.05446.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/ad0a6c/pdf

Solar Energetic Particle (SEP) events and their major subclass, Solar Proton Events (SPEs), can result in unfavorable consequences to numerous aspects of life and technology, making them one of the most prevalent and harmful effects of solar activity. Garnering knowledge leading up to such events by studying proton and soft X-ray (SXR) flux data to alleviate the burdens they cause is therefore critical for their forecasting. Our previous SEP prediction study, Sadykov et al. 2021 indicated that it may be sufficient to utilize only proton and SXR parameters for SPE forecasts considering a limited data set from Solar Cycle (SC) 24. In this work we report the completion of a catalog of ≥ 10 MeV ≥10 particle flux unit (pfu) SPEs observed by Geostationary Operational Environmental Satellite (GOES) detectors operated by the National Oceanic and Atmospheric Administration (NOAA), with records of their properties spanning through SCs 22-24. We report an additional catalog of daily proton and SXR flux statistics. We use these catalogs to test the application of machine learning (ML) for the prediction of SPEs using a Support Vector Machine (SVM) algorithm. We explore how previous SCs can train and test on each other using both earlier and longer data sets during the training phase, evaluating how transferable an algorithm is across different time periods. Validation against the effects of cross-cycle transferability is an understudied area in SEP research, but should be considered for verifying the cross-cycle robustness of an ML-driven forecast.   **2006-12-06, 2006-12-10**

Solar Cycle Variation of 0.3–1.29 MeV Nucleon−1 Heavy Ion Composition During Quiet Times Near 1 au in Solar Cycles 23 and 24

B. L. **Alterman**1, Mihir I. Desai1,2, Maher A. Dayeh1,2, Glenn M. Mason3, and George Ho3

2023 ApJ 952 42

https://iopscience.iop.org/article/10.3847/1538-4357/acd24a/pdf

We report on the annual variation of quiet-time suprathermal ion composition for C through Fe using Advanced Composition Explorer (ACE)/Ultra-Low Energy Isotope Spectrometer data over the energy range 0.3–1.28 MeV nuc−1 from 1998 through 2019, covering solar cycle 23's rising phase through Solar Cycle 24's declining phase. Our findings are: (1) quiet-time suprathermal abundances resemble CIR-associated particles during solar minima; (2) quiet-time suprathermals are M/Q fractionated in a manner that is consistent with M/Q fractionation **in large gradual solar energetic particle events (GSEP)** during solar maxima; and (3) variability within the quiet-time suprathermal pool increases as a function of M/Q and is consistent with **the analogous variability in GSEP events**. From these observations, we infer that **quiet-time suprathermal ions are remnants of CIRs in solar minima and GSEP events in solar maxima**. Coincident with these results, we also unexpectedly show that S behaves like a low FIP ion in the suprathermal regime, and is therefore drawn from low FIP solar sources.

Influence of Earth-directed Coronal Mass Ejections on the Sun's Shadow Observed by the Tibet-III Air Shower Array

M. **Amenomori**1, X. J. Bi2, D. Chen3, T. L. Chen4, W. Y. Chen2, S. W. Cui5, Danzengluobu4, L. K. Ding2, C. F. Feng6, Zhaoyang Feng2 .....

2018 ApJ 860 13 DOI [10.3847/1538-4357/aac2e6](https://doi.org/10.3847/1538-4357/aac2e6)
We examine the possible influence of Earth-directed coronal mass ejections (ECMEs) on the Sun's shadow in the 3 TeV cosmic-ray intensity observed by the Tibet-III air shower (AS) array. We confirm a clear solar-cycle variation of the intensity deficit in the Sun's shadow during ten years between 2000 and 2009. This solar-cycle variation is overall reproduced by our Monte Carlo (MC) simulations of the Sun's shadow based on the potential field model of the solar magnetic field averaged over each solar rotation period. We find, however, that the magnitude of the observed intensity deficit in the Sun's shadow is significantly less than that predicted by MC simulations, particularly during the period around solar maximum when a significant number of ECMEs is recorded.
The χ 2 tests of the agreement between the observations and the MC simulations show that the difference is larger during the periods when the ECMEs occur, and the difference is reduced if the periods of ECMEs are excluded from the analysis. This suggests the first experimental evidence of the ECMEs affecting the Sun's shadow observed in the 3 TeV cosmic-ray intensity.

Characterizing High-Energy Solar Proton Events with Energies Below and Above 100 MeV.

Ameri, D., Valtonen, E., Al-Sawad, A. et al.
Sol Phys 299, 133 (**2024**).
https://doi.org/10.1007/s11207-024-02378-9
https://link.springer.com/content/pdf/10.1007/s11207-024-02378-9.pdf
We analyzed 58 high-energy proton events that occurred during the years 1996 – 2022. In 32 out of the 58 (55%) events, the proton energies extended up to ∼68 MeV but did not reach 100 MeV. In the remaining 26 events, the proton energies exceeded 100 MeV. We studied the differences in the characteristics of these proton events and their associations with solar and interplanetary phenomena to improve understanding proton sources and acceleration processes.
The coronal mass ejections (CMEs) associated with >100 MeV proton events appeared to be, on average, more energetic than those associated with <100 MeV proton events. The peak and integrated fluxes (fluence) of the soft X-ray (SXR) flares were higher in > 100 MeV proton events, but there was almost no difference in the rise times of the flares. In a major part of the >100 MeV proton events, protons were released over the rise phase of the SXR flares, whereas in most of the <100 MeV events the proton releases occurred after the peak of the SXR flares. We established limits for the CME speed VCME and SXR peak flux Fpk or total fluence Fi, which helped us to distinguish the events in the two groups. Solar eruptions with VCME >1000 km s−1 and Fpk>5·10−5 W m−2 had a high probability to produce proton events of >100 MeV. On the other hand, eruptions with VCME>900 km s−1 and Fi<5·10−4 J m−2 and eruptions with VCME<900 km s−1 irrespective of the SXR total fluence were very likely to produce proton events of <100 MeV.
All proton events were associated with decametric Type III radio bursts, and most of them had Type II bursts associations either in metric or decametric–hectometric (DH) wavelengths or both. Both metric- and DH-Type II emissions were observed in 50% of <100 MeV proton events while they were observed in 88% of >100 MeV events. Our analysis showed that protons in most of the >100 MeV events were released low in the corona (≤3.0 R⨀) before the onsets of the DH-Type II radio bursts. Conversely, protons in most of the <100 MeV events were released higher in the corona (>3 R⨀) and after the DH-Type II onsets.
We conclude that protons in most of the >100 MeV events are accelerated either by the flare reconnection processes or by shocks low in the corona and could undergo reacceleration higher in the corona in CME shocks manifested in DH-Type II radio emission. In the <100 MeV events, protons are mainly accelerated in CME shocks at coronal heights >3 R⨀. **10 Jun 2000, 14 Aug 2010**
Table 2 List of high-energy proton events with associated soft X-ray flares, CMEs, and radio emissions during 1996 – 2022.

Empirical forecasting models for peak intensities of energetic storm particles at 1 AU

Dheyaa **Ameri** a b, Rami Vainio b, Eino Valtonen b
Advances in Space Research Volume 73, Issue 1, 1 January **2024**, Pages 1050-1063
https://doi.org/10.1016/j.asr.2023.11.021
https://www.sciencedirect.com/science/article/pii/S0273117723009067
We have investigated the dependence of the peak intensities of energetic storm particles (ESPs) on various parameters characterising the coronal mass ejections (CMEs) and associated phenomena. The aim of this study is to suggest empirical models for forecasting the peak intensities of ESP events at 1 AU based on solar and interplanetary (IP) space observations.
For this study we searched for the associations of front-side full and partial halo CMEs with linear speeds >400 km s−1during the years 1996–2015 with IP shocks at 1 AU and ESP events observed near the time when the shock passes the observer. We found 88 CME-driven IP shocks associated with ESP events at proton energy range 5.0–7.2 MeV (nominal energy 6.0 MeV) and 59 shocks at the energy range 15.1–21.9 MeV (nominal energy 18.2 MeV).

At these two energies 71 % and 68 % of the ESP events were associated with solar energetic particle (SEP) events, 85 % and 84 % were associated with decametric–hectometric (DH) type II radio bursts while 67 % and 66 % were associated with both.
For each CME - shock pair we calculated the predicted shock transit speed (VTR) by using the method of Belov et al. (2022) and used this as the primary parameter in the investigation. We performed correlation analyses between the logarithm of the peak intensities of the ESP events (log10 [IESPpeak]) and the solar parameters related to the CMEs, solar flares, IP shocks, SEP events, and type II radio bursts. When using a single explanatory variable, we found best correlation coefficients for VTR(0.68 ±0.05 and 0.71 ±0.06), the CME space speed (VCMEspace) (0.59 ± 0.05 and 0.68 ± 0.07), and the logarithm of SEP peak intensity (log10 [ISEPpeak]) (0.55 ± 0.08 and 0.70 ±0.08) at 6.0 and 18.2 MeV, respectively. Weak to moderate correlations were found for the logarithm of the soft X-ray flux (log10 [SXRF]) and the logarithm of the duration of DH type II radio burst (log10 [DTII]).
Using linear combinations of two or more variables improved the correlations. The best two-variable combination explaining log10 [IESPpeak] was VTRcombined with log10 [ISEPpeak] and the best three- and four-variable combinations also included these two parameters. We found two methods for forecasting ESP peak intensities, one of which can be used for long lead time and the other for medium lead time forecasting. For long lead time forecasting VTR, VCMEspaceand log10 [SXRF] are used. The correlation coefficients between the calculated and observed log10 [IESPpeak] were 0.71 ±0.05 at 6.0 MeV and 0.74 ±0.06 at 18.2 MeV. This method only depends on the coronagraph and X-ray observations at the Sun. For medium lead time forecasting the four parameters used are VTR, log10 [ISEPpeak], VCMEspace(or log10 [SXRF]), and log10 [DTII]. The correlation coefficients were 0.80 ±0.04 at 6.0 MeV and 0.84 ±0.05 at 18.2 MeV. Coronagraph observations at the Sun and solar energetic particle and DH type II burst measurements in IP space are required for this method. The medium lead time forecasting provides an average warning time of 30 ±16 h.

Relationships between energetic storm particle events and interplanetary shocks driven by full and partial halo coronal mass ejections

D. **Ameri**, E. Valtonen, A. Al-Sawad, R. Vainio

Adv. Space Res., Volume 71, Issue 5, (**2023**), pp. 2521-2533,
https://doi.org/10.1016/j.asr.2022.12.014
https://www.sciencedirect.com/science/article/pii/S0273117722011061

We have analysed energetic storm particle (ESP) events in 116 interplanetary (IP) shocks driven by front-side full and partial halo coronal mass ejections (CMEs) with speeds >400 km s^{-1}during the years 1996–2015. We investigated the occurrence and relationships of ESP events with several parameters describing the IP shocks, and the associated CMEs, type II radio bursts, and solar energetic particle (SEP) events. Most of the shocks (57 %) were associated with an ESP event at proton energies >1 MeV.
The shock transit speeds from the Sun to 1 AU of the shocks associated with an ESP event were significantly greater than those of the shocks without an ESP event, and best distinguished these two groups of shocks from each other. The occurrence and maximum intensity of the ESP events also had the strongest dependence on the shock transit speed compared to the other parameters investigated. The correlation coefficient between ESP peak intensities and shock transit speeds was highest (0.73 ± 0.04) at 6.2 MeV. Weaker dependences were found on the shock speed at 1 AU, Alfvénic and magnetosonic Mach numbers, shock compression ratio, and CME speed. On average all these parameters were significantly different for shocks capable to accelerate ESPs compared to shocks not associated with ESPs, while the differences in the shock normal angle and in the width and longitude of the CMEs were insignificant.
The CME-driven shocks producing energetic decametric–hectometric (DH) type II radio bursts and high-intensity SEP events proved to produce also more frequently ESP events with larger particle flux enhancements than other shocks. Together with the shock transit speed, the characteristics of solar DH type II radio bursts and SEP events play an important role in the occurrence and maximum intensity of ESP events at 1 AU.

Properties of High-Energy Solar Particle Events Associated with Solar Radio Emissions

Dheyaa **Ameri**, Eino Valtonen, Silja Pohjolainen

Solar Physics September **2019**, 294:122
sci-hub.se/10.1007/s11207-019-1512-9

We have analysed 58 high-energy proton events and 36 temporally related near-relativistic electron events from the years 1997 – 2015 for which the velocity dispersion analysis of the first-arriving particles gave the apparent path lengths between 1 and 3 AU. We investigated the dependence of the characteristics of the proton events on the associations of type II, III, and IV radio bursts. We also examined the properties of the soft X-ray flares and coronal mass ejections associated with these events. All proton events were associated with decametric type III radio bursts, while type IV emission was observed only in the meter wavelengths in some of the events (32/58). Almost all proton events (56/58) were associated with radio type II bursts: 11 with metric (m) type II only, 11 with decametric–hectometric (DH) only, and 34 with type II radio bursts at both wavelength ranges. By examining several characteristics of the proton events, we discovered that the proton events can be divided into two categories. The characteristics of events belonging to the same category were similar, while they significantly differed between events in different categories. The distinctive factors between the categories were the wavelength range of the associated type II radio emission and the temporal relation of the proton release with respect to the type II onset. In Category 1 are the events which were associated with only metric type II emission or both m and DH type II and the release time of protons was before the DH type II onset (18/56 events). Category 2 consists of the events which were associated with only DH type II emission or both m and DH type II and the protons were released at or after the DH type II onset (31/56 events). For seven of the 56 events we were not able to determine a definite category due to timing uncertainties. The events in Category 1 had significantly higher intensity rise rates, shorter rise times, lower release heights, and harder energy spectra than Category 2 events. Category 1 events also originated from magnetically well-connected regions and had only small time differences between the proton release times and the type III onsets. The soft X-ray flares for these events had significantly shorter rise times and durations than for Category 2 events. We found 36 electron events temporally related to the proton events, which fulfilled the same path length criterion as the proton events. We compared the release times of protons and electrons at the Sun, and discovered that in 19 of the 36 events protons were released almost simultaneously (within ±7±7 minutes) with the electrons, in 16 events protons were released later than the electrons, and in one event electrons were released after the protons. The simultaneous proton and electron events and the delayed proton events did not unambiguously fall in the two categories of proton events, although most of the events in which the protons were released after the electrons belonged to Category 2. We conclude that acceleration of protons in Category 1 events occurred low in the corona, either by CME-driven shocks or below the CMEs in solar flares or in CME initiation related processes. It seems plausible that protons in Category 2 events were accelerated by CME-driven shocks high in the solar corona. Large delays of protons with respect to type III onsets in the events where protons were released after the electrons suggest late acceleration or release of protons close to the Sun, but the exact mechanism causing the delay remained unclear. **18 June 2000, 11 April 2004**

Table 2 Event list with proton VDA results and onset times of associated solar radio emissions, soft X-ray flares, and CMEs.

Table 3 VDA results for the 36 solar electron events associated with the proton events

Solar Energetic Particle Event occurrence prediction using Solar Flare Soft X-ray measurements and Machine Learning

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J. Space Weather Space Clim. **2021**, 11, 59

https://www.swsc-journal.org/articles/swsc/pdf/2021/01/swsc210024.pdf

https://doi.org/10.1051/swsc/2021043

The prediction of the occurrence of Solar Energetic Particle (SEP) events has been investigated over many years, and multiple works have presented significant advances in this problem. The accurate and timely prediction of SEPs is of interest to the scientific community as well as mission designers, operators, and industrial partners due to the threat SEPs pose to satellites, spacecrafts, and crewed missions. In this work, we present a methodology for the prediction of SEPs from the soft X-rays of solar flares associated with SEPs that were measured in 1 AU. We use an expansive dataset covering 25 years of solar activity, 1988–2013, which includes thousands of flares and more than two hundred identified and catalogued SEPs. Neural networks are employed as the predictors in the model, providing probabilities for the occurrence or not of a SEP, which are converted to yes/no predictions. The neural networks are designed using current and state-of-the-art tools integrating recent advances in the machine learning field. The results of the methodology are extensively evaluated and validated using all the available data, and it is shown that we achieve very good levels of accuracy with correct SEP occurrence prediction higher than 85% and correct no-SEP predictions higher than 92%. Finally, we discuss further work towards potential improvements and the applicability of our model in real-life conditions.

Prediction of Solar Proton Event Fluence spectra from their Peak flux spectra

Sigiava **Aminalragia-Giamini**1*, Piers Jiggens2, Anastasios Anastasiadis3, Ingmar Sandberg1, Angels Aran4, Rami Vainio5, Constantinos Papadimitriou1, Athanasios Papaioannou3, Antonis Tsigkanos1, Evangelos Paouris3, Georgios Vasalos3, Miikka Paassilta5 and Mark Dierckxsens6

J. Space Weather Space Clim. **2020**, 10, 1

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190050.pdf

Solar Proton Events (SPEs) are of great importance and significance for the study of Space Weather and Heliophysics. These populations of protons are accelerated at high energies ranging from a few MeVs to hundreds

of MeVs and can pose a significant hazard both to equipment on board spacecrafts as well as astronauts as they are ionizing radiation. The ongoing study of SPEs can help to understand their characteristics, relative underlying physical mechanisms, and help in the design of forecasting and nowcasting systems which provide warnings and predictions. In this work, we present a study on the relationships between the Peak Flux and Fluence spectra of SPEs. This study builds upon existing work and provides further insights into the characteristics and the relationships of SPE Peak flux and Fluence spectra. Moreover it is shown how these relationships can be quantified in a sound manner and exploited in a simple methodology with which the Fluence spectrum of an SPE can be well predicted from its given Peak spectrum across two orders of magnitude of proton energies, from 5 MeV to 200 MeV. Finally it is discussed how the methodology in this work can be easily applied to forecasting and nowcasting systems.

The virtual enhancements − solar proton event radiation (VESPER) model

Sigiava **Aminalragia-Giamini**1,2*, Ingmar Sandberg1,2, Constantinos Papadimitriou1,2,Ioannis A. Daglis1,3 and Piers Jiggens

J. Space Weather Space Clim. **2018**, 8, A06

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170059.pdf

A new probabilistic model introducing a novel paradigm for the modelling of the solar proton environment at 1 AU is presented. The virtual enhancements − solar proton event radiation model (VESPER) uses the European space agency's solar energetic particle environment modelling (SEPEM) Reference Dataset and produces virtual time-series of proton differential fluxes. In this regard it fundamentally diverges from the approach of existing SPE models that are based on probabilistic descriptions of SPE macroscopic characteristics such as peak flux and cumulative fluence. It is shown that VESPER reproduces well the dataset characteristics it uses, and further comparisons with existing models are made with respect to their results. The production of time-series as the main output of the model opens a straightforward way for the calculation of solar proton radiation effects in terms of time-series and the pairing with effects caused by trapped radiation and galactic cosmic rays. **11-14 Jul 1982, 27-Nov-1989 to 05-Dec-1989**

Solar energetic particles in the inner heliosphere: status and open questions **Review**

Anastasios **Anastasiadis**, David Lario, Athanasios Papaioannou, Athanasios Kouloumvakos and Angelos Vourlidas

Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID: 20180100 **2019 File**

https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0100

Solar energetic particle (SEP) events are related to both solar flares and coronal mass ejections (CMEs) and they present energy spectra that span from a few keV up to several GeV. A wealth of observations from widely distributed spacecraft have revealed that SEPs fill very broad regions of the heliosphere, often all around the Sun. High-energy SEPs can sometimes be energetic enough to penetrate all the way down to the surface of the Earth and thus be recorded on the ground as ground level enhancements (GLEs). The conditions of the radiation environment are currently unpredictable due to an as-yet incomplete understanding of solar eruptions and their corresponding relation to SEP events. This is because the complex nature and the interplay of the injection, acceleration and transport processes undergone by the SEPs in the solar corona and the interplanetary space prevent us from establishing an accurate understanding (based on observations and modelling). In this work, we review the current status of knowledge on SEPs, focusing on GLEs and multi-spacecraft events. We extensively discuss the forecasting and nowcasting efforts of SEPs, dividing these into three categories. Finally, we report on the current open questions and the possible direction of future research efforts. **Хороший справочник литературы**

2. Solar energetic particle events short- and long-term forecasting

(a) Empirical or semi-empirical (b) Physics based (c) Other

Predicting Flares and Solar Energetic Particle Events: The FORSPEF Tool

A. **Anastasiadis**, A. Papaioannou, I. Sandberg, M. Georgoulis, K. Tziotziou, A. Kouloumvakos, P. Jiggens

Solar Physics September **2017**, 292:134

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1163-7.pdf

A novel integrated prediction system for solar flares (SFs) and solar energetic particle (SEP) events is presented here. The tool called forecasting solar particle events and flares (FORSPEF) provides forecasts of solar eruptive events, such as SFs with a projection to occurrence and velocity of coronal mass ejections (CMEs), and the likelihood of occurrence of an SEP event. In addition, the tool provides nowcasting of SEP events based on actual SF and CME near real-time data, as well as the SEP characteristics (e.g. peak flux, fluence, rise time, and duration) per parent solar event. The prediction of SFs relies on the effective connected magnetic field strength (BeffBeff) metric, which is based on an assessment of potentially flaring active-region (AR) magnetic

configurations, and it uses a sophisticated statistical analysis of a large number of AR magnetograms. For the prediction of SEP events, new statistical methods have been developed for the likelihood of the SEP occurrence and the expected SEP characteristics. The prediction window in the forecasting scheme is 24 hours with a refresh rate of 3 hours, while the respective prediction time for the nowcasting scheme depends on the availability of the near real-time data and ranges between 15 – 20 minutes for solar flares and 6 hours for CMEs. We present the modules of the FORSPEF system, their interconnection, and the operational setup. Finally, we demonstrate the validation of the modules of the FORSPEF tool using categorical scores constructed on archived data, and we also discuss independent case studies. **26 Oct-Nov 2003, 20 Jan 2005, 7 March 2012, 2014-12-18**
http://tromos.space.noa.gr/forspef/
CESRA Highlight #1551, Oct 2017 http://www.astro.gla.ac.uk/users/eduard/cesra/?p=1551

Acceleration of solar energetic particles: the case of solar flares
Anastasiadis, A.:
2002, J. Atmos. Solar-Terr. Phys. 64(5), 481. DOI
http://sci-hub.tw/10.1016/S1364-6826(02)00003-2
Solar energetic particles are believed to originate from two different sources, solar flares and coronal mass ejections. These two sources are the most energetic particle accelerators in the heliosphere, as they can accelerate electrons from 10keV to a few MeV and protons from a few MeV to a few GeV. In this contribution, we restrict our presentation to the case of solar flares, by reviewing the key observations of solar energetic particles, as well as the theoretical acceleration models, such as wave–particle acceleration, DC electric fields, and shock acceleration. Finally, we present a new theoretical approach connecting the acceleration with the energy release during solar flares, which might lead to a global modeling of solar flare energetics.

Intense Ground-Level Enhancements of Solar Cosmic Rays During the Last Solar Cycles
M. **Andriopoulou** · H. Mavromichalaki · C. Plainaki · A. Belov · E. Eroshenko
Solar Phys (2011) 269: 155–168, **File**
Ground-level enhancements of solar cosmic rays are sharp increases of short duration in the counting rates of ground-based neutron monitors. Their study is of particular importance, mainly due to their involvement in a vast range of applications such as the prediction of particle fluxes that may be harmful for satellite systems and telecommunication, the analysis of the interplanetary conditions, and the prediction of strong geomagnetic storms. In this work, we make a statistical analysis of the ground-level enhancements events occurring during solar Cycles 22 and 23, in an effort to reveal their common properties and possible physical mechanisms. Data of one- and five-minute resolutions are used, obtained from the worldwide network of neutron monitors and from the high-resolution NMDB database. The analysis includes onset-time calculations, determination of the maximum cosmic ray intensity, and determination of the longitudinal and latitudinal distribution. Moreover, a brief description of the most intense events is given. Finally, the importance of such a statistical analysis in space weather studies is discussed.

Charged Particle Transport in the Interplanetary Medium **Review**
Angels **Aran**, Neus Agueda, Alexandr Afanasiev, and Blai Sanahuja
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis
Chapter 3, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
The scenario and fundamentals of the physics of charged particle interplanetary transport are briefly introduced. Relevant characteristics of solar energetic particle (SEP) events and of the interplanetary magnetic field are described. Next, the motion of a charged particle and the main assumptions leading to the description of the focused and diffusive particle transport equations utilised in the next chapters are discussed. Finally, two different models are applied to interpret SEP events. **April 4, 2000**

Comparing proton fluxes of central meridian SEP events with those predicted by SOLPENCO.
Aran, A., B. Sanahuja, and D. Lario.
Adv. Space Res., 42, 1492–1499, **2008**,
http://sci-hub.se/10.1016/j.asr.2007.08.003

We have developed an operational code, SOLPENCO, that can be used for space weather prediction schemes of solar energetic particle (SEP) events. SOLPENCO provides proton differential flux and cumulated fluence profiles from the onset of the event up to the arrival of the associated traveling interplanetary shock at the observer's position (either 1.0 or 0.4 AU). SOLPENCO considers a variety of interplanetary scenarios where the SEP events develop. These scenarios include solar longitudes of the parent solar event ranging from E75 to W90, transit speeds of the associated shock ranging from 400 to 1700 km s_1, proton energies ranging from 0.125 to 64 MeV, and interplanetary conditions for the energetic particle transport characterized by specific mean free paths. We compare the results of SOLPENCO with flux measurements of a set of SEP events observed at 1 AU that fulfill the following four conditions: (1) the association between the interplanetary shock observed at 1 AU and the parent solar event is well established; (2) the heliolongitude of the active region site is within 30_ of the Sun–Earth line; (3) the event shows a significant proton flux increase at energies below 96 MeV; (4) the pre-event intensity background is low. The results are discussed in terms of the transit velocity of the shock and the proton energy. We draw conclusions about both the use of SOLPENCO as a prediction tool and the required improvements to make it useful for space weather purposes. **See** http://dev.sepem.oma.be/help/solpenco2_intro.html

SOLPEN CO: a solar particle engineering code.

Aran, A., B. Sanahuja, and D. Lario.
Adv. Space Res., 37, 1240–1246, **2006**,
http://sci-hub.se/10.1016/j.asr.2005.09.019
We present SOLPENCO (SOLar Particle ENgineering COde), the first step towards an operational tool able to quantitatively predict proton flux and fluence profiles of solar energetic particle (SEP) events associated with interplanetary shocks. The main components of this code are the following: a data base containing synthetic proton flux and fluence profiles for a set of 448 different scenarios at 1 AU and at 0.4 AU, for proton energies ranging from 0.125 to 64 MeV; and a user-friendly interface which permits rapid acquisition, by interpolation, of the flux and cumulative fluence profiles in the upstream part of an SEP event for a given solar-interplanetary scenario selected by the user (from among 697,800 cases). SOLPENCO also provides an estimate for the transit time and average speed of the CME-driven shock. We have started the validation of the outputs of this code by comparing them with several observed and modeled SEP events. As an example, we discuss here the case of the 4–6 April 2000 event. The main conclusions are that the code fits well the peak flux for several energy channels, and that the average parameters used to synthesize the flux and fluence profiles must be studied in more detail by performing a statistical study with a large set of observed and modeled SEP scenarios.

Fluxes and fluences of SEP events derived from SOLPENCO

A. **Aran**1, B. Sanahuja2,1, and D. Lario3
Ann. Geophys., 23, 3047-3053, **2005**
sci-hub.se/10.5194/angeo-23-3047-2005
We have developed aran04 a tool for rapid predictions of proton flux and fluence profiles observed during gradual solar energetic particle (SEP) events and upstream of the associated traveling interplanetary shocks. This code, named SOLPENCO (for SOLar Particle ENgineering COde), contains a data base with a large set of interplanetary scenarios under which SEP events develop. These scenarios are basically defined by the solar longitude of the parent solar activity, ranging from E75 to W90, and by the position of the observer, located at 0.4 AU or at 1.0 AU, from the Sun. We are now analyzing the performance and reliability of SOLPENCO. We address here two features of SEP events especially relevant to space weather purposes: the peak flux and the fluence. We analyze how the peak flux and the fluence of the synthetic profiles generated by SOLPENCO vary as a function of the strength of the CME-driven shock, the heliolongitude of the solar parent activity and the particle energy considered. In particular, we comment on the dependence of the fluence on the radial distance of the observer (which does not follow an inverse square law), and we draw conclusions about the influence of the shock as a particle accelerator in terms of its evolving strength and the heliolongitude of the solar site where the SEP event originated.

Neutron monitor yield function for solar neutrons: A new computation†

A. **Artamonov**, G.L. Kovaltsov, A.L. Mishev, I.G. Usoskin
JGR   Volume 121, Issue 1, pp. 117-128   **2016**
http://sci-hub.cc/10.1002/2015JA021993
A new yield function of a standard neutron monitor 6NM64 for solar neutrons is presented and tabulated in the attached lookup tables. It corresponds to a wide range of altitudes of the neutron monitor locations and angles of incidence for neutrons entering the Earth's atmosphere. The computations were made by Monte-Carlo using the GEANT4-based PLANETOCOSMICS tool. The yield function was validated against the measured data for solar neutron events of **03-Jun-1982 and 24-May-1990** and good agreement was found within a wide range of the altitudes of the neutron monitor location and angles of incidence of solar neutron arrival. The sensitivity of the world NM network for registration of solar neutron events was re-assessed. The neutron monitor network is shown

to be, in addition to other methods, a sensitive tool for monitoring of high-energy solar-flare neutrons with ≈95% probability to detect statistically significantly (>5σ) a solar neutron event similar to that of 03-Jun-1982.

GeV Particle Acceleration in Solar Flares and Ground Level Enhancement (GLE) Events

Review

Markus J. **Aschwanden**

Space Sci. Rev. Space Science Reviews, Volume 171, Numbers 1-4 (**2012**), 3-21, **File**

{sl Ground Level Enhancement (GLE)} events represent the most energetic class of {sl solar energetic particle (SEP)} events, requiring acceleration processes to boost gapprox 1 GeV ions in order to produce showers of secondary particles in the Earth's atmosphere with sufficient intensity to be detected by ground-level neutron monitors, above the background of cosmics rays. Although the association of GLE events with both solar flares and coronal mass ejections (CMEs) is undisputed, the question arises about the location of the responsible acceleration site: coronal flare reconnection sites, coronal CME shocks, or interplanetary shocks? To investigate the first possibility we explore the timing of GLE events with respect to hard X-ray production in solar flares, considering the height and magnetic topology of flares, the role of extended acceleration, and particle trapping. **We find that 50\% (6 out of 12) of recent (non-occulted) GLE events are accelerated during the impulsive flare phase, while the remaining half are accelerated significantly later. It appears that the prompt GLE component, which is observed in virtually all GLE events according to a recent study by Vashenyuk et al. (Astrophys. Space Sci. Trans. 7(4):459–463, 2011), is consistent with a flare origin in the lower corona, while the delayed gradual GLE component can be produced by both, either by extended acceleration and/or trapping in flare sites, or by particles accelerated in coronal and interplanetary shocks.**

GeV Particle Acceleration in Solar Flares and Ground Level Enhancement (GLE) Events

Markus J. **Aschwanden**1

E-print, 30 April **2010**, **File_1**, Space Sci. Rev.

Ground Level Enhancement (GLE) events represent the largest class of solar energetic particle (SEP) events that require acceleration processes to produce >~ 1 GeV ions in order to produce showers of secondary particles in the Earth's atmosphere with sufficient intensity to be detected by ground-level neutron monitors, above the background of cosmics rays. Although the association of GLE events with solar flares and coronal mass ejections (CMEs) is unambiguous, the question arises about the location of the responsible acceleration site: coronal flare sites or interplanetary CMEassociated shocks? To answer this question we scrutinize the timing of GLE events with respect to hard X-ray production in solar flares, the height and magnetic morphology of active regions, the role of extended acceleration and particle trapping, as well as the maximum observed energies in solar gamma rays. **We conclude that 70% of most recent 13 GLE events are consistent with acceleration during the impulsive flare phase, while the remaining 30% could be subject to extended acceleration and trapping, or partially originate in CME-associated shocks.**

E-print, **revised, Oct 7, 2010**, **File_2**, Space Sci. Rev.

Ground Level Enhancement (GLE) events represent the largest class of solar energetic particle (SEP) events that require acceleration processes to produce **>**~ 1 GeV ions in order to produce showers of secondary particles in the Earth's atmosphere with sufficient intensity to be detected by ground-level neutron monitors, above the background of cosmics rays. Although the association of GLE events with both solar flares and coronal mass ejections (CMEs) is undisputed, the question arises about the location of the responsible acceleration site: coronal flare sites or heliospheric CMEassociated shocks? To investigate the first possibility we explore the timing of GLE events with respect to hard X-ray production in solar flares, including corrections for the parth difference of GLE-producing protons, the height and magnetic topology of active regions, the role of extended acceleration and particle trapping, as well as the maximum observed energies in solar gamma rays. We find that 85% (11 out of 13) recent GLE events are accelerated during the impulsive flare phase, while the remaining 15% are accelerated later, which could possibly be explained by extended acceleration and/or trapping in flare sites. It appears that the prompt GLE component, which is observed in virtually all GLE events, is caused by flare-accelerated particles in the lower corona, while the delayed GLE component is more likely to be produced by particles accelerated in CME-associated shocks during their propagation through the corona and heliosphere.

E-print, **revised, Dec 21, 2011**, **File_3**, Space Sci. Rev. Space Science Reviews, Volume 171, Numbers 1-4 (**2012**), 3-21, **File**

{sl Ground Level Enhancement (GLE)} events represent the most energetic class of {sl solar energetic particle (SEP)} events, requiring acceleration processes to boost gapprox 1 GeV ions in order to produce showers of secondary particles in the Earth's atmosphere with sufficient intensity to be detected by ground-level neutron monitors, above the background of cosmics rays. Although the association of GLE events with both solar flares and coronal mass ejections (CMEs) is undisputed, the question arises about the location of the responsible acceleration site: coronal flare reconnection sites, coronal CME shocks, or interplanetary shocks? To investigate the first possibility we explore the timing of GLE events with respect to hard X-ray production in solar flares, considering the height and magnetic topology of flares, the role of extended acceleration, and particle trapping. **We find that**

50\% (6 out of 12) of recent (non-occulted) GLE events are accelerated during the impulsive flare phase, while the remaining half are accelerated significantly later. It appears that the prompt GLE component, which is observed in virtually all GLE events according to a recent study by Vashenyuk et al. (Astrophys. Space Sci. Trans. 7(4):459–463, 2011), is consistent with a flare origin in the lower corona, while the delayed gradual GLE component can be produced by both, either by extended acceleration and/or trapping in flare sites, or by particles accelerated in coronal and interplanetary shocks.

Flare Acceleration for GeV Particles

Markus **Aschwanden**

Presentation at "Ground Level Enhancement (GLE)"

Comparative Data Analysis Workshop (CDAW), LMSAL, Jan 6-9, **2009**

Conclusion:

1) The maximum energy of accelerated particles in flares is observed up to 100 MeV for electron bremsstrahlung and up to 1 GeV for protons and pions.

2) The maximum energy of accelerated particles observed in solar flare gamma rays implies severe constraints for sub-Dreicer electric field acceleration mechanisms, but is achievable with super-Dreicer fields or stochastic acceleration.

3) The altitude of acceleration regions in flare sites is confined to hacc=5000-35,000 km (<0.05 solar radii) according to time-of-flight measurements and direct hard X-ray imaging. Acceleration sites at larger distances to the Sun (as inferred for GLE events) are likely to be associated with CME shocks.

4) The vertical symmetry of acceleration sites warrants simultaneous acceleration in upward and downward direction (e.g., electric DC fields, wave turbulence regions, fast shocks in Petschek-type) and **allows charged particles to escape into interplanetary space and produce GLEs.**

The escape of flare-accelerated particles into interplanetary is faciliated on one hand by temporarily opened fields during the magnetic reconnetion process. For instance, during the "magnetic break-out model" (Antiochos et al. 1999), a temporary opening of a secondary arcade occurs during the reconnection process.

On the other hand, there are also pre-existing open field lines that allow particles to escape. Schrijver & DeRosa (2003) found from potential field extrapolations that a fraction of the IMF connects directly to plages of active regions (<10% in solar min. 30-50% at cycle max.)

THE LOCALIZATION OF PARTICLE ACCELERATION SITES IN SOLAR FLARES AND CMES

MARKUS J. **ASCHWANDEN**

Space Science Reviews (**2006**) 124: 361–372, **File**

Study of the Geoeffectiveness and Galactic Cosmic-Ray Response of VarSITI-ISEST Campaign Events in Solar Cycle 24

O. P. M. **Aslam**, Badruddin

Solar Physics September **2017**, 292:135

We analyze and compare the geomagnetic and galactic cosmic-ray (GCR) response of selected solar events, particularly the campaign events of the group International Study of Earth-affecting Solar Transients (ISEST) of the program Variability of the Sun and Its Terrestrial Impact (VarSITI). These selected events correspond to Solar Cycle 24, and we identified various of their features during their near-Earth passage. We evaluated the hourly data of geomagnetic indices and ground-based neutron monitors and the concurrent data of interplanetary plasma and field parameters. We recognized distinct features of these events and solar wind parameters when the geomagnetic disturbance was at its peak and when the cosmic-ray intensity was most affected. We also discuss the similarities and differences in the geoeffectiveness and GCR response of the solar and interplanetary structures in the light of plasma and field variations and physical mechanism(s), which play a crucial role in influencing the geomagnetic activity and GCR intensity. **14 July 2012, 8 Oct 2012, 17 March 2013, 31 May 2013, 17 March 2015, 21 June 2015,**

Analysis of Ground Level Enhancements (GLE): Extreme solar energetic particle events have hard spectra

E. **Asvestari**, T. Willamo, A. Gil, I.G. Usoskin, G.A. Kovaltsov, V.V. Mikhailov, A. Mayorov

Advances in Space Research Volume 60, Issue 4, 15 August **2017**, Pages 781-787

https://arxiv.org/pdf/1612.02446v1.pdf

https://doi.org/10.1016/j.asr.2016.08.043

https://sci-hub.st/10.1016/j.asr.2016.08.043

Nearly 70 Ground Level Enhancements (GLEs) of cosmic rays have been recorded by the worldwide neutron monitor network since the 1950s depicting a big variety of energy spectra of solar energetic particles (SEP). Here we studied a statistical relation between the event-integrated intensity of GLEs (calculated as count-rate relative excess, averaged over all available polar neutron monitors, and expressed in percent-hours) and the hardness of the solar particle energy spectra. For each event the integral omnidirectional event-integrated fluences of particles with energy above 30 MeV (F30) and above 200 MeV (F200) were computed using the reconstructed spectra, and the ratio between the two fluences was considered as a simple index of the event's hardness. We also provided a justification of the spectrum estimate in the form of the Band-function, using direct PAMELA data for GLE 71 (**17-May-2012**). We found that, while there is no clear relation between the intensity and the hardness for weak events, all strong events with the intensity greater 100 \%*hr are characterized by a very hard spectrum. This implies that a hard spectrum can be securely assumed for all extreme GLE events, e.g., those studied using cosmogenic isotope data in the past.

Table 1: Parameters of the studied GLE events.

Modeling Solar Proton Event-induced Martian Surface Radiation Dose

Dimitra **Atri**, Caitlin MacArthur, Ian Dobbs-Dixon

ApJ **2020**

https://arxiv.org/pdf/2012.00568.pdf

Solar Proton Events (SPEs) can cause abrupt and significant enhancements to the Martian surface radiation dose. Observations of the impact of SPEs on the Martian surface are available from satellites and surface detectors, but the data set is very limited in time, and the energy range is limited in scope, which makes it insufficient to estimate the impact of major events on the Martian surface. On the other hand, long-term data of SPEs impacting the Earth spanning a large energy range is widely available, and can be used to estimate the impact of major events on Mars on long timescales. Herein, we take major SPEs observed during the past several decades on Earth (1956 - 2014), along with PAMELA observations (2006 - 2014) and use the GEANT4 Monte Carlo code to calculate the Martian surface radiation dose. We study the contribution of proton fluence and spectral shape of events on the surface radiation dose and estimated the impact of possible major SPEs on the Martian surface in the future. These results have major implications for the planned human exploration of Mars. Overall we find that the radiation dose from extreme events can have a significant impact on astronaut health, and in rare, worst case scenarios, the estimated dose can even reach lethal levels.

Relativistic proton levels from region AR2673 (GLE \#72) and the heliospheric current sheet as a Sun-Earth magnetic connection

C. R. A. **Augusto**, C. E. Navia, M. N. de Oliveira, A. A. Nepomuceno, A. C. Fauth, V. Kopenkin, T. Sinzi

Publications of the Astronomical Society of the Pacific, Volume 131, Issue 996, pp. 024401 (**2019**).

https://arxiv.org/pdf/1805.02678.pdf

https://iopscience.iop.org/article/10.1088/1538-3873/aaeb7f/pdf

On **10 September 2017** Neutron Monitors (NMs) apparatus located at ground level and high latitudes detected an increase in the counting rate associated to solar energetic particles (SEP) emission from X8.2 class solar flare and its associated CME. This was the second highest flare of the current solar cycle. The origin was the active region AR 2673 when it was located at the edge of the west solar disc, without a direct magnetic connection with Earth. However, there was a peculiar condition, the solar protons accelerated by the CME shocks were injected within a heliospheric current sheet (HCS) region and when the Earth was crossing this region. We show that the HCS played the role of a magnetic connection between Sun and Earth. The fast-moving protons penetrated the magnetosphere near the north and south poles and their interaction in the atmosphere produced a ground level enhancement (GLE \#72), this was the second in the current solar cycle. In the NOAA Space Weather Scale, SEP is cataloged as radiation storms, from S1(minor) to S5 (extreme), and in the present case, it reached S3 (strong). In addition, four days before, on **6 September**, AR 2673 erupted, was an X9.3-class flare (the strongest flare of the current cycle). It was associated with a halo CME toward Earth, triggering the second strongest geomagnetic storm of the current solar cycle on 7 September. We detail these observations.

Muon Excess at Sea Level during the Progress of a Geomagnetic Storm and High Speed Stream Impact Near the Time of Eath's Heliospheric Sheet Crossing

C. R. A. **Augusto**, C. E. Navia, M. N. de Oliveira, A. A. Nepomuceno, V. Kopenkin, T. Sinzi

Solar Phys. 292:107 **2017**

https://arxiv.org/pdf/1706.00775.pdf

In this article we present results of the study on the association between the muon flux variation at ground level, registered by the \textit{\textit{New-Tupi}} muon telescopes (22053′00″S,43006′13′W; 3 m above sea level) and a geomagnetic storm of **25\,--\,29 August 2015** that has raged for several days as a result of a coronal mass ejection

(CME) impact on Earth's magnetosphere. A sequence of events started with an M3.5 X-ray class flare on **22 August 2015** at 21:19 UTC. The \textit{\textit{New-Tupi}} muon telescopes observed a Forbush decrease (FD) triggered by this geomagnetic storm, with onset on 26 August 2015. After the Earth crossed a heliospheric current sheet (HCS), an increase in the particle flux was observed on 28 August 2015 by spacecrafts and ground level detectors. The observed peak was in temporal coincidence with the impact of a high speed stream (HSS). We study this increase, that has been observed with a significance above 1.5\% by ground level detectors in different rigidity regimes. We also estimate the lower limit of the energy fluence injected on Earth. In addition, we consider the origin of this increase, such as acceleration of particles by shock waves on the front of the HSS and the focusing effect of the HCS crossing. Our results show possible evidence of a prolonged energetic (up to GeV energies) particle injection within the Earth atmosphere system, driven by the HSS. In most cases these injected particles are directed to polar regions. However, the particles from the high energy tail of the spectrum can reach middle latitudes, and that could have consequences for the atmospheric chemistry, for instance, the creation of NOx species may be enhanced and can lead to increased ozone depletion. This topic requires further study.

Ground level observations of relativistic solar particles on Oct 29th, 2015: Is it a new GLE on the current solar cycle?

C. R. A. **Augusto**, C. E. Navia, M. N. de Oliveira, A. A. Nepomuceno, A. C. Fauth
2016
http://arxiv.org/pdf/1603.08863v1.pdf

On **Oct. 29th, 2015**, the Earth crossed through a fold in the heliospheric current sheet. This is called a "solar sector boundary crossing". Under this circumstances, a large coronal mass ejection (CME) occurred at 2:24 UT, behind the west limb on the sun. Therefore, the boundary crossing occurred when in the blast's nearby environment was filled with energetic particles accelerated by the CME shock waves, spacecraft measurements (ACE and GOES) have shown that in such a case, protons with energies at least up to 30 MeV were stored within the range of the sector boundary. Thus, a fraction of the solar energetic particles (SEP) from CME, reached Earth around 03:00 UT in the aftermath of the solar blast, reaching the condition of an S1 (minor) radiation storm level. The effect at ground level was a small increase in the counting rate in some ground based detectors, such as the South Pole Neutron Monitor (NM) and a sharp peak observed in the counting rate in the New-Tupi detector in Rio de Janeiro, Brazil and Thule NM. The event is being classified as a new GLE (Ground Level Enhancement) in the current solar cycle, as the GLE 73. However, in all cases, the counting rate increase is smaller or near than 2\%. The Earth crossed through a fold in the heliospheric current sheet also caused a geomagnetic disturbance, below the minor geomagnetic storm threshold, observed in the ACE spacecraft and a small decrease in the counting rates of some ground level detectors, such as the New-Tupi detector and Thuly NM. Details of these observations are reported.

Signals at ground level of relativistic solar particles associated to the "All Saints" filament eruption on 2014

C. R. A. **Augusto**, C. E. Navia, M. N. de Oliveira, H. Shigueoka, A.A. Nepomuceno, A. C. Fauth
2015
http://arxiv.org/pdf/1507.03954v1.pdf

Far away from any sunspot, a bright flare erupted on **November 1st, 2014**, with onset at 4:44 UT and a duration of around three hours, causing a C2.7-class flare. The blast was associated with the sudden disappearance of a large dark solar filament. The rest of the filament flew out into space, forming the core of a massive CME. Despite the location of the explosion over the sun's southeastern region (near the eastern edge of the sun) not be geoeffective, a radiation storm, that is, solar energetic particles (SEP) started to reach the Earth around 14:00 UT, reaching the condition of an S1 (minor) radiation storm level on Nov. 2th. In coincidence with onset of the S1 radiation storm (SEP above 5 MeV), the Tupi telescopes located at 22090′S; 43020′W, within the South Atlantic Anomaly (SAA) detected a muon enhancement caused by relativistic protons from this solar blast. In addition an increase in the particle intensity was found also at South Pole neutron monitor. This means that there was a transverse propagation to the interplanetary magnetic field of energetic solar particles. However, we show that perpendicular diffusion alone cannot explain these observations, it is necessary a combination with further processes as a very high speed, at least of a fraction the CME shocks, close to the ecliptic plane.

VARIATIONS OF THE MUON FLUX AT SEA LEVEL ASSOCIATED WITH INTERPLANETARY ICMEs AND COROTATING INTERACTION REGIONS

C. R. A. **Augusto**1, V. Kopenkin1, C. E. Navia1, K. H. Tsui1, H. Shigueoka1, A. C. Fauth2, E. Kemp2, E. J. T. Manganote2, M. A. Leigui de Oliveira3, P. Miranda4, R. Ticona4, and A. Velarde
2012 ApJ 759 143
We present the results of an ongoing survey on the association between the muon flux variation at ground level (3 m above sea level) registered by the Tupi telescopes (Niteri-Brazil, 229S, 432W, 3 m) and the Earth-directed transient disturbances in the interplanetary medium propagating from the Sun (such as coronal mass ejections (CME), and corotating interaction regions (CIRs)). Their location inside the South Atlantic Anomaly region enables the muon telescopes to achieve a low rigidity of response to primary and secondary charged particles. The present study is primarily based on experimental events obtained by the Tupi telescopes in the period from 2010 August to 2011 December. This time period corresponds to the rising phase of solar cycle 24. The Tupi events are studied in correlation with data obtained by space-borne detectors (SOHO, ACE, GOES). Identification of interplanetary structures and associated solar activity was based on the nomenclature and definitions given by the satellite observations, including an incomplete list of possible interplanetary shocks observed by the CELIAS/MTOF Proton Monitor on the Solar and Heliospheric Observatory (SOHO) spacecraft. Among 29 experimental events reported in the present analysis, there are 15 possibly associated with the CMEs and sheaths, and 3 events with the CIRs (forward or reverse shocks); the origin of the remaining 11 events has not been determined by the satellite detectors. We compare the observed time (delayed or anticipated) of the muon excess (positive or negative) signal on Earth (the Tupi telescopes) with the trigger time of the interplanetary disturbances registered by the satellites located at Lagrange point L1 (SOHO and ACE). The temporal correlation of the observed ground-based events with solar transient events detected by spacecraft suggests a real physical connection between them. We found that the majority of observed events detected by the Tupi experiment were delayed in relation to the satellite triggers. This result agrees with theoretical expectations. Our experimental data indicate that the Tupi experiment is able to add new information and can be complementary to other techniques designed to interpret the origin of some interplanetary disturbances observed by satellites.

The GLE on Oct. 28, 2003 - radio diagnostics of relativistic electron and proton injection

H. **Aurass**, G. Mann, G. Rausche and A. Warmuth
A&A 457, 681-692 (**2006**); **File**
Timing discrepancies between signatures of accelerated particles at the sun and the arrival times of the particles at near-earth detectors are a matter of fundamental interest for space-weather applications. The solar injection times of various components of energetic particles were derived by Klassen et al. (2005, JGR, 110, A09S04) for the October 28, 2003, X-class/γ-ray flare in NOAA AR 10486. This flare occured in connection with a fast halo coronal mass ejection and a neutron monitor-observed ground level event (GLE).We used radio (Astrophysikalisches Institut Potsdam, *WIND*, Nançay Multifrequency Radio Heliograph), Hα (Observatorium Kanzelhöhe), *RHESSI*, *SOHO* (EIT, LASCO, MDI), and *TRACE* data to study the associated chromospheric and low coronal phenomena. We identify three source sites of accelerated particles in this event. Firstly, there is a source in projection 0.3 $R_{\_}$ away from AR 10486, which is the site of the reconnection outflow termination, as revealed by a termination shock signature in the dynamic radio spectrum. Secondly, there is the extended current sheet above a giant coronal postflare loop system in the main flare phase. Thirdly, there is a source situated on a magnetic separatrix surface between several magnetic arcades and neighbouring active regions. This source is 0.2 $R_{\_}$ away from AR 10486 and acts during onset and growth of high energy proton injection in space. It is not clear if this source is related to the acceleration of protons, or if it only confirms that energetic particles penetrate a multistructure magnetic loop system after being previously accelerated near the main HXR- and γ-ray sources. The result is in favour of energetic particle acceleration in the low corona (<0.5 $R_{\_}$ above the photosphere) and in contrast to acceleration of the relativistic particles at remotely propagating
shock waves.

A Summary of NOAA Space Weather Prediction Center Proton Event Forecast Performance and Skill

H. M. **Bain**, R. A. Steenburgh, T. G. Onsager, E. M. Stitely
Space Weather **Volume19, Issue7** e2020SW002670 May **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002670
https://doi.org/10.1029/2020SW002670
The effects of solar radiation storms at Earth are felt across a number of technology-based industries. Energetic particles present during these storms impact electrical components on spacecraft, disrupt high frequency (HF) radio communications, and pose a radiation risk for passengers and crew on polar flight routes, as well as for astronauts. An essential aspect of space weather forecasting is therefore to predict the occurrence and properties of a solar proton event before it occurs. In this paper, we review radiation storm products issued by the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA SWPC) during Solar Cycles 23 and 24. These include three-day probabilistic proton event forecasts and short-term Warning and Alert hazard products. We present performance metrics and forecast skill scores for SWPC probabilistic forecasts and Warning products, which

can be used as a benchmark for assessing the performance of radiation storm forecast models. **21 Apr 2002, 7 Sep 2005**

Shock Connectivity in the August 2010 and July 2012 Solar Energetic Particle Events Inferred from Observations and ENLIL Modeling

H. M. **Bain**, M. L. Mays, J. G. Luhmann, Y. Li, L. K. Jian, and D. Odstrcil

2016 ApJ 825 1 **File**

During periods of increased solar activity, coronal mass ejections (CMEs) can occur in close succession and proximity to one another. This can lead to the interaction and merger of CME ejecta as they propagate in the heliosphere. The particles accelerated in these shocks can result in complex solar energetic particle (SEP) events, as observing spacecraft form both remote and local shock connections. It can be challenging to understand these complex SEP events from in situ profiles alone. Multipoint observations of CMEs in the near-Sun environment, from the Solar Terrestrial Relations Observatory"Sun Earth Connection Coronal and Heliospheric Investigation and the Solar and Heliospheric Observatory Large Angle and Spectrometric Coronagraph, greatly improve our chances of identifying the origin of these accelerated particles. However, contextual information on conditions in the heliosphere, including the background solar wind conditions and shock structures, is essential for understanding SEP properties well enough to forecast their characteristics. Wang"Sheeley?Arge WSA-ENLIL + Cone modeling provides a tool to interpret major SEP event periods in the context of a realistic heliospheric model and to determine how much of what is observed in large SEP events depends on nonlocal magnetic connections to shock sources. We discuss observations of the SEP-rich periods of **2010 August** and **2012 July** in conjunction with ENLIL modeling. We find that much SEP activity can only be understood in the light of such models, and in particular from knowing about both remote and local shock source connections. These results must be folded into the investigations of the physics underlying the longitudinal extent of SEP events, and the source connection versus diffusion pictures of interpretations of SEP events.

Prediction of solar flare proton spectral slope from radio burst data

Bakshi, P. ; Barron, W.

JGR Volume84, IssueA1 1 January **1979** Pages 131-137

https://doi.org/10.1029/JA084iA01p00131

We have studied the correlations between the width of the U-shaped peak flux density spectra of solar radio bursts and the slope of the associated proton energy spectra observed by satellites. We find the wider radio spectra U's lead to shallow proton energy slopes (harder spectrum), while narrower U's lead to steeper slopes (softer spectrum). Out of the straight line, power law, and exponential forms used to study the correlations, the power law form yields the best correlation (r ≈ 0.77). This leads to a practical prediction scheme which can be used in real time for forecasting the spectral character of the protons that can be expected to arrive in the vicinity of the earth on the basis of the continuously monitored radio burst data.

Prediction of the proton flux magnitudes from radio burst data

Bakshi, P. ; Barron, W.

1978

No text https://ui.adsabs.harvard.edu/abs/1978STIN...7925969B/abstract

Various radio-burst and proton spectral parameters were considered as correlation variables in the development of an improved prediction scheme for the proton peak flux magnitudes. Besides the time integrated radio fluxes at individual frequencies, a frequency integration over two different ranges was used. The peak flux of protons (with energy greater than 10 MeV), their average energy and their duration were considered and a solar longitudinal correction was applied. Results lead to an improved prediction scheme and provide a better understanding of the correlation phenomena.

Spectral correlations between solar flare radio bursts and associated proton fluxes, 2

Bakshi, P. ; Barron, W.

1975

No text https://ui.adsabs.harvard.edu/abs/1975STIN...7627153B/abstract

An earlier study of the solar flare U-shaped radio burst spectra and associated proton flux data has been extended to include additional events. The slope of the proton peak-flux profile is correlated to the radio frequency ratio (omega3)/(omega sub 2) where (omega3) equals frequency of maximum radio peak flux of the upper branch of the U, and (omega2) equals cut-off frequency for the lower branch of the U. The use of the slope allows inclusion of the pre-Explorer (1966-67) events, recorded on various different proton-energy channels.

Spectral correlations between solar flare radio bursts and associated proton fluxes, 1

Bakshi, P. Barron, W.

Interim Report Boston Coll., Chestnut Hill, MA. Dept. of Physics. **1974**
No text
The present study is directed towards establishing a correlation between certain characteristics of the radio spectrum and the relative intensities of the proton spectrum as measured by peak proton fluxes. This study essentially provides a prediction on the hardness (shallow spectrum) or softness (steep spectrum) of the proton spectrum (peak proton flux vs. energy range).

Updated verification of the Space Weather Prediction Center's solar energetic particle prediction model

Christopher C. **Balch**
SPACE WEATHER, VOL. 6, S01001, doi:10.1029/2007SW000337, **2008**
http://sci-hub.si/10.1029/2007SW000337
This paper evaluates the performance of an operational proton prediction model currently being used at NOAA's Space Weather Prediction Center. The evaluation is based on proton events that occurred between 1986 and 2004. Parameters for the associated solar events determine a set of necessary conditions, which are used to construct a set of control events. Model output is calculated for these events and performance of the model is evaluated using standard verification measures. For probability forecasts we evaluate the accuracy, reliability, and resolution and display these results using a standard attributes diagram. We identify conditions for which the model is systematically inaccurate. The probability forecasts are also evaluated for categorical forecast performance measures. We find an optimal probability and we calculate the false alarm rate and probability of detection at this probability. We also show results for peak flux and rise time predictions. These findings provide an objective basis for measuring future improvements.

Balch CC. **1999**. SEC proton prediction model: verification and analysis. Rad Meas 30: 231–250. https://doi.org/10.1016/S1350-4487(99)00052-9.

Comparative analysis of NOAA REFM and SNB3GEO tools for the forecast of the fluxes of high-energy electrons at GEO

M. A. **Balikhin**, J. V. Rodriguez, R. J. Boynton, S. N. Walker, H. Aryan, D. G. Sibeck, S. A. Billings
Space Weather Volume 14, Issue 1 January **2016** Pages 22–31
Reliable forecasts of relativistic electrons at geostationary orbit (GEO) are important for the mitigation of their hazardous effects on spacecraft at GEO. For a number of years the Space Weather Prediction Center at NOAA has provided advanced online forecasts of the fluence of electrons with energy >2 MeV at GEO using the Relativistic Electron Forecast Model (REFM). The REFM forecasts are based on real-time solar wind speed observations at L1. The high reliability of this forecasting tool serves as a benchmark for the assessment of other forecasting tools. Since 2012 the Sheffield SNB3GEO model has been operating online, providing a 24 h ahead forecast of the same fluxes. In addition to solar wind speed, the SNB3GEO forecasts use solar wind density and interplanetary magnetic field Bz observations at L1.The period of joint operation of both of these forecasts has been used to compare their accuracy. Daily averaged measurements of electron fluxes by GOES 13 have been used to estimate the prediction efficiency of both forecasting tools. To assess the reliability of both models to forecast infrequent events of very high fluxes, the Heidke skill score was employed. The results obtained indicate that SNB3GEO provides a more accurate 1 day ahead forecast when compared to REFM. It is shown that the correction methodology utilized by REFM potentially can improve the SNB3GEO forecast.

BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity

Band, D., Matteson, J., Ford, L., et al.
1993, Astrophys. J., 413, 281
http://articles.adsabs.harvard.edu/pdf/1993ApJ...413..281B
We studied the time-averaged gamma-ray burst spectra accumulated by the spectroscopy detectors of the Burst and Transient Source Experiment (BATSE). The spectra are described well at low energy by a power-law continuum with an exponential cutoff N_E_(E) is proportional to Ealpha^ exp (- E/E_0_), and by a steeper power law, N_E_(E) is proportional to Ebeta^ with α > β at high energy. However, the spectral parameters α, β, and E_0_ vary from burst to burst with no universal values. The break in the spectrum, E_0_, ranges from below 100 keV to more than 1 MeV, but peaks below 200 keV with only a small fraction of the spectra breaking above 400 keV. Consequently, it is unlikely that a majority of the burst spectra are shaped directly by pair processes, unless bursts originate from a broad redshift range. We find that the correlations among burst parameters do not fulfill the predictions of the cosmological models of burst origin, but our burst sample may not be appropriate for such a test. No correlations with burst morphology or the spatial distribution were found. We also studied the process of fitting the BATSE

spectral data. For example, we demonstrate the importance of using a complete spectral description even if a partial description (e.g., a model without a high-energy tail) is statistically satisfactory.
the Band-function spectral shape (double power law with an exponential junction – Band et al. 1993) to the integral rigidity spectral fluence

Observations of Energetic-Particle Population Enhancements along Intermittent Structures near the Sun from Parker Solar Probe
Riddhi **Bandyopadhyay**, W. H. Matthaeus, T. N. Parashar, R. Chhiber, D. Ruffolo, M. L. Goldstein, B. A. Maruca, A. Chasapis, R. Qudsi, D. J. McComas, E. R. Christian, J. R. Szalay, C. J. Joyce, J. Giacalone, N. A. Schwadron, D. G. Mitchell, M. E. Hill, M. E. Wiedenbeck, R. L. McNutt Jr., M. I. Desai, Stuart D. Bale, J. W. Bonnell, Thierry Dudok de Wit, Keith Goetz, Peter R. Harvey, Robert J. MacDowall, David M. Malaspina, Marc Pulupa, M. Velli, J.C. Kasper, K.E. Korreck, M. Stevens, A.W. Case, N. Raouafi
ApJS, PSP special issue Volume 246, Issue 2, id.61 **2020**
https://arxiv.org/pdf/1912.03424.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/ab6220/pdf
Observations at 1 au have confirmed that enhancements in measured energetic particle fluxes are statistically associated with "rough" magnetic fields, i.e., fields having atypically large spatial derivatives or increments, as measured by the Partial Variance of Increments (PVI) method. One way to interpret this observation is as an association of the energetic particles with trapping or channeling within magnetic flux tubes, possibly near their boundaries. However, it remains unclear whether this association is a transport or local effect; i.e., the particles might have been energized at a distant location, perhaps by shocks or reconnection, or they might experience local energization or re-acceleration. The Parker Solar Probe (PSP), even in its first two orbits, offers a unique opportunity to study this statistical correlation closer to the corona. As a first step, we analyze the separate correlation properties of the energetic particles measured by the \isois instruments during the first solar encounter. The distribution of time intervals between a specific type of event, i.e., the waiting time, can indicate the nature of the underlying process. We find that the \isois observations show a power-law distribution of waiting times, indicating a correlated (non-Poisson) distribution. Analysis of low-energy \isois data suggests that the results are consistent with the 1 au studies, although we find hints of some unexpected behavior. A more complete understanding of these statistical distributions will provide valuable insights into the origin and propagation of solar energetic particles, a picture that should become clear with future PSP orbits.

A survey of gradual solar energetic particle events
Barnard, L.; Lockwood, M.
J. Geophys. Res., Vol. 116, No. A5, A05103, **2011**
We develop a database of 110 gradual solar energetic particle (SEP) events, over the period 1967–2006, providing estimates of event onset, duration, fluence, and peak flux for protons of energy E > 60 MeV. The database is established mainly from the energetic proton flux data distributed in the OMNI 2 data set; however, we also utilize the McMurdo neutron monitor and the energetic proton flux from GOES missions. To aid the development of the gradual SEP database, we establish a method with which the homogeneity of the energetic proton flux record is improved. A comparison between other SEP databases and the database developed here is presented which discusses the different algorithms used to define an event. Furthermore, we investigate the variation of gradual SEP occurrence and fluence with solar cycle phase, sunspot number (SSN), and interplanetary magnetic field intensity (Bmag) over solar cycles 20–23. We find that the occurrence and fluence of SEP events vary with the solar cycle phase. Correspondingly, we find a positive correlation between SEP occurrence and solar activity as determined by SSN and Bmag, while the mean fluence in individual events decreases with the same measures of solar activity. Therefore, although the number of events decreases when solar activity is low, the events that do occur at such times have higher fluence. Thus, large events such as the “Carrington flare” may be more likely at lower levels of solar activity. These results are discussed in the context of other similar investigations.

W.**Barron**

Multispacecraft Observations of Protons and Helium Nuclei in Some Solar Energetic Particle Events toward the Maximum of Cycle 25
S. **Bartocci**1, R. Battiston2,3, S. Benella4, S. Beolè5,6, W. J. Burger3, +++
2024 ApJ 974 176
https://iopscience.iop.org/article/10.3847/1538-4357/ad7395/pdf
The intricate behavior of particle acceleration and transport mechanisms complicates the overall efforts in formulating a comprehensive understanding of solar energetic particle (SEP) events; these efforts include observations of low-energy particles (from tens of keV to hundreds of MeV) by space-borne instruments and

measurements by the ground-based neutron monitors of the secondary particles generated in the Earth atmosphere by SEPs in the GeV range. Numerous space-borne missions provided good data on the nature/characteristics of these solar particles in past solar cycles, but more recently—concurrently with the rise toward the maximum of solar cycle 25—the High-Energy Particle Detector (HEPD-01) proved to be well suited for the study of solar physics and space weather. Its nominal 30–300 MeV energy range for protons can enlarge the detection capabilities of solar particles at low Earth orbit, closer to the injection limit of many SEP events. In this work, we characterize three SEP events within the first six months of 2022 through spectral and velocity dispersion analysis, assessing the response of HEPD-01 to >M1 events. **2022 January 20, 2022 February 15, 2022 May 11**

Modelling Solar Energetic Particle transport near a wavy Heliospheric Current Sheet

Markus **Battarbee**, Silvia Dalla, Mike S. Marsh
2018 ApJ 854 23
https://arxiv.org/pdf/1712.03729.pdf
Understanding the transport of Solar Energetic Particles (SEPs) from acceleration sites at the Sun into interplanetary space and to the Earth is an important question for forecasting space weather. The Interplanetary Magnetic Field (IMF), with two distinct polarities and a complex structure, governs energetic particle transport and drifts.
We analyse for the first time the effect of a wavy Heliospheric Current Sheet (HCS) on the propagation of SEPs. We inject protons close to the Sun and propagate them by integrating fully 3D trajectories within the inner heliosphere in the presence of weak scattering. We model the HCS position using fits based on neutral lines of magnetic field source surface maps (SSMs).
We map 1 au proton crossings, which show efficient transport in longitude via HCS, depending on the location of the injection region with respect to the HCS. For HCS tilt angles around 30-30 grad , we find significant qualitative differences between A+ and A configurations of the IMF, with stronger fluences along the HCS in the former case but with a distribution of particles across a wider range of longitudes and latitudes in the latter.
We show how a wavy current sheet leads to longitudinally periodic enhancements in particle fluence. We show that for an A+ IMF configuration, a wavy HCS allows for more proton deceleration than a flat HCS. We find that A IMF configurations result in larger average fluences than A+ IMF configurations, due to a radial drift component at the current sheet.

Multi-spacecraft observations and transport simulations of solar energetic particles for the May 17th 2012 GLE event

M. **Battarbee**, J. Guo, S. Dalla, R. Wimmer-Schweingruber, B. Swalwell, D. J. Lawrence
A&A 612, A116 **2018**
https://arxiv.org/pdf/1706.08458.pdf
http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2018/04/aa31451-17/aa31451-17.html
https://www.aanda.org/articles/aa/pdf/2018/04/aa31451-17.pdf
The injection, propagation and arrival of solar energetic particles (SEPs) during eruptive solar events is an important and current research topic of heliospheric physics. During the largest solar events, particles may have energies up to a few GeVs and sometimes even trigger ground-level enhancements (GLEs) at Earth. We study the first GLE-event of solar cycle 24, from 17th May 2012, using data from multiple spacecraft (SOHO, GOES, MSL, STEREO-A, STEREO-B and MESSENGER). These spacecraft are located throughout the inner heliosphere, at heliocentric distances between 0.34 and 1.5 astronomical units (au), covering nearly the whole range of heliospheric longitudes. We present and investigate sub-GeV proton time profiles for the event at several energy channels, obtained via different instruments aboard the above spacecraft. We investigate issues due to magnetic connectivity, and present results of three-dimensional SEP propagation simulations. We gather virtual time profiles and perform qualitative and quantitative comparisons with observations, assessing longitudinal injection and transport effects as well as peak intensities. We distinguish different time profile shapes for well-connected and weakly connected observers, and find our onset time analysis to agree with this distinction. At select observers, we identify an additional low-energy component of Energetic Storm Particles (ESPs). Using well-connected observers for normalisation, our simulations are able to accurately recreate both time profile shapes and peak intensities at multiple observer locations. This synergetic approach combining numerical modeling with multi-spacecraft observations is crucial for understanding the propagation of SEPs within the interplanetary magnetic field. Our novel analysis provides valuable proof of the ability to simulate SEP propagation throughout the inner heliosphere, at a wide range of longitudes.

Solar Energetic Particle transport near a Heliospheric Current Sheet

Markus **Battarbee**, Silvia Dalla, Mike S. Marsh
ApJ **836** 138 **2017**
https://arxiv.org/pdf/1701.04286v1.pdf
Solar Energetic Particles (SEPs), a major component of space weather, propagate through the interplanetary medium strongly guided by the Interplanetary Magnetic Field (IMF). In this work, we analyse the implications a flat

Heliospheric Current Sheet (HCS) has on proton propagation from SEP release sites to the Earth. We simulate proton propagation by integrating fully 3-D trajectories near an analytically defined flat current sheet, collecting comprehensive statistics into histograms, fluence maps and virtual observer time profiles within an energy range of 1--800 MeV. We show that protons experience significant current sheet drift to distant longitudes, causing time profiles to exhibit multiple components, which are a potential source of confusing interpretation of observations. We find that variation of current sheet thickness within a realistic parameter range has little effect on particle propagation. We show that IMF configuration strongly affects deceleration of protons. We show that in our model, the presence of a flat equatorial HCS in the inner heliosphere limits the crossing of protons into the opposite hemisphere.

Injection of thermal and suprathermal seed particles into coronal shocks of varying obliquity ⋆

M. **Battarbee**1, R. Vainio2, T. Laitinen3 and H. Hietala

A&A 558, A110 (**2013**)

Context. Diffusive shock acceleration in the solar corona can accelerate solar energetic particles to very high energies. Acceleration efficiency is increased by entrapment through self-generated waves, which is highly dependent on the amount of accelerated particles. This, in turn, is determined by the efficiency of particle injection into the acceleration process.

Aims. We present an analysis of the injection efficiency at coronal shocks of varying obliquity. We assessed injection through reflection and downstream scattering, including the effect of a cross-shock potential. Both quasi-thermal and suprathermal seed populations were analysed. We present results on the effect of cross-field diffusion downstream of the shock on the injection efficiency.

Methods. Using analytical methods, we present applicable injection speed thresholds that were compared with both semi-analytical flux integration and Monte Carlo simulations, which do not resort to binary thresholds. Shock-normal angle θBn and shock-normal velocity Vs were varied to assess the injection efficiency with respect to these parameters.

Results. We present evidence of a significant bias of thermal seed particle injection at small shock-normal angles. We show that downstream isotropisation methods affect the θBn-dependence of this result. We show a non-negligible effect caused by the cross-shock potential, and that the effect of downstream cross-field diffusion is highly dependent on boundary definitions.

Conclusions. Our results show that for Monte Carlo simulations of coronal shock acceleration a full distribution function assessment with downstream isotropisation through scatterings is necessary to realistically model particle injection. Based on our results, seed particle injection at quasi-parallel coronal shocks can result in significant acceleration efficiency, especially when combined with varying field-line geometry.

Dynamic of the Occurrence Rate of the Solar Energetic Particle Events During Solar Activity Cycles 21-24

Bazilevskaya, G.A., Logachev, Yu.I., Daibog, E.I., Ginzburg, E.A., Ishkov, V.N., Lazutin, L.L., Nguyen, V.D., Surova, G.M., Vlasova, N.A., Yakovchouk, O.S.:

2019 In: 11th Workshop, Solar Influences on the Magnetosphere, Ionosphere, and Atmosphere. P. 1-6

http://ws-sozopol.stil.bas.bg/2019Primorsko/Proceedings2019.pdf

Once again about origin of the solar cosmic rays **Review**

G A **Bazilevskaya**1

Journal of Physics: Conference Series, Volume 798, International Conference on Particle Physics and Astrophysics 10–14 October 2016, Moscow, Russian Federation

Citation G A Bazilevskaya **2017** J. Phys.: Conf. Ser. 798 012034

https://iopscience.iop.org/article/10.1088/1742-6596/798/1/012034/pdf

Discussion about sources of energetic particles - solar cosmic rays (SCRs), or solar energetic particles (SEPs) - emerging in the interplanetary space after an explosive energy release on the Sun lasts during more than 20 years. The main candidates for the SEP sources are a solar flare and a coronal mass ejection (CME). This paper briefly outlines the main observational results related to the problem of the SEP origin. Main focus is directed to the recently discovered manifestations of the sudden energy release on the Sun - long lasting high-energy solar gamma emission, new information on solar neutrons and THz radio emission. Actually, description of particle acceleration on the Sun appears to be even more complicated than it was believed earlier.

Solar Cycle in the Heliosphere and Cosmic Rays **Review**

Galina A. **Bazilevskaya**, Edward W. Cliver, Gennady A. Kovaltsov, Alan G. Ling, M. A. Shea, D. F. Smart, Ilya G. Usoskin
Space Science Reviews, December **2014**, Volume 186, Issue 1-4, pp 409-435
Manifestations of the 11-year solar cycle and longer time-scale variability in the heliosphere and cosmic rays are considered. We briefly review the cyclic variability of such heliospheric parameters as solar wind speed and density and heliospheric magnetic field, open magnetic flux and latitude variations of the heliospheric current sheet. It is discussed whether the local in-situ observation near Earth can represent the global 3D heliospheric pattern. Variability of cosmic rays near Earth provides an indirect useful tool to study the heliosphere. We discuss details of the heliospheric modulation of galactic cosmic rays, as recorded at and near Earth, and their relation to the heliospheric conditions in the outer heliosphere. On the other hand, solar energetic particles can serve as probes for explosive phenomena on the Sun and conditions in the corona and inner heliosphere. The occurrence of major solar proton events depicts an overall tendency to follow the solar cycle but individual events may appear at different phases of the solar cycle, as defined by various factors. The solar cycle in the heliosphere and cosmic rays depicts a complex pattern which includes different processes and cannot be described by a simple correlation with sunspot number.

Solar energetic particle events in 2006-2012 in the PAMELA experiment data

G A **Bazilevskaya** et al
2013 J. Phys.: Conf. Ser. 409 012188
http://iopscience.iop.org/1742-6596/409/1/012188/pdf/1742-6596_409_1_012188.pdf

Solar proton events recorded in the stratosphere during cosmic ray balloon observations in 1957–2008

G.A. **Bazilevskaya**, a, , V.S. Makhmutova, Y.I. Stozhkova, A.K. Svirzhevskayaa and N.S. Svirzhevskya
Advances in Space Research, Volume 45, Issue 5, 1 March **2010**, Pages 603-613
Long-term balloon observations have been performed by the Lebedev Physical Institute since 1957 up to the present time. The observations are taken several times a week at the polar and mid latitudes and allow us to study dynamics of galactic and solar cosmic ray as well as secondary particle fluxes in the atmosphere and in the near-Earth space. Solar energetic particles (120) – mostly protons – (SEP) events with >100 MeV proton intensity above 1 cm^{-2} s^{-1} s^{-1} were recorded during 1958–2006. Before the advent of the SEP monitoring on spacecraft these results constituted the only homogeneous series of >100 MeV SEP events. The SEP intensities and energy spectra inferred from the Lebedev Physical Institute observations are consistent with the results taken in the adjacent energy intervals by the spacecraft and neutron monitors. Joint consideration of the SEP events series recorded by balloons and by neutron monitors during solar cycles 20–23 makes it possible to restore the probable number of events in solar cycle 19, which was not properly covered by observations. Some correlation was found between duration of SEP event production in a solar cycle and sunspot cycle characteristics.

On the early phase of relativistic solar particle events: Are there signatures of acceleration mechanism?

G.A. **Bazilevskaya**
Advances in Space Research
Volume 43, Issue 4, 16 February **2009**, Pages 530-536, **File**
Many physical processes precede and accompany the solar energetic particles (SEP) occurrence on the Earth's orbit. Explosive energy release on the Sun gives rise to a flare and a coronal mass ejection (CME). X-ray and gamma emissions are believed to be connected with flares. Radio emission is signature of disturbances traveling through the corona and interplanetary space. Particles can gain energy both in the flare and the accompanying wave processes. The beginning of the SEP events has the advantage of being the phase most close to the time of acceleration. Influence of interplanetary transport is minimal in the case of first arriving relativistic solar protons recorded by ground based neutron monitors in so called ground-level enhancements (GLE). The early phase of the SEP events attracts attention of many scientists searching for the understanding of particle acceleration. However, they come to the opposite conclusions. While some authors find arguments for coronal mass ejections as a sole accelerator of SEPs, others prove a flare to be the SEP origin. Here, the circumstances of SEP generation for several GLEs of the 23rd solar cycle are considered. Timing of X-ray, CME, and radio emissions shows a great variety from event to event. However, the time of particle ejection from the Sun is closer to maximum of X-ray emission than to any other phenomena considered. No correlation is found between the particle fluxes and the CME characteristics.

ПРИХОД ПЕРВЫХ РЕЛЯТИВИСТСКИХ СОЛНЕЧНЫХ ПРОТОНОВ И УСЛОВИЯ В СОЛНЕЧНОЙ КОРОНЕ

Г. А. **Базилевская**, А. К. Свиржевская
Геомагнетизм и аэрономия, 48(4), 443-449, **2008, File**
События, когда солнечные космические лучи (СКЛ) можно наблюдать наземными приборами (GLE), часто характеризуются быстрым нарастанием интенсивности релятивистских протонов в начальной фазе, что позволяет оценить время выхода частиц из короны Солнца. Эта фаза события привлекает внимание исследователей благодаря своей близости по времени к моменту ускорения частиц. Известно, что наблюдаемые характеристики СКЛ носят следы воздействия многих физических процессов, в том числе и различных механизмов ускорения, относительная роль которых до настоящего времени не ясна. Основными претендентами на роль ускорителя СКЛ выступают вспышечные процессы и ускорение ударной волной, связанной с выбросом корональной массы (ВКМ). В работе рассмотрено несколько мощных солнечных протонных событий 23-го цикла солнечной активности, оценены время выхода первых частиц из короны и динамика ВКМ. Анализируются временные последовательности рентгеновских и радиовсплесков, близких по времени к выходу частиц. Делается вывод, что первые релятивистские частицы, скорее всего, были ускорены во вспышечных процессах.
Arrival of the first relativistic solar protons and conditions in the solar corona
Bazilevskaya G.A., Svirzhevskaya A.K.
Geomagnetism and Aeronomy. **2008**. Т. 48. № 4. С. 425-431.

Features of the solar X-ray bursts related to solar energetic particle events
Bazilevskaya, G. A.; Sladkova, A. I.; Svirzhevskaya, A. K.
Advances in Space Research, Volume 37, Issue 8, p. 1421-1425. **2006**
https://doi.org/10.1016/j.asr.2005.04.065
Solar X-ray bursts appear to be most convincing signatures of particle acceleration during solar flares. It is not clear what part of this population escapes the flare region. Majority of solar energetic particles observed in the space after powerful and long lasting solar flares are probably not connected with flares and assumed to be accelerated by the shocks related to the coronal mass ejections. However, there is a significant correlation between intensity of the X-ray bursts and solar energetic particle energy. The paper considers characteristics of the X-ray bursts followed by solar energetic particle occurrences and those bursts not associated with solar energetic particles. It is shown that correlation between X-ray bursts and solar energetic particles increases with growing of X-ray burst class and solar energetic particle energy. In our opinion, it emphasizes the role of processes in the flare region for solar energetic particles occurrence.

Solar Energetic Particle Events and Forbush Decreases Driven by the Same Solar Sources
Belov, Anatoly ; Shlyk, Nataly ; Abunina, Maria ; Belova, Elena ; Abunin, Artem ; Papaioannou, Athanasios
Universe **2022**, 8(8), 403;
https://doi.org/10.3390/universe8080403
https://www.mdpi.com/2218-1997/8/8/403/pdf
The characteristics of Forbush decreases (FDs) and solar energetic particle (SEP) events driven by the same solar source (i.e., coronal mass ejection and associated solar flare) are investigated. The part of the solar disk (04∘ E–35∘ W) in which most of the solar events lead both to an FD and SEP event on Earth was chosen. SEPs for different energies (E > 10 MeV, E > 100 MeV, and Ground Level Enhancements) and with different flux thresholds were considered independently. The obtained results were compared with the control group of FDs that had solar sources within the same longitudinal zone but were not accompanied by any SEPs. It is shown that coronal mass ejections (CMEs) followed by SEPs have a very high probability of creating a large FD in the Earth's orbit and to further cause a geomagnetic storm. It is also found that the accelerative and modulating efficiencies of powerful solar events are well correlated; this can be explained mostly by high speeds of the corresponding CMEs. **15–16 May 1997, 14–15 December 2006., 5–7 October 2011, 14–17 July 2012, 12–14 September 2014**

The Global Survey Method Applied to Ground-level Cosmic Ray Measurements
A. **Belov**1 · E. Eroshenko1 · V. Yanke1 · V. Oleneva1 ·A. Abunin1 · M. Abunina1 · A. Papaioannou2,3 · H. Mavromichalaki2
Solar Phys (**2018**) 293:68
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1277-6.pdf
sci-hub.tw/10.1007/s11207-018-1277-6
The global survey method (GSM) technique unites simultaneous ground-level observations of cosmic rays in different locations and allows us to obtain the main characteristics of cosmic-ray variations outside of the atmosphere and magnetosphere of Earth. This technique has been developed and applied in numerous studies over many years by the Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation (IZMIRAN).We here describe the IZMIRAN version of the GSM in detail. With this technique, the hourly data of the world-wide

neutron-monitor network from July 1957 until December 2016 were processed, and further processing is enabled upon the receipt of new data. The result is a database of homogeneous and continuous hourly characteristics of the density variations (an isotropic part of the intensity) and the 3D vector of the cosmic-ray anisotropy. It includes all of the effects that could be identified in galactic cosmic-ray variations that were caused by large-scale disturbances of the interplanetary medium in more than 50 years. These results in turn became the basis for a database on Forbush effects and interplanetary disturbances. This database allows correlating various space-environment parameters (the characteristics of the Sun, the solar wind, *et cetera*) with cosmic-ray parameters and studying their interrelations.We also present features of the coupling coefficients for different neutron monitors that enable us to make a connection from ground-level measurements to primary cosmicray variations outside the atmosphere and the magnetosphere. We discuss the strengths and weaknesses of the current version of the GSM as well as further possible developments and improvements. The method developed allows us to minimize the problems of the neutron- monitor network, which are typical for experimental physics, and to considerably enhance its advantages.
17 – 22.09.1957, 5 – 11.05.1960, 07 – 11 May 2016, 01 – 05 August 2016.

Some characteristics of GLE on 2017 September 10

Anatoly **Belov**1, Karel Kudela2, Victoria Kurt3 and Boris Yushkov3
Contrib. Astron. Obs. Skalnat.e Pleso 35, (1 – 11 ?), (**2018**) **File**
http://www.ta3.sk/caosp/Eedition/FullTexts/vol48no2/pp329-338.pdf
We present a short overview of the event associated with the recent strong solar flare 2017 September 10 (X8.9) based on the available data both from satellite GOES-13, and from selected neutron monitors. The onset time of SPE/GLE at 1 AU was found between 16:06–16:08 UT. The GLE effect was anisotropic with a maximum increase of 6%. The maximum energy of accelerated protons was _ 6 GeV. We estimated release time of sub-relativistic protons release time into open field lines was during time interval of 15:53–15:55 UT.
See Kurt et al. (2018)

Flares, ejections, proton events

A. V. **Belov**
Geomagnetism and Aeronomy volume 57, pages727–737(**2017**)
Geomagnetizm i Aeronomiya, **2017**, Vol. 57, No. 6, pp. 783–793
https://doi.org/10.1134/S0016793217060020
https://link.springer.com/content/pdf/10.1134/S0016793217060020.pdf
Statistical analysis is performed for the relationship of coronal mass ejections (CMEs) and X-ray flares with the fluxes of solar protons with energies >10 and >100 MeV observed near the Earth. The basis for this analysis was the events that took place in 1976–2015, for which there are reliable observations of X-ray flares on GOES satellites and CME observations with SOHO/LASCO coronagraphs. A fairly good correlation has been revealed between the magnitude of proton enhancements and the power and duration of flares, as well as the initial CME speed. The statistics do not give a clear advantage either to CMEs or the flares concerning their relation with proton events, but the characteristics of the flares and ejections complement each other well and are reasonable to use together in the forecast models. Numerical dependences are obtained that allow estimation of the proton fluxes to the Earth expected from solar observations; possibilities for improving the model are discussed.

Possible ground level enhancements at the beginning of the maximum of Solar Cycle 24.

Belov, A., Eroshenko, E., Kryakunova, O., Nikolayevskiy, N., Malimbayev, A., Tsepakina, I., Yanke, V.,
Aug. **2015**. J. Phys. Conf. Ser. 632 (1), 012063.
http://iopscience.iop.org/article/10.1088/1742-6596/632/1/012063/pdf
Three solar energetic proton events in the beginning of 2012 (January and March) revealed significant increases of the integral proton fluxes with energies >100 MeV were analyzed by the data from subpolar neutron monitors (>500 MeV). As it was found the event on **January 27, 2012** was followed by cosmic ray enhancement of about 2% at several subpolar and high latitude neutron monitors which coincided with the onset of the intensity increase in the GOES channels. This was also confirmed with the GOES/HEPAD data that allow us to consider the event on January 27, 2012 as a Ground Level Enhancement. The events in **March 2012 (7.03 and 13.03)** occurred under very complicated situation in the interplanetary space and a more detailed analysis is needed. Nevertheless, these events may contain some contribution of solar cosmic rays in the ground level observations.

Ground level enhancements of solar cosmic rays during the last three solar cycles

Belov, A. V.; Eroshenko, E. A.; Kryakunova, O. N.; Kurt, V. G.; Yanke, V. G.
Geomagnetism and Aeronomy **50 (1)**, 21–33 (**2010**) **File**

https://link.springer.com/content/pdf/10.1134/S0016793210010032.pdf

The catalog of ground level enhancements of solar cosmic rays during cycles 21—23 of solar activity has been presented. The main properties, time distribution, and relation of these events to solar sources and proton enhancements observed on satellites have been studied.

Ground level enhancements of the solar cosmic rays and Forbush decreases in 23rd solar cycle

A. V. **Belov**, E. A. Eroshenko, V. A. Oleneva, V. G. Yanke

PROCEEDINGS OF THE 31st ICRC, Ł ´ OD´Z **2009** **File**

The outstanding effects of solar activity in 23rd solar cycle, such as ground level enhancements of solar cosmic rays and the largest Forbush decreases (FD), are investigated. The analysis shows that both GLEs and great Forbush effects are connected with anomalously fast ejections of solar matter with similar properties. The main difference between those is in the longitude: the sources of the greatest Forbush effects (FE) are usually located in a central part of visible solar disk whereas flares associated with GLEs are mostly in the western part of disk. It is shown that accelerative and modulative efficiencies of the solar events are tightly correlated. Coronal mass ejection followed by GLE creates with a big probability a very large FE in the Earth orbit. **April, 15-22 2001, 28 Oct - 4 Nov 2003**

TABLE I: GLEs of 23rd cycle

TABLE II: The largest Forbush effects of 23-rd solar cycle

Properties of solar X-ray flares and proton event forecasting

A. Belov

Advances in Space Research

Volume 43, Issue 4, 16 February **2009**, Pages 467-473 **File**

http://sci-hub.cc/10.1016/j.asr.2008.08.011

X-ray flares and acceleration processes are in one complex of sporadic solar events (together with CMEs, radio bursts, magnetic field dissipation and reconnection). This supposes the connection (if not physical, but at least statistical) between characteristics of the solar energetic proton events and flares. The statistical analysis indicates that probability and magnitude of the near-Earth proton enhancement depends heavily on the flare importance and their heliolongitude. These relations may be used for elaboration of the forecasting models, which allow us to calculate probability of the solar proton events from the X-ray observations.

The models of probability for different kinds of solar proton events are obtained on the basis of all accumulated data of X-ray flares on the Sun and solar proton enhancements near the Earth. These models describe well enough the available data, are suitable for practical use and, really, are already utilized in the IZMIRAN prognostic practice. However, we should remember about the limitation of accumulated statistics. X-ray flares and proton enhancements have been observed for so short time that any new burst of solar activity is able to add something to our understanding of the relation “solar flares – proton enhancements”.

Peak-Size Distributions of Proton Fluxes and Associated Soft X-Ray Flares

A. **Belov** · V. Kurt · H. Mavromichalaki · M. Gerontidou

Solar Phys (**2007**) 246: 457–470, **File**

http://www.springerlink.com/content/e6k0t5wj86575052/fulltext.pdf

A database combining information about solar proton enhancements (SPEs) near the Earth and soft X-ray flares (GOES measurements) has been used for the study of different correlations through the period from 1975 to May 2006. The emphasis of this work is on the treatment of peak-size distributions of SXR flares and SPEs. The frequency of SXR flares and solar proton events (>10 and >100 MeV, respectively) for the past three solar cycles has been found to follow mainly a power-law distribution over three to five orders of magnitude of fluxes, which is physically correct beyond the “sensitivity” problem with the smallest peak values. The absence of significant spectral steepening in the domain of the highest peak values demonstrates that during the period considered, lasting 30 years, the limit of the highest flare’s energy release has not yet been achieved. The power-law exponents were found to be −2.19 ± 0.04, −1.34 ± 0.02, and −1.46 ± 0.04, for the total SXR flare distribution and the total SPE distributions (for both $E_P > 10$ MeV and $E_P > 100$ MeV), respectively. For SPEs associated with flares located to the West of 20°W, the exponents are −1.22 ± 0.05 ($E_P > 10$ MeV) and −1.26 ± 0.03 ($E_P > 100$ MeV). The size distribution for corresponding flares follows a power law with a slope of −1.29 ± 0.12. Thus, X-ray and proton fluxes produced in the same solar events have very similar distribution shapes. Moreover, the derived slopes are not incompatible with a linear dependence between X-ray flare power and proton fluxes near the Earth. A similar statistical relation is obtained independently from the direct comparison of the X-ray and proton fluxes. These all argue for a statistically significant relationship between X-ray and proton emissions.

Proton enhancements and their relation to the X-ray flares during the three last solar cycles

A.**Belov**, H.Garsia, V.Kurt, H. Mavomichalaki and M. Gerontidou.

Solar Physics (**2005**) 229: 135–159, **File**

https://doi.org/10.1007/s11207-005-4721-3

Energetic proton measurements obtained from the GOES and IMP-8 satellites as well as from ground-based neutron monitors are compared with the GOES soft X-ray measurements of the associated solar flares for the period 1975–2003. The present study investigates a broad range of phenomenology relating proton events to flares (with some references to related interplanetary disturbances), including correlations of occurrence, intensities, durations and timing of both the particle event and the flare as well as the role of the heliographic location of the designated active region. 1144 proton events of > 10 MeV energy were selected from this 28-year period. Owing primarily to the low particle flux threshold employed more than half of this number was found to be reliably connected with an X-ray flare. The statistical analysis indicates that the probability and magnitude of the near-Earth proton enhancement depends critically on the flare's importance and its heliolongitude. In this study all flares of X-ray importance > X5 and located in the most propitious heliolongitude range, 15∘W to 75∘W, were succeeded by a detectable proton enhancement. It was also found that the heliolongitude frequently determines the character of the proton event time profile. In addition to intensity, duration and timing, proton events were found to be related to the other flare properties such as lower temperatures and longer loop lengths.

A study of the ground level enhancement of 23 February 1956.

Belov, A., Eroshenko, E., Mavromichalaki, H., Plainaki, C., Yanke, V.,

2005. Adv. Space Res. 35, 697–701.

TIME EVOLUTION OF SOLAR ENERGY SPECTRA AT THE EART ORBIT AND POSSIBILITY OF MULTI-STEP PARTICLE ACCELERATION

Belov *A., Chertok I., Struminsky A.*

24th International Cosmic Ray Conference, Vol. 4, held August 28-September 8, 1995 in Rome, Italy.

1995, P. D127-D130.

http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1995ICRC....4..127B&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf

Spectral dynamic of solar protons during several hours after a start of the microwave emission was studied for powerful solar proton events of the 1989-1992 years. According to the GOES-7 data of some events a considerably softer spectrum of >100 MeV protons was observed during a first hour after a particle onset at the Earth orbit than it can be expected from theoretical models for an ejection of protons with constant spectrum. We argue that a late arrival of the more energetic protons is an evidence of the multi-step and/or long-duration acceleration. The continuos acceleration possibly takes place in a vertical current sheet behind a rising coronal mass ejection and/or by a shock wave in front of it.

IDENTIFICATION OF SUPER- AND SUBCRITICAL REGIONS IN SHOCKS DRIVEN BY CORONAL MASS EJECTIONS

A. **Bemporad** and S. Mancuso

2011 ApJ 739 L64, **File**

In this work, we focus on the analysis of a coronal mass ejection (CME) driven shock observed by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph Experiment. We show that white-light coronagraphic images can be employed to estimate the compression ratio $X = \rho_d / \rho_u$ all along the front of CME-driven shocks. X increases from the shock flanks (where X 1.2) to the shock center (where X 3.0 is maximum). From the estimated X values, we infer the Alfvén Mach number for the general case of an oblique shock. It turns out that only a small region around the shock center is supercritical at earlier times, while higher up in the corona the whole shock becomes subcritical. This suggests that CME-driven shocks could be efficient particle accelerators at the initiation phases of the event, while at later times they progressively loose energy, also losing their capability to accelerate high-energy particles. This result has important implications on the localization of particle acceleration sites and in the context of predictive space weather studies.

Shock acceleration of solar cosmic rays

E. G. **Berezhko**, S. N. Taneev
Astronomy Letters, June **2013**, Volume 39, Issue 6, pp 393-403
The solar cosmic ray (SCR) acceleration by the shocks driven by coronal mass ejections is studied by taking into account the generation of Alfvén waves by accelerated particles. Detailed numerical calculations of the SCR spectra produced during the shock propagation through the solar corona have been performed within a quasi-linear approach with a realistic set of coronal parameters. The resultant SCR energy spectrum is shown to include a power-law part $N \propto \varepsilon^{-\gamma}$ with an index $\gamma = 1.7–3.5$ that ends with an exponential tail. The maximum SCR energy lies within the range $\varepsilon_{max} = 0.01–10$ GeV, depending on the shock velocity $V_S = 750–2500$ km s^{-1}. The decrease of the shock Alfvénic Mach number due to the increase Alfvén velocity with heliocentric distance r leads to the end of the efficient SCR acceleration when the shock size reaches $R_S \approx 4R_\odot$. In this case, the diffusive SCR propagation begins to exceed the shock velocity; as a result, SCRs escape intensively from the shock vicinity. The self-consistent generation of Alfvén waves by accelerated particles is accompanied by a steepening of the particle spectrum and an increase of their maximum energy. Comparison of the calculated SCR fluxes expected near the Earth's orbit with the available experimental data shows that the theory explains the main observed features.

On the Turbulent Reduction of Drifts for Solar Energetic Particles

J. P. van den **Berg**1,2, N. E. Engelbrecht1,3, N. Wijsen4, and R. D. Strauss1,3
2021 ApJ 922 200
https://doi.org/10.3847/1538-4357/ac2736
Particle drifts perpendicular to the background magnetic field have been proposed by some authors as an explanation for the very efficient perpendicular transport of solar energetic particles (SEPs). This process, however, competes with perpendicular diffusion caused by magnetic turbulence, which can also disrupt the drift patterns and reduce the magnitude of drift effects. The latter phenomenon is well known in cosmic-ray studies, but not yet considered in SEP models. Additionally, SEP models that do not include drifts, especially for electrons, use turbulent drift reduction as a justification of this omission, without critically evaluating or testing this assumption. This article presents the first theoretical step for a theory of drift suppression in SEP transport. This is done by deriving the turbulence-dependent drift reduction function with a pitch-angle dependence, as is applicable for anisotropic particle distributions, and by investigating to what extent drifts will be reduced in the inner heliosphere for realistic turbulence conditions and different pitch-angle dependencies of the perpendicular diffusion coefficient. The influence of the derived turbulent drift reduction factors on the transport of SEPs are tested, using a state-of-the-art SEP transport code, for several expressions of theoretically derived perpendicular diffusion coefficients. It is found, for realistic turbulence conditions in the inner heliosphere, that cross-field diffusion will have the largest influence on the perpendicular transport of SEPs, as opposed to particle drifts.

A Primer on Focused Solar Energetic Particle Transport **Review**
Basic Physics and Recent Modelling Results

Jabus van den **Berg**, Du Toit Strauss & Frederic Effenberger
Space Science Reviews volume 216, Article number: 146 (**2020**)
https://link.springer.com/content/pdf/10.1007/s11214-020-00771-x.pdf
https://arxiv.org/pdf/2012.07570
The basics of focused transport as applied to solar energetic particles are reviewed, paying special attention to areas of common misconception. The micro-physics of charged particles interacting with slab turbulence are investigated to illustrate the concept of pitch-angle scattering, where after the distribution function and focused transport equation are introduced as theoretical tools to describe the transport processes and it is discussed how observable quantities can be calculated from the distribution function. In particular, two approximations, the diffusion-advection and the telegraph equation, are compared in simplified situations to the full solution of the focused transport equation describing particle motion along a magnetic field line. It is shown that these approximations are insufficient to capture the complexity of the physical processes involved. To overcome such limitations, a finite-difference model, which is open for use by the public, is introduced to solve the focused transport equation. The use of the model is briefly discussed and it is shown how the model can be applied to reproduce an observed solar energetic electron event, providing insights into the acceleration and transport processes involved. Past work and literature on the application of these concepts are also reviewed, starting with the most basic models and building up to more complex models**. 9 Sep 1998, 17 May 2012, 1 Aug 2014**

The Solar Particle Event on 10 September 2017 as observed onboard the International Space Station (ISS)

T. **Berger** , D. Matthiä , S. Burmeister , R. Rios, K. Lee, E. Semones, D. M. Hassler, N. Stoffle , C. Zeitlin
Space Weather **Volume16, Issue9** Pages 1173-1189 **2018**
http://sci-hub.tw/10.1029/2018SW001920

The nominal radiation environment in low Earth orbit, especially for the International Space Station (ISS), is dominated by two sources. The first is galactic cosmic radiation, which is modulated by the interplanetary and the Earth's magnetic fields, and the second is trapped radiation in the form of the Van Allen belts. The trapped radiation inside the ISS is mostly due to protons of the inner radiation belt. In addition to these sources sporadic solar particle events (SPEs) can produce high doses inside and outside the ISS, depending on the intensity and energy spectrum of the event. Before 2017, the last SPE observed inside the ISS with relevant radiation detectors occurred in May 2012. Even though we are currently approaching the next solar minimum, an SPE was observed in September 2017, which was (a) a ground-level enhancement, (b) measured with various radiation detector systems onboard the ISS, and (c) observed on the surface of Mars. This paper gives an overview of the **10 September 2017** SPE measured with the DOSIS 3D-DOSTEL and the ISS-RAD (Radiation Assessment Detector) instruments, both located at this time in close proximity to each other in the Columbus Laboratory of the ISS. The additional dose received during the SPE was 146.2 μGy in Si as measured by ISS-RAD and 67.8 μGy in Si as measured by the DOSIS 3D-DOSTEL instruments. In comparison, the dose measured on the surface of Mars with the Mars Science Laboratory-RAD instrument accounted to 418 μGy in Si.

The relativistic solar particle event of May 17th, 2012 observed on board the International Space Station

Francesco **Berrilli**1*, Marco Casolino2,3, Dario Del Moro1, Luca Di Fino1,2, Marianna Larosa1,2, Livio Narici1,2, Roberto Piazzesi1, Piergiorgio Picozza1,2, Stefano Scardigli1, Roberta Sparvoli1,2, Marco Stangalini4 and Veronica Zaconte

J. Space Weather Space Clim. 4 (**2014**) A16

http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130061.pdf

High-energy charged particles represent a severe radiation risk for astronauts and spacecrafts and could damage ground critical infrastructures related to space services. Different natural sources are the origin of these particles, among them galactic cosmic rays, solar energetic particles and particles trapped in radiation belts. Solar particle events (SPE) consist in the emission of high-energy protons, alpha-particles, electrons and heavier particles from solar flares or shocks driven by solar plasma propagating through the corona and interplanetary space. Ground-level enhancements (GLE) are rare solar events in which particles are accelerated to near relativistic energies and affect space and ground-based infrastructures. During the current solar cycle 24 a single GLE event was recorded on May 17th, 2012 associated with an M5.1-class solar flare. The investigation of such a special class of solar events permits us to measure conditions in space critical to both scientific and operational research. This event, classified as GLE71, was detected on board the International Space Station (ISS) by the active particle detectors of the ALTEA (Anomalous Long Term Effects in Astronauts) experiment. The collected data permit us to study the radiation environment inside the ISS. In this work we present the first results of the analysis of data acquired by ALTEA detectors during GLE71 associated with an M5.1-class solar flare. We estimate the energy loss spectrum of the solar particles and evaluate the contribution to the total exposure of ISS astronauts to solar high-energy charged particles.

The *energetic relationship* among geoeffective solar flares, associated CMEs and SEPs

Nipa J **Bhatt**1, Rajmal Jain2 and Arun Kumar Awasthi2

Res. Astron. Astrophys. 13 978, **2013**

https://iopscience.iop.org/article/10.1088/1674-4527/13/8/009/pdf

Major solar eruptions (flares, coronal mass ejections (CMEs) and solar energetic particles (SEPs)) strongly influence geospace and space weather. Currently, the mechanism of their influence on space weather is not well understood and requires a detailed study of the energetic relationship among these eruptive phenomena. From this perspective, we investigate 30 flares (observed by RHESSI), followed by weak to strong geomagnetic storms. Spectral analysis of these flares suggests a new power-law relationship (r ~ 0.79) between the hard X-ray (HXR) spectral index (before flare-peak) and linear speed of the associated CME observed by LASCO/SOHO. For 12 flares which were followed by SEP enhancement near Earth, HXR and SEP spectral analysis reveals a new scaling law (r ~ 0.9) **between *the hardest X-ray flare spectrum and the hardest SEP spectrum*. Furthermore, *a strong correlation is obtained between the linear speed of the CME and the hardest spectrum of the corresponding SEP event* (r ~ 0.96). We propose that the potentially geoeffective flare and associated CME and SEP are well-connected** through a possible feedback mechanism, and should be regarded within the framework of a solar eruption. Owing to their space weather effects, these new results will help improve our current understanding of the Sun-Earth relationship, which is a major goal of research programs in heliophysics. **28-29 Oct 2003**

Table 1 Characteristics of X-ray Flares, associated CMEs and SEPs (2002-2006)

Transport of Solar Energetic Particles along Stochastic Parker Spirals

N. H. **Bian**1 and Gang Li1

2022 ApJ 924 120

https://iopscience.iop.org/article/10.3847/1538-4357/ac2fab/pdf

It was recently shown that, owing to the turbulent nature of the solar wind, the interplanetary magnetic field lines can be well described by stochastic Parker spirals. These are realizations of Brownian diffusion on a sphere of increasing radius, superimposed on the angular drift due to the solar rotation. In this work, we present a model for the transport of solar energetic particles along stochastic Parker spirals in the inner heliosphere. The transport model is governed by a set of four stochastic differential equations for the heliographic position $(r, \alpha = \cos\theta, \phi)$ of the guiding centers and the cosine of the pitch angle between the velocity vector and the Parker field. The model accounts for the role played by the combination of pitch angle scattering and magnetic focusing in the interplanetary medium. The effects of the dynamical evolution of the turbulence are included in the model by taking the field line angular diffusivity to be a function of the radial distance from the Sun. The heliolongitudinal distribution of particles propagating along stochastic Parker spirals is given by the wrapped Gaussian distribution. This angular distribution can also well be represented by the von Mises distribution that interpolates between the Gaussian distribution at small angular spread and the uniform distribution at large distances from the acceleration region of energetic particles in the aftermath of a solar eruption.

Delay-time Distributions of Solar Energetic Particles. II. Effects of Magnetic Focusing

N. H. **Bian** and A. Gordon Emslie

2020 ApJ 897 34

sci-hub.tw/10.3847/1538-4357/ab9364

We extend a recently published analytic model for the intensity–time profile of solar energetic particle (SEP) events, in which the dominant physical mechanism is turbulent pitch-angle scattering of a collimated distribution of particles accelerated at the Sun. The present model includes the effect of magnetic focusing in the expanding magnetic field geometry of the inner heliosphere. For a power-law variation of the magnetic field strength with distance ($B \sim s^{-\alpha}$) that lacks a characteristic focusing length scale, the fundamental shape of the intensity–time profile (i.e., a Lévy distribution at times up to and just past the time of peak intensity, followed by an exponential decay) is preserved. The effect of magnetic focusing is essentially to produce a rescaling of the stochastic process describing the angular diffusion of the particles, making the typical time that characterizes the SEP time profile quantitatively lower by a factor of $(\alpha + 1)$, 3 for the radial field geometry $B \sim s^{-2}$.

Delay-time Distributions of Solar Energetic Particles

N. H. **Bian** and A. Gordon Emslie

2019 ApJ 880 11

sci-hub.se/10.3847/1538-4357/ab2648

We present an analytic model for the intensity-time profile of solar energetic particle events, based on considerations related to the delay-time distribution that results from interplanetary scattering of a focused distribution of energetic particles. For instantaneous injection, the intensity-time profile is shown to be well described by a Lévy distribution at times up to and just past the time of peak intensity. This allows a fitting procedure that uses velocity dispersion analysis of both the onset time and the peak time to estimate the time of particle release, the magnetic connection length, and the scattering length (and its dependence on velocity). Furthermore, the delay-time distribution can be used as a Green function response when taking into account particle injections of finite duration, in order to infer the release time profile in extended events.

GIANT GROUND LEVEL ENHANCEMENT OF RELATIVISTIC SOLAR PROTONS ON 2005 JANUARY 20. I. SPACESHIP EARTH OBSERVATIONS

J. W. **Bieber**1, J. Clem1, P. Evenson1, R. Pyle1, A. Sáiz2,3, and D. Ruffolo

2013 ApJ 771 92

A ground level enhancement (GLE) is a solar event that accelerates ions (mostly protons) to GeV range energies in such great numbers that ground-based detectors, such as neutron monitors, observe their showers in Earth's atmosphere above the Galactic cosmic ray background. GLEs are of practical interest because an enhanced relativistic ion flux poses a hazard to astronauts, air crews, and aircraft electronics, and provides the earliest direct indication of an impending space radiation storm. The giant GLE of 2005 January 20 was the second largest on record (and largest since 1956), with up to 4200% count rate enhancement at sea level. We analyzed data from the Spaceship Earth network, supplemented to comprise 13 polar neutron monitor stations with distinct asymptotic viewing directions and Polar Bare neutron counters at South Pole, to determine the time evolution of the relativistic proton density, energy spectrum, and three-dimensional directional distribution. We identify two energy-dispersive peaks, indicating two solar injections. The relativistic solar protons were initially strongly beamed, with a peak maximum-to-minimum anisotropy ratio over 1000:1. The directional distribution is characterized by an axis of symmetry, determined independently for each minute of data, whose angle from the magnetic field slowly varied from about 60° to low values and then rose to about 90°. The extremely high relativistic proton flux from certain directions allowed 10 s tracking of count rates, revealing fluctuations of period 2 minutes with up to 50% fractional changes, which we attribute to fluctuations in the axis of symmetry.

Solar Energetic Particles measured by AMS-02

V. **Bindi**

34th ICRC 30 July- 6 August, **2015** The Hague, The Netherlands

https://pos.sissa.it/archive/conferences/236/108/ICRC2015_108.pdf

The Alpha Magnetic Spectrometer (AMS-02), with its acceptance of about 0.45 m2 sr, is the largest Solar Energetic Particle (SEP) detector in space. AMS-02 was installed on the International Space Station (ISS) on May 19, 2011, where it will take data for the duration of the station, currently extended till 2024. During the first three years of operation, AMS-02 measured increases in the proton flux near 1 GV and above associated with twenty of the highest energy solar events, produced during M- and X-class flares and fast coronal mass ejections (CME) magnetically well-connected with the Earth. Thanks to its large acceptance and particle detection capabilities, AMS-02 is able to perform precise measurements in a short period of time which is typical of these transient phenomena and collect enough statistics to measure fine structures and time evolution of the proton spectrum. The events observed by AMS-02 since the beginning of its mission will be presented and some preliminary results will be shown. AMS-02 observations of protons and helium, with their unprecedented resolution and high statistics, will improve the understanding of SEP behavior at high energies and constrain models of SEP production.**May 17, 2012**
Table 1: List of intense solar events between May 2011 and Feb 2014 associated with a proton increase observed by AMS-02 near 1 GV and above

Energetic-particle-flux decreases related to magnetic cloud passages as observed by the Helios 1 and 2 spacecraft

J. J. **Blanco**1, M. A. Hidalgo1, R. Gómez-Herrero1, J. Rodríguez-Pacheco1, B. Heber2, R. F. Wimmer-Schweingruber2 and C. Martín

A&A 556, A146 (**2013**)

It has been observed that a magnetic cloud (MC) can affect the propagation conditions of solar energetic particles and low-energy cosmic rays. This effect is commonly observed as a decrease in the energetic-particle fluxes, which are partially excluded from the interior of the cloud. The twin spacecraft Helios 1 and Helios 2 explored the inner heliosphere between 0.29 AU and 1 AU from the mid 1970s to early 1980s. The E6 Experiment onboard Helios is the energetic-particle detector able to measure electrons, protons and alphas in the range of 300 keV/n to >50 MeV/n. It has been shown previously that, in absence of strong solar-particle events, the single detector rates of the E6 anti-coincidence and saphire Cherenkov detectors are sensitive to cosmic rays with rigidities above GV. Because their statistical precision is in the order of hundreds of counts per second, both detectors are very well suited for studying the short-term decreases observed in their count rates during magnetic cloud passages. A total of 35 magnetic clouds have been identified at the Helios locations. Nineteen of them were free of solar energetic-particle contamination. This subset led us to investigate the effect of magnetic clouds on the galactic cosmic ray (GCR) flux. The depth of the decreases are studied in terms of the solar wind and magnetic field properties of the magnetic cloud. We found dependences with the MC magnetic field strength, magnetic rigidity and with the MC time of flight, with the latter supporting the idea of magnetically closed MCs, i.e. with the two legs rooted in the Sun. We also studied MC properties and found evidence of MC expansion during its journey through the inner heliosphere.

AN IMPROVED MODEL FOR RELATIVISTIC SOLAR PROTON ACCELERATION APPLIED TO THE 2005 JANUARY 20 AND EARLIER EVENTS

D. J. **Bombardieri**,1 M. L. Duldig,2 J. E. Humble,3,2 and K. J. Michael1,4

Astrophysical Journal, 682:1315Y1327, **2008**

http://www.journals.uchicago.edu/toc/apj/2008/682/2

This paper presents results on modeling the ground-level response of the higher energy protons for the 2005 January 20 ground-level enhancement (GLE). This event, known as GLE 69, produced the highest intensity of relativistic solar particles since the famous event on 1956 February 23. The location of recent X-ray and _-ray emission (N14_ W61_) was near Sun-Earth connecting magnetic field lines, thus providing the opportunity to directly observe the acceleration source from Earth. We restrict our analysis to protons of energy _450 MeV to avoid complications arising from transport processes that can affect the propagation of low-energy protons. In light of this revised approach we have reinvestigated two previous GLEs: those of **2000 July 14 (GLE 59) and 2001 April 15 (GLE 60)**. Within the limitations of the spectral forms employed, we find that from the peak (06:55 UT) to the decline (07:30 UT) phases of GLE 69, neutronmonitor observations from450 MeVto 10 GeVare best fitted by the Gallegos-Cruz&Perez-Peraza stochastic acceleration model. In contrast, the Ellison & Ramaty spectra did not fit the neutron monitor observations as well. This result suggests that for GLE 69, a stochastic process cannot be discounted as a mechanism for relativistic particle acceleration, particularly during the initial stages of this solar event. For GLE 59 we find evidence that more than one acceleration mechanism was present, consistent with both shock and stochastic acceleration processes dominating at different times of the event. For GLE 60 we find that Ellison & Ramaty spectra better represent the neutron monitor observations compared to stochastic acceleration spectra. The results for GLEs 59 and 60 are in agreement with our previous work.

Toward a Quantitative Model for Simulation and Forecast of Solar Energetic Particle Production during Gradual Events.
I. Magnetohydrodynamic Background Coupled to the SEP Model
D. **Borovikov**1,2, I. V. Sokolov1, I. I. Roussev3, A. Taktakishvili4,5, and T. I. Gombosi1
2018 ApJ 864 88
https://doi.org/10.3847/1538-4357/aad68d
Solar energetic particles (SEPs) are an important aspect of space weather. SEP events possess a high destructive potential, since they may cause disruptions of communication systems on Earth and be fatal to crew members on board spacecraft and, in extreme cases, harmful to people on board high-altitude flights. However, currently the research community lacks efficient tools to predict such a hazardous threat and its potential impacts. Such a tool is a first step for mankind to improve its preparedness for SEP events and ultimately to be able to mitigate their effects. The main goal of the presented research effort is to develop a computational tool that will have the forecasting capability and can serve as an operational system that will provide live information on the current potential threats posed by SEP based on the observations of the Sun. In the present paper we discuss the fundamentals of magnetohydrodynamical simulations to be employed as a critical part of the desired forecasting system.

Propagation of Cosmic Rays in Heliosphere: the HelMod Model
M.J. **Boschini**, S. Della Torre, M. Gervasi, G. La Vacca, P. G. Rancoita
Advances in Space Research **2017**
https://arxiv.org/pdf/1704.03733.pdf
The heliospheric modulation model \helmod{} is a two dimensional treatment dealing with the helio-colatitude and radial distance from Sun and is employed to solve the transport-equation for the GCR propagation through the heliosphere down to Earth. This work presents the current version 3 of the \helmod{} model and reviews how main processes involved in GCR propagation were implemented.~The treatment includes the so-called particle drift effects --~e.g., those resulting, for instance, from the extension of the neutral current sheet inside the heliosphere and from the curvature and gradient of the IMF --, which affect the transport of particles entering the solar cavity as a function of their charge sign.~The \helmod{} model is capable to provide modulated spectra which well agree within the experimental errors with those measured by AMS-01, BESS, PAMELA and AMS-02 during the solar cycles 23 and 24.~Furthermore, the counting rate measured by Ulysses at +/- 80degree of solar latitude and 1 to 5\,AU was also found in agreement with that expected by \helmod{} code version 3.

On the production of highest energy solar protons at 20 January 2005
Bostanjyan, N. Kh.; Chilingarian, A. A.; Eganov, V. S.; Karapetyan, G. G.
Advances in Space Research, Volume 39, Issue 9, p. 1454-1457, **2007**
On January 20, 2005, 7:02-7:05 UT the Aragats Multidirectional Muon Monitor (AMMM) located at 3200 m a.s.l. registered enhancement of the high energy secondary muon flux (threshold ˜5 GeV). The enhancement, lasting for 3 min, has statistical significance of ˜4 σ and is related to the X7.1 flare seen by the GOES, and very fast (>2500 km/s) CME seen by SOHO, and the Ground Level Enhancements (GLE) #69 detected by the world-wide network of neutron monitors and muon detectors. The energetic and temporal characteristics of the muon signal from the AMMM are compared with the characteristics of other monitors located at the Aragats Space-Environmental Center (ASEC) and with other neutron and muon detectors. Since secondary muons with energies >5 GeV are corresponding to solar proton primaries with energies 20-30 GeV we conclude that in the episode of the particle acceleration at 7:02-7:05 UT 20 January 2005 solar protons were accelerated up to energies in excess of 20 GeV.

On the Prediction of >100 MeV Solar Energetic Particle Events Using GOES Satellite Data
Soukaina Filali **Boubrahimi**, Berkay Aydin, Petrus Martens, Rafal Angryk
2017 In: 2017 IEEE International Conference on Big Data (Big Data). pp. 2533–2542**.**
https://arxiv.org/pdf/1712.03998.pdf
Solar energetic particles are a result of intense solar events such as solar flares and Coronal Mass Ejections (CMEs). These latter events all together can cause major disruptions to spacecraft that are in Earth's orbit and outside of the magnetosphere. In this work we are interested in establishing the necessary conditions for a major geo-effective solar particle storm immediately after a major flare, namely the existence of a direct magnetic connection. To our knowledge, this is the first work that explores not only the correlations of GOES X-ray and proton channels, but also the correlations that happen across all the proton channels. We found that proton channels auto-correlations and cross-correlations may also be precursors to the occurrence of an SEP event. In this paper, we tackle the problem of predicting >100 MeV SEP events from a multivariate time series perspective using easily interpretable decision tree models. **2001-04-02 , 2001-04-15, 2011-04-15**,
TABLE II > 100 MEV SEP EVENT LIST WITH THEIR PARENT EVENTS (CME/FLARE)
TABLE III NON SEP EVENT LIST

Tree rings reveal two strong solar proton events in 7176 and 5259 BCE

Nicolas **Brehm**, Marcus Christl, Florian Adolphi, Raimund Muscheler, …..Ilya Usoskin, Lukas Wacker

Research Square **2021**

https://assets.researchsquare.com/files/rs-753272/v1_covered.pdf

https://www.researchsquare.com/article/rs-753272/v1

DOI: 10.21203/rs.3.rs-753272/v1

The Sun sporadically produces eruptive events leading to intense fluxes of solar energetic particles (SEPs) that dramatically disrupt the near-Earth radiation environment. Such events are directly studied for the last decades but little is known about the occurrence and magnitude of rare, extreme SEP events. Presently, a few events that produced measurable signals in cosmogenic radionuclides such as 14C, 10Be and 36Cl have been found. Analyzing annual 14C concentrations in tree-rings from Switzerland, Germany, Ireland, Russia, and the USA we discovered two spikes in atmospheric 14C corresponding to 7176 and 5259 BCE. The ~2% increases of atmospheric 14C recorded for both events exceed all previously known 14C peaks but after correction for the geomagnetic field, they are comparable to the largest event of this type discovered so far at 775 CE. These strong events serve as accurate time markers for the synchronization with floating tree-ring and ice core records and provide critical information on the previous occurrence of extreme solar events which threaten modern infrastructure.

Very narrow coronal mass ejections producing solar energetic particles

K. **Bronarska**1, M. S. Wheatland2, N. Gopalswamy3 and G. Michalek1

A&A 619, A34 (**2018**)

sci-hub.tw/10.1051/0004-6361/201833237

http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2018/11/aa33237-18/aa33237-18.html

Aims. Our main aim is to study the relationship between low-energy solar particles (energies below 1 MeV) and very narrow coronal mass ejections (“jets” with angular width ≤ 20°).
Methods. For this purpose, we considered 125 very narrow coronal mass ejections (CMEs) from 1999 to 2003 that are potentially associated with low-energy solar particles (LESPs). These events were chosen on the basis of their source location. We studied only very narrow CMEs at the western limb, which are expected to have good magnetic connectivity with Earth.
Results. We found 24 very narrow CMEs associated with energetic particles such as ions (protons and 3He), electrons, or both. We show that arrival times at Earth of energetic particles are consistent with onset times of the respective CMEs, and that in the same time intervals, there are no other potential sources of energetic particles. We also demonstrate statistical differences for the angular width distributions using the Kolmogorov–Smirnov test for angular widths for these 24 events. We consider a coherent sample of jets (mostly originating from boundaries of coronal holes) to identify properties of events that produce solar energetic particles (velocities, widths, and position angles). Our study presents a new approach and result: very narrow CMEs can generate low-energy particles in the vicinity of Earth without other activity on the Sun. The results could be very useful for space weather forecasting.
2000/07/10, 14 December 2001
Table 2. Properties of 24 very narrow CMEs generating low-energy SEPs

Characteristics of active regions associated to large solar energetic proton events ☆

K. **Bronarska**, , G. Michalek

Advances in Space Research Volume 59, Issue 1, 1 January **2017**, Pages 384–392

https://reader.elsevier.com/reader/sd/pii/S0273117716305245?token=D8D1B59210EF42E0576A22E03A1F6AD05DE5C2721164C42465E95E51879D8BB84CC3F5C5352236A499F0EFE94994B32D

The relationship between properties of active regions (ARs) and solar energetic particles (SEP events, protons with energy ⩾10 MeV) is examined. For this purpose we study 84 SEP events recorded during the SOHO era (1996–2014). We compare properties of these SEP events with associated ARs, flares and CMEs. The ARs are characterized by McIntosh classification. Statistical analysis demonstrates that SEP events are more likely to be associated to the ARs having complex magnetic structures and the most energetic SEPs are ejected only from the associated ARs having a large and asymmetric penumbra. This tendency is used to estimate intensities of potential SEP events. For this purpose we express a probability of occurrence of an SEP event from a given AR which is correlated with fluxes of associated SEPs. We find that SEP events associated with ARs from eastern longitudes have to be more complex to produce SEP events at Earth. On the other hand, SEP particles originating from mid-longitudes (30°<longitude<70°30°<longitude<70°) on the west side of solar disk are associated to the least complex ARs. These results could be useful for forecasting of space weather.

Signature and escape of highly fractionated plasma in an active region

David H. **Brooks**, Stephanie L. Yardley

MNRAS Volume 508, Issue 2, December **2021**, Pages 1831–1841,

https://doi.org/10.1093/mnras/stab2681

https://arxiv.org/pdf/2109.11157.pdf
Accurate forecasting of space weather requires knowledge of the source regions where solar energetic particles (SEP) and eruptive events originate. Recent work has linked several major SEP events in 2014, January, to specific features in the host active region (AR 11944). In particular, plasma composition measurements in and around the footpoints of hot, coronal loops in the core of the active region were able to explain the values later measured in-situ by the Wind spacecraft. Due to important differences in elemental composition between SEPs and the solar wind, the magnitude of the Si/S elemental abundance ratio emerged as a key diagnostic of SEP seed population and solar wind source locations. We seek to understand if the results are typical of other active regions, even if they are not solar wind sources or SEP productive. In this paper, we use a novel composition analysis technique, together with an evolutionary magnetic field model, in a new approach to investigate a typical solar active region (AR 11150), and identify the locations of highly fractionated (high Si/S abundance ratio) plasma. Material confined near the footpoints of coronal loops, as in AR 11944, that in this case have expanded to the AR periphery, show the signature, and can be released from magnetic field opened by reconnection at the AR boundary. Since the fundamental characteristics of closed field loops being opened at the AR boundary is typical of active regions, this process is likely to be general. **2011, Jan 31-Feb 1**

The source of the major solar energetic particle events from super active region 11944

David H. **Brooks**1,* and Stephanie L. Yardley2
Science Advances 03 Mar **2021**: Vol. 7, no. 10, eabf0068 **File**
DOI: 10.1126/sciadv.abf0068
https://advances.sciencemag.org/content/advances/7/10/eabf0068.full.pdf
https://arxiv.org/ftp/arxiv/papers/2103/2103.13621.pdf
Shock waves associated with fast coronal mass ejections (CMEs) accelerate solar energetic particles (SEPs) in the long duration, gradual events that pose hazards to crewed spaceflight and near-Earth technological assets, but the source of the CME shock-accelerated plasma is still debated. Here, we use multi-messenger observations from the Heliophysics System Observatory to identify plasma confined at the footpoints of the hot, core loops of active region 11944 as the source of major gradual SEP events in January 2014. We show that the elemental composition signature detected spectroscopically at the footpoints explains the measurements made by particle counting techniques near Earth. Our results localize the elemental fractionation process to the top of the chromosphere. The plasma confined closest to that region, where the coronal magnetic field strength is high (a few hundred Gauss), develops the SEP composition signature. This source material is continually released from magnetic confinement and accelerated as SEPs following M-, C-, and X-class flares. **5-8 Jan 2014**
RHESSI Science Nuggets #405 March **2021**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Tracing_the_sources_of_gradual_solar_energetic_particle_events

A new method to determine solar energetic particle anisotropies and their associated uncertainties demonstrated for STEREO/SEPT

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A&A 663, A89 (**2022**)
https://www.aanda.org/articles/aa/pdf/2022/07/aa42761-21.pdf
https://doi.org/10.1051/0004-6361/202142761
Context. The shape of the pitch-angle distribution (PAD) of solar energetic particles (SEPs) can be used to infer information about their source and interplanetary transport. In modeling and observational studies of SEP events, these PADs are frequently applied to determine the anisotropy which is a proxy for the strength of the pitch-angle scattering during transport. For the determination of the PAD, derivation of the pitch angle of SEPs takes on a crucial role. For most instrument-sampled PADs, the particle's pitch angle cannot be resolved directly but is usually approximated by considering the time-averaged in situ magnetic field direction, and the center viewing direction of the telescope. However, variations of the magnetic field, and the extent of the physical opening of the instrument lead to uncertainty on the determination of the pitch angle and therefore to uncertainty on the anisotropy and its interpretation.
Aims. In this work, we present a new method to determine a distribution of anisotropy values which allows us to estimate the corresponding uncertainty ranges. We apply our method to electron measurements by the Solar Electron and Proton Telescope on board each STEREO spacecraft.
Methods. We determined a distribution of anisotropy values by solving an inversion problem that takes into account the directional response of the instrument, the variation of the in situ magnetic field, and the stochastic nature of particle detection. Using 95% confidence intervals, we estimate the uncertainty on the anisotropy.
Results. The application of our method to a solar electron event observed by STEREO B on **14 August 2010** yields a maximum anisotropy of 1.9 with an uncertainty on the order of ±0.1. During the background period, the anisotropy shows strong fluctuations, and absolute uncertainties on the order of ±0.5 that are attributable to low counting statistics.

Statistical Relationship Between Long-duration High-Energy Gamma-Ray Emission and Solar Energetic Particles

Alessandro **Bruno**, Georgia A. de Nolfo, James M. Ryan, Ian G. Richardson, Silvia Dalla

ApJ **2023**

https://arxiv.org/pdf/2306.14671.pdf **File**

Large solar eruptions are often associated with long-duration gamma-ray emission extending well above 100 MeV. While this phenomenon is known to be caused by high-energy ions interacting with the solar atmosphere, the underlying dominant acceleration process remains under debate. Potential mechanisms include continuous acceleration of particles trapped within large coronal loops or acceleration at coronal mass ejection (CME)-driven shocks, with subsequent back-propagation towards the Sun. As a test of the latter scenario, previous studies have explored the relationship between the inferred particle population producing the high-energy gamma-rays, and the population of solar energetic particles (SEPs) measured in situ. However, given the significant limitations on available observations, these estimates unavoidably rely on a number of assumptions. In an effort to better constrain theories of the gamma-ray emission origin, we re-examine the calculation uncertainties and how they influence the comparison of these two proton populations. We show that, even accounting for conservative assumptions related to gamma-ray flare, SEP event and interplanetary scattering modeling, their statistical relationship is only poorly/moderately significant. However, though the level of correlation is of interest, it does not provide conclusive evidence for or against a causal connection. The main result of this investigation is that the fraction of the shock-accelerated protons required to account for the gamma-ray observations is >20-40% for six of the fourteen eruptions analyzed. Such high values argue against current CME-shock origin models, predicting a <2% back-precipitation, hence the computed numbers of high-energy SEPs appear to be greatly insufficient to sustain the measured gamma-ray emission.

Table 1. Relevant heliographic coordinates and CME parameters for the fourteen LDGRF-associated SEP events analyzed by de Nolfo et al. (2019). 2011-2014

Table 3. Onset times (hh:mm) and durations (hours) for the LDGRF events analyzed by Gopalswamy et al. (2019, G2019), Share et al. (2018, S2018), Winter et al. (2018, W2018) and Ajello et al. (2021, A2021). 2011-2017

Empirical Model of 10-130 MeV Solar Energetic Particle Spectra at 1 AU Based on Coronal Mass Ejection Speed and Direction

Alessandro **Bruno**, Ian G. Richardson

Solar Phys. **296**, Article number: 36 **2021**

https://arxiv.org/pdf/2101.04234.pdf **File**

https://link.springer.com/content/pdf/10.1007/s11207-021-01779-4.pdf

https://doi.org/10.1007/s11207-021-01779-4

We present a new empirical model to predict solar energetic particle (SEP) event-integrated and peak intensity spectra between 10 and 130 MeV at 1 AU, based on multi-point spacecraft measurements from the Solar TErrestrial RElations Observatory (STEREO), the Geostationary Operational Environmental Satellites (GOES) and the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment. The analyzed data sample includes 32 SEP events occurring between 2010 and 2014, with a statistically significant proton signal at energies in excess of a few tens of MeV, unambiguously recorded at three spacecraft locations. The spatial distributions of SEP intensities are reconstructed by assuming an energy-dependent 2D Gaussian functional form, and accounting for the correlation between the intensity and the speed of the parent coronal mass ejection (CME), and the magnetic field line connection angle. The CME measurements used are from the SpaceWeather Database Of Notifications, Knowledge, Information (DONKI). The model performance, including its extrapolations to lower/higher energies, is tested by comparing with the spectra of 20 SEP events not used to derive the model parameters. Despite the simplicity of the model, the observed and predicted event-integrated and peak intensities at Earth and at the STEREO spacecraft for these events show remarkable agreement, both in the spectral shapes and their absolute values.

Table 1. List of CMEs associated with the SEP events analyzed in this work. (2010-2014)

Table 4. List of CMEs associated with the SEP events used for testing the empirical model (2011-2017)

Correction: *Solar Physics* **volume 296**, Article number: 45 (2021)
https://doi.org/10.1007/s11207-021-01795-4

Space Weather Observations during September 2017 with CALET on the International Space Station

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36th International cosmic-ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A

https://pos.sissa.it/358/1063/pdf
A period of extreme solar activity was observed in early September 2017, during the decaying phase of solar cycle 24. A large number of bright eruptions were registered, including a X9.3 flare on **6 September** and a X8.2 flare on **10 September**, the two strongest soft X-ray flares in almost 11 years. Both were associated with fast Coronal Mass Ejections (CMEs) and produced Solar Energetic Particle (SEP) events measured by several spacecraft. In particular, the second event was energetic enough to induce a Ground Level Enhancement (GLE) detected by the worldwide neutron monitor network, the second GLE of solar cycle 24. In this work we present a preliminary analysis of the September 2017 SEP events made with the CALorimetric Electron Telescope (CALET) onboard the International Space Station (ISS). We also investigate the relativistic electron precipitation (REP) events associated with the geomagnetic storms occurring in the same period. Data are compared with those of other space- and ground-based detectors.

Spectral Analysis of the September 2017 Solar Energetic Particle Events

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Space Weather Volume17, Issue3 Pages 419-437 **2019**

https://arxiv.org/pdf/1902.03969.pdf
sci-hub.tw/10.1029/2018SW002085
An interval of exceptional solar activity was registered in early **September 2017**, late in the decay phase of solar cycle 24, involving the complex Active Region 12673 as it rotated across the western hemisphere with respect to Earth. A large number of eruptions occurred between **4 and 10 September**, including four associated with X-class flares. The X9.3 flare on **6 September** and the X8.2 flare on 10 September are currently the two largest during cycle 24. Both were accompanied by fast coronal mass ejections and gave rise to solar energetic particle (SEP) events measured by near-Earth spacecraft. In particular, the partially occulted solar event on 10 September triggered a ground-level enhancement (GLE), the second GLE of cycle 24. A further, much less energetic SEP event was recorded on **4 September**. In this work we analyze observations by the Advanced Composition Explorer (ACE) and the Geostationary Operational Environmental Satellites (GOES), estimating the SEP event-integrated spectra above 300 keV and carrying out a detailed study of the spectral shape temporal evolution. Derived spectra are characterized by a low-energy break at few/tens of MeV; the **10 September** event spectrum, extending up to ~1 GeV, exhibits an additional rollover at several hundred MeV. We discuss the spectral interpretation in the scenario of shock acceleration and in terms of other important external influences related to interplanetary transport and magnetic connectivity, taking advantage of multipoint observations from the Solar Terrestrial Relations Observatory. Spectral results are also compared with those obtained for the **17 May 2012** GLE event.

Solar energetic particle events observed by the PAMELA mission

A. **Bruno**, G. A. Bazilevskaya, M. Boezio, E. R. Christian, G. A. de Nolfo, M. Martucci, M. Merge', V. V. Mikhailov, R. Munini, I. G. Richardson, J. M. Ryan, S. Stochaj, O. Adriani, G. C. Barbarino, R. Bellotti, E. A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, C. De Santis, V. Di Felice, A. M. Galper, A. V. Karelin, S. V. Koldashov, S. Koldobskiy, S. Y. Krutkov, A. N. Kvashnin, A. Leonov, V. Malakhov, L. Marcelli, A. G. Mayorov, W. Menn, E. Mocchiutti, A. Monaco, N. Mori, G. Osteria, B. Panico, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. Simon, R. Sparvoli, P. Spillantini, Y. I. Stozhkov, A. Vacchi, E. Vannuccini, G. I. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa

Astrophysical Journal, 862:97 **2018**
https://arxiv.org/pdf/1807.10183.pdf
http://sci-hub.se/10.3847/1538-4357/aacc26
Despite the significant progress achieved in recent years, the physical mechanisms underlying the origin of solar energetic particles (SEPs) are still a matter of debate. The complex nature of both particle acceleration and transport poses challenges to developing a universal picture of SEP events that encompasses both the low-energy (from tens of keV to a few hundreds of MeV) observations made by space-based instruments and the GeV particles detected by the worldwide network of neutron monitors in ground-level enhancements (GLEs). The high-precision data collected by the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment offer a unique opportunity to study the SEP fluxes between ~80 MeV and a few GeV, significantly improving the characterization of the most energetic events. In particular, PAMELA can measure for the first time with good accuracy the spectral features at moderate and high energies, providing important constraints for current SEP models. In addition, the PAMELA observations allow the relationship between low and high-energy particles to be investigated, enabling a clearer view of the SEP origin. No qualitative distinction between the spectral shapes of GLE, sub-GLE and non-GLE events is observed, suggesting that GLEs are not a separate class, but are the subset of a continuous distribution of SEP events that are more intense at high energies. While the spectral forms found are to be consistent with diffusive shock acceleration theory, which predicts spectral rollovers at high energies that are

attributed to particles escaping the shock region during acceleration, further work is required to explore the relative influences of acceleration and transport processes on SEP spectra.
Table SEP events observed by the PAMELA mission (2006-2014)

Calibration of the GOES 13/15 high-energy proton detectors based on the PAMELA solar energetic particle observations

A. **Bruno**
Space Weather Volume15, Issue9 September **2017** Pages 1191-1202
https://doi.org/10.1002/2017SW001672
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001672
The Energetic Proton, Electron, and Alpha Detector (EPEAD) and High Energy Proton and Alpha Detector (HEPAD) instruments on the Geostationary Operational Environmental Satellite (GOES) spacecraft have served over many years as monitors of the solar particle intensities, surveying the Sun and measuring in situ its effect on the near-Earth solar-terrestrial environment. However, the reconstruction of the differential energy spectra is affected by large uncertainties related to the poor energy resolution, the small geometrical factor, and the high contamination by out-of-acceptance particles. In this work, the high-quality data set from the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) space mission is used to calibrate the high-energy (>80 MeV) proton channels of the EPEAD and the HEPAD sensors on board the GOES 13 and 15, bringing the measured spectral intensities inline with those registered by PAMELA. Suggested corrections significantly reduce the uncertainties on the response of GOES detectors, thus improving the reliability of the spectroscopic observations of solar energetic particle events.

Origin of 3He abundance enhancements in gradual solar energetic particle events

Radoslav **Bucik**, Samuel T. Hart, Maher A. Dayeh, Mihir I. Desai, Glenn M. Mason, Mark E. Wiedenbeck
IAU Symposium 388 Proceedings **2024**
https://arxiv.org/pdf/2410.15515
We examined the origin of 3He abundance enhancement in 23 high-energy (25-50 MeV) solar proton events that coincide with 3He-rich periods detected by ACE ULEIS in 1997-2021. In seven events, 3He enhancement was due to 3He leftover from preceding events or independent 3He events occurring during proton events. One event is the most likely impulsive (3He-rich), and another is unclear. Reaccelerated remnant flare material was the most probable cause of 3He enhancements in the remaining 14 proton events. Imaging observations showed coronal jets in the parent active regions in six of these 14 events. Remarkably, the highest 3He/4He occurred in events with jets, implying their contribution to 3He enhancement. **2010-Jun-12, 2012-Jan-19, 25-Oct-2013, 2014-May-07, 2015-Sep-20**
Table 1. 25–50 MeV proton event characteristics 2010-2015

Recurrent 3He-rich solar energetic particle injections observed by Solar Orbiter at ∼0.5 au⋆

R. **Bučík**1, G. M. Mason2, N. V. Nitta3, V. Krupar4,5, L. Rodriguez6, G. C. Ho2, S. T. Hart7,1, M. A. Dayeh1, J. Rodríguez-Pacheco8, R. Gómez-Herrero8 and R. F. Wimmer-Schweingruber9
A&A 673, L5 (**2023**)
https://www.aanda.org/articles/aa/pdf/2023/05/aa45875-23.pdf
We report Solar Orbiter observations of six recurrent solar energetic particle injections in **2022 March 3−6** at ∼0.5 au. All but one were associated with jets emanating from a plage near a large sunspot in active region 12 957. We saw large jets in injections with high 3He and Fe enrichments and minor jets in injections with no or lower enrichments. Furthermore, the event with the highest enrichment showed a more compact configuration of the underlying photospheric magnetic field. The higher fluences as well as harder spectra were seen in the event with a simultaneous jet and wider eruption. However, in this case, the energy buildup time in the source might be required to produce such spectra. Extreme-ultraviolet images from Solar Orbiter revealed a number of intersecting loops at the base of jets not seen from 1 au that might be a precondition for the recurrent events.
Solar Orbiter science nuggets #12 **2023** https://www.cosmos.esa.int/web/solar-orbiter/-/3he-rich-solar-energetic-particle-events-observed-close-to-the-sun-on-solar-orbiter

The first gradual solar energetic particle event with enhanced 3He abundance on Solar Orbiter

R. **Bučík**, G. M. Mason, R. Gómez-Herrero, V. Krupar, +++
A&A 669, A13 (**2023**)
https://arxiv.org/pdf/2210.16403.pdf
https://www.aanda.org/articles/aa/pdf/2023/01/aa45037-22.pdf

The origin of 3He abundance enhancements in coronal mass ejection (CME)-driven shock gradual solar energetic particle (SEP) events remains largely unexplained. Two mechanisms have been suggested - the re-acceleration of remnant flare material in interplanetary space and concomitant activity in the corona. We explore the first gradual SEP event with enhanced 3He abundance observed by Solar Orbiter. The event started on **2020 November 24** and was associated with a relatively fast halo CME. During the event, the spacecraft was at 0.9 au from the Sun. The event averaged 3He/4He abundance ratio is 24 times higher than the coronal or solar wind value, and the 3He intensity had timing similar to other species. We inspected available imaging, radio observations, and spacecraft magnetic connection to the CME source. It appears the most probable cause of the enhanced 3He abundance are residual 3He ions remaining from a preceding long period of 3He-rich SEPs on **2020 November 17-23**.

Impulsive Solar Energetic Particle Events: EUV Waves and Jets   MINI **REVIEW**

R. **Bucik**

Front. Astron. Space Sci. 8 807961 **2022** **File**

https://www.frontiersin.org/articles/10.3389/fspas.2021.807961/full

https://doi.org/10.3389/fspas.2021.807961

https://arxiv.org/abs/2112.14282

Impulsive solar energetic particle (ISEP) events show peculiar elemental composition, with enhanced 3He and heavy-ion abundances, markedly different from our solar system composition. Furthermore, the events are characterized by a wide variety of energy spectral shapes from power laws to rounded spectra toward the low energies. Solar sources of the events have been firmly associated with coronal jets. Surprisingly, new observations have shown that events are often accompanied by so-called extreme-ultraviolet (EUV) coronal waves – a large-scale phenomenon compared to jets. This paper outlines the current understanding of the linkage of EUV waves with jets and energetic ions in ISEP events. **2007 May 23, 2008 Nov 4, 2009 Dec 22, 2010 January 26, 2010 Feb 2, 2010 Jun 12, 2011 Jan 27, 2011 Feb 18, 2014 May 16**

Table 1. The ISEP events with reported EUV wave speed.

The long period of 3He-rich solar energetic particles measured by Solar Orbiter 2020 November 17–23

R. **Bucík** ˇ 1 , G. M. Mason2 , R. Gómez-Herrero3 , D. Lario4 , L. Balmaceda4, 5 , N. V. Nitta6 , et al.

Astronomy & Astrophysics , Lett. **2021**

https://www.aanda.org/articles/aa/pdf/forth/aa41009-21.pdf

https://arxiv.org/pdf/2109.05570.pdf

We report observations of a relatively long period of 3He-rich solar energetic particles (SEPs) measured by Solar Orbiter. The period consists of several well-resolved ion injections. The high-resolution STEREO-A imaging observations reveal that the injections coincide with extreme ultraviolet jets and brightenings near the east limb, not far from the nominal magnetic connection of Solar Orbiter. The jets originated in two adjacent, large, and complex active regions, as observed by the Solar Dynamics Observatory when the regions rotated into the Earth's view. It appears that the sustained ion injections were related to the complex configuration of the sunspot group and the long period of 3He-rich SEPs to the longitudinal extent covered by the group during the analyzed time period

Temperature in Solar Sources of 3He-rich Solar Energetic Particles and Relation to Ion Abundances

R. **Bucik**, S. M. Mulay, G. M. Mason, N. V. Nitta, M. I. Desai, M. A. Dayeh

ApJ **908** 243 **2021**

https://arxiv.org/pdf/2012.15390.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/abd62d/pdf

3He-rich solar energetic particles (SEPs) are believed to be accelerated in solar flares or jets by a mechanism that depends on the ion charge-to-mass (Q/M) ratio. It implies that the flare plasma characteristics (e.g., temperature) may be effective in determining the elemental abundances of 3He-rich SEPs. This study examines the relation between the suprathermal (<0.2 MeV/nuc) abundances of the He-Fe ions measured on the Advanced Composition Explorer and temperature in the solar sources for 24 3He-rich SEP events in the period 2010-2015. The differential emission measure technique is applied to derive the temperature of the source regions from the extreme ultraviolet imaging observations on the Solar Dynamics Observatory. The obtained temperature distribution peaks at 2.0-2.5 MK that is surprisingly consistent with earlier findings based on in-situ elemental abundance or charge state measurements. We have found a significant anti-correlation between 3He/4He ratio and solar source temperature with a coefficient -0.6. It is most likely caused by non-charge-stripping processes, as both isotopes would be fully ionized in the inferred temperature range. This study shows that the elemental ratios 4He/O, N/O, Ne/O, Si/O, S/O, Ca/O, Fe/O generally behave with temperature as expected from abundance enhancement calculations at ionization equilibrium. The C and Mg, the two species with small changes in the Q/M ratio in the obtained temperature range, show no such behavior with temperature and could be influenced by similar processes as for the 3He/4He ratio.

2012 June 8

Table 1. Properties of 3He-rich SEP events and associated solar sources. (2010-2015)

3He-Rich Solar Energetic Particles: Solar Sources Review

Radoslav **Bučík**

Space Science Reviews volume 216, Article number: 24 (**2020**) **File**

https://arxiv.org/pdf/2002.09442.pdf

https://doi.org/10.1007/s11214-020-00650-5

3He-rich solar energetic particles (SEPs), showing up to a 10,000-fold abundance enhancement of rare elements like 3He or ultra-heavy nuclei, have been a puzzle for more than 50 years. One reason for the current lack of understanding of 3He-rich SEPs is the difficulty resolving the source regions of these commonly occurring events. Since their discovery, there has been strong evidence that 3He-rich SEP production is associated with flares on the Sun. Anomalous abundances of 3He-rich SEPs have been attributed to a unique acceleration mechanism that must routinely operate at flare sites. Flares associated with 3He-rich SEPs have been often observed in jet-like forms indicating an acceleration in magnetic reconnection involving field lines open to interplanetary space. Owing to a fleet of spacecraft around the Sun, providing a greatly improved resolution of solar imaging observations, 3He-rich SEP sources are now explored in unprecedented detail. This paper outlines the current understanding of 3He-rich SEPs, mainly focusing on their solar sources**. 2010 January 26, 2010 February 7, 2011 February 18, 2011 July 8 - 16, 2014 April 29, 2014 May 16, 2014 July 17, and 2014 July 19**

3He-rich Solar Energetic Particles from Sunspot Jets

Radoslav **Bučík**1,2, Mark E. Wiedenbeck3, Glenn M. Mason4, Raúl Gómez-Herrero5, Nariaki V. Nitta6, and Linghua Wang7

2018 ApJL 869 L21

sci-hub.tw/10.3847/2041-8213/aaf37f

https://arxiv.org/pdf/1812.07735.pdf

https://www.academia.edu/38528947/3He-rich_Solar_Energetic_Particles_from_Sunspot_Jets?auto=bookmark

Solar sources of suprathermal (<1 MeV nucleon−1) 3He-rich solar energetic particles (SEPs) have been commonly associated with jets originating in small, compact active regions at the periphery of near-equatorial coronal holes. Sources of relatively rare, high-energy (>10 MeV nucleon−1) 3He-rich SEPs remain unexplored. Here we present two of the most intense 3He-rich (3He/4He > 1) SEP events of the current solar cycle 24 measured on the Advanced Composition Explorer at energy >10 MeV nucleon−1. Although 3He shows high intensities, Z > 2 ions are below the detection threshold. The events are accompanied by type-III radio bursts, but no type-II emission as typically seen for suprathermal 3He-rich SEPs. The corresponding solar sources were analyzed using high-resolution, extreme-ultraviolet imaging and photospheric magnetic field observations on the Solar Dynamics Observatory. We find the sources of these events associated with jets originating at the boundary of large sunspots with complex βγδ magnetic configuration. Thus, details of the underlying photospheric field apparently are important to produce 3He to high energies in the examined events. **2011 February 18, 2015 August 24**

Spectroscopic EUV observations of impulsive solar energetic particle event sources

R. **Bucik**, A. Fludra, R. Gomez-Herrero, D. E. Innes, B. Kellett, R. Kumar, S. Mackovjak

A&A 617, A40 **2018**

https://arxiv.org/pdf/1807.00861.pdf

http://star.mpae.gwdg.de/stereo/impact/data/publ/aa33120-18.pdf

Context. The remote observations of solar flare ion acceleration are rather limited. There are theoretical predictions for signatures of ion acceleration in EUV line profiles. Previous tests involve observations of flares with no evidence for energetic ions.

Aims. We aim to examine a source flare of impulsive (or 3He-rich) solar energetic particle events with EUV line spectroscopy.

Methods. We inspect all (90+) reported 3He-rich flares of previous solar cycle 23 and find only four (recurrent) jets in the field of view of SOHO CDS. The jet with the most suitable spatial and temporal coverage is analyzed in detail.

Results. Two enhanced (non-thermal) line broadenings are observed in the cooler chromospheric / transition-region lines and they are localized near the site where the closed magnetic loops reconnect with the open magnetic field lines. Both enhanced broadenings are found in the sites with redshifts in the lines, surrounded by the region with blueshifts. One enhanced line broadening is associated with a small flare without energetic particle signatures while another occurs just after the particle acceleration signatures of the main flare terminated.

Conclusions. The observed excess broadening appears to be not directly related to the energetic ion production and motions. Further investigations where the critical impulsive phase of the flare is covered are required, ideally with high-resolution spectrometers intentionally pointed to the 3He-rich solar energetic particle source.

2002 August 18-20

3He-Rich Solar Energetic Particles in Helical Jets on the Sun

Radoslav **Bucik**, Davina E. Innes, Glenn M. Mason, Mark E. Wiedenbeck, Raul Gomez-Herrero, Nariaki V. Nitta

2018 ApJ 852 76

https://arxiv.org/pdf/1711.09394.pdf

sci-hub.tw/10.3847/1538-4357/aa9d8f

Particle acceleration in stellar flares is ubiquitous in the Universe, however, our Sun is the only astrophysical object where energetic particles and their source flares can both be observed. The acceleration mechanism in solar flares, tremendously enhancing (up to a factor of ten thousand) rare elements like 3He and ultra-heavy nuclei, has been puzzling for almost 50 years. Here we present some of the most intense 3He- and Fe-rich solar energetic particle events ever reported. The events were accompanied by non-relativistic electron events and type III radio bursts. The corresponding high-resolution, extreme-ultraviolet imaging observations have revealed for the first time a helical structure in the source flare with a jet-like shape. The helical jets originated in relatively small, compact active regions, located at the coronal hole boundary. A mini-filament at the base of the jet appears to trigger these events. The events were observed with the two Solar Terrestrial Relations Observatories STEREO on the backside of the Sun, during the period of increased solar activity in 2014. The helical jets may be a distinct feature of these intense events that is related to the production of high 3He and Fe enrichments. **2014 Apr 30, 17July 2014, 2014 Jul 19, 2014 Jul 20**

Energy spectra of 3He-rich solar energetic particles associated with coronal waves

R. **Bučík**, D. E. Innes, G. M. Mason, M. E. Wiedenbeck

Journal of Physics: Conference Series (JPCS) **2016**

http://arxiv.org/pdf/1609.07266v1.pdf

In addition to their anomalous abundances, 3He-rich solar energetic particles (SEPs) show puzzling energy spectral shapes varying from rounded forms to power laws where the later are characteristics of shock acceleration. Solar sources of these particles have been often associated with jets and narrow CMEs, which are the signatures of magnetic reconnection involving open field. Recent reports on new associations with large-scale EUV waves bring new insights on acceleration and transport of 3He-rich SEPs in the corona. We examined energy spectra for 32 3He-rich SEP events observed by ACE at L1 near solar minimum in 2007-2010 and compared the spectral shapes with solar flare signatures obtained from STEREO EUV images. We found the events with jets or brightenings tend to be associated with rounded spectra and the events with coronal waves with power laws. This suggests that coronal waves may be related to the unknown second stage mechanism commonly used to interpret spectral forms of 3He-rich SEPs. **2010 February 18.**

Table 1. 3He-rich SEP events.

Association of 3He-Rich Solar Energetic Particles with Large-Scale Coronal Waves

Radoslav **Bucik**, Davina E. Innes, Glenn M. Mason, Mark E. Wiedenbeck

ApJ 833 63 **2016**

http://arxiv.org/pdf/1609.05346v1.pdf

Small 3He-rich solar energetic particle (SEP) events have been commonly associated with extreme-ultraviolet (EUV) jets and narrow coronal mass ejections (CMEs) which are believed to be the signatures of magnetic reconnection involving field lines open to interplanetary space. The elemental and isotopic fractionation in these events are thought to be caused by processes confined to the flare sites. In this study we identify **32 3He-rich SEP** events observed by the Advanced Composition Explorer near the Earth during the solar minimum period 2007-2010 and examine their solar sources with the high resolution Solar Terrestrial Relations Observatory (STEREO) EUV images. Leading the Earth, STEREO-A provided for the first time a direct view on 3He-rich flares, which are generally located on the Sun's western hemisphere. *Surprisingly, we find that about half of the 3He-rich SEP events in this survey are associated with large-scale EUV coronal waves*. An examination of the wave front propagation, the source-flare distribution and the coronal magnetic field connections suggests that the EUV waves may affect the injection of 3He-rich SEPs into interplanetary space.

OBSERVATIONS OF EUV WAVES IN 3He-RICH SOLAR ENERGETIC PARTICLE EVENTS

R. **Bučík**[1,2,3], D. E. Innes[1,2], L. Guo[1,2], G. M. Mason[4], and M. E. Wiedenbeck

2015 ApJ 812 53

http://arxiv.org/pdf/1512.04664v1.pdf

Small 3He-rich solar energetic particle (SEP) events with their anomalous abundances, markedly different from the solar system, provide evidence for a unique acceleration mechanism that operates routinely near solar active regions.

Although the events are sometimes accompanied by coronal mass ejections (CMEs), it is believed that mass and isotopic fractionation is produced directly in the flare sites on the Sun. We report on a large-scale extreme-ultraviolet (EUV) coronal wave observed in association with 3He-rich SEP events. In the two examples discussed, the observed waves were triggered by minor flares and appeared concurrently with EUV jets and type III radio bursts, but without CMEs. The energy spectra from one event are consistent with so-called class-1 (characterized by power laws) 3He-rich SEP events, while the other with class-2 (characterized by rounded 3He and Fe spectra), suggesting different acceleration mechanisms in the two. The observation of EUV waves suggests that large-scale disturbances, in addition to more commonly associated jets, may be responsible for the production of 3He-rich SEP events. **2010 January 26, 2010 February 2**

Long-lived energetic particle source regions on the Sun

R. **Bucik**, D. E. Innes, N.-H. Chen, G. M. Mason, R. Gomez-Herrero, M. E. Wiedenbeck
Journal of Physics: Conference Series 642, 012002 **2015**
http://arxiv.org/pdf/1507.02840v1.pdf
Discovered more than 40 years ago, impulsive solar energetic particle (SEP) events are still poorly understood. The enormous abundance enhancement of the rare 3He isotope is the most striking feature of these events, though large enhancements in heavy and ultra-heavy nuclei are also observed. Recurrent 3He-rich SEPs in impulsive events have only been observed for limited time periods, up to a few days which is typically the time that a single stationary spacecraft is magnetically connected to the source active regions on the Sun. With the launch of the two STEREO spacecraft we now have the possibility of longer connection time to solar active regions. We examined the evolution of source regions showing repeated 3He-rich SEP emissions for relatively long time periods. We found that recurrent 3He-rich SEPs in these long-lived sources occur after the emergence of magnetic flux.

Multi-Spacecraft Observations of Recurrent 3He-Rich Solar Energetic Particles

R. **Bucik**, D. E. Innes, U. Mall, A. Korth, G. M. Mason, R. Gomez-Herrero
2014 ApJ 786 71
http://arxiv.org/pdf/1403.4856v1.pdf
We study the origin of 3He-rich solar energetic particles (<1 MeV/nucleon) that are observed consecutively on STEREO-B, ACE, and STEREO-A spacecraft when they are separated in heliolongitude by more than 90{\deg}. The 3He-rich period on STEREO-B and STEREO-A commences on **2011 July 1** and **2011 July 16**, respectively. The ACE 3He-rich period consists of two sub-events starting on **2011 July 7** and **2011 July 9**. We associate the STEREO-B July 1 and ACE July 7 3He-rich events with the same sizeable active region producing X-ray flares accompanied by prompt electron events, when it was near the west solar limb as seen from the respective spacecraft. The ACE July 9 and STEREO-A July 16 events were dispersionless with enormous 3He enrichment, lacking solar energetic electrons and occurring in corotating interaction regions. We associate these events with a small, recently emerged active region near the border of a low-latitude coronal hole that produced numerous jet-like emissions temporally correlated with type III radio bursts. For the first time we present observations of 1) solar regions with long-lasting conditions for 3He acceleration and 2) solar energetic 3He that is temporary confined/re-accelerated in interplanetary space.

Ground-Based Measurements of Energetic Particles by Neutron Monitors Review

Rolf **Bütikofer**
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 6, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
Since the International Geophysical Year (IGY) in 1957/58, the worldwide network of neutron monitors is the standard instrument to investigate the variations of the cosmic ray flux near Earth (11-year modulation of the galactic cosmic rays, Forbush decreases, solar cosmic ray events) in the GeV range. The ensemble of neutron monitors together with the geomagnetic field acts as a giant spectrometer and enables to deduce information about the primary cosmic ray spectrum near Earth in the energy range 500 MeV to 15 GeV. For the interpretation of the ground-based neutron monitor measurements, the transport of the cosmic rays in the Earth's magnetic field as well as the transport in the Earth's atmosphere and the detection efficiency of the secondary nucleons by the neutron monitors must be known. The Neutron Monitor Data Base (NMDB) developed in 2008/09 enables a rapid accessibility to the data of the worldwide neutron monitor network. A considerable number of neutron monitor stations send their data to NMDB in real-time which enables the operation of space weather applications based on neutron monitor data.

Cosmic Ray Particle Transport in the Earth's Magnetosphere Review

Rolf **Bütikofer**

In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 5, **2018**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf

File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf

The transport of the cosmic ray particles in the Earth's magnetic field must be considered for cosmic ray investigations based on cosmic ray measurements in the geomagnetosphere. The motion of charged particles in a magnetic field is defined by the Lorentz force. The trajectories of cosmic ray particles are curved by the Earth's magnetic field. In a first approximation the geomagnetic field can be described by a dipole magnetic field. For a more accurate description the geomagnetic magnetic field is divided into two parts: the inner part generated by an internal dynamo and the outer part induced by different current systems in the ionosphere and the magnetosphere. Models have been developed that describe the inner and the outer magnetic field. The computations of the propagation of the cosmic ray particles in the Earth's magnetosphere are made with computer programs based on numerical integration of the equation of motion. For the specification of geomagnetic effects on cosmic ray particles the concept of cutoff rigidities and of asymptotic directions have been introduced.

The solar cosmic ray ground-level enhancements on 20 January 2005 and 13 December 2006

Rolf **Bütikofer**, Erwin O. Flückiger[a], Laurent Desorgher[a], Michael R. Moser[a] and Benoît Pirard[a]

Advances in Space Research

Volume 43, Issue 4, 16 February **2009**, Pages 499-503

Close to the current solar activity minimum, two large solar cosmic ray ground-level enhancements (GLE) were recorded by the worldwide network of neutron monitors (NM). The enormous GLE on 20 January 2005 is the largest increase observed since the famous GLE in 1956, and the solar cosmic-ray event recorded on 13 December 2006 is among the largest in solar cycle 23. From the recordings of the NMs during the two GLEs, we determined the characteristics of the solar particle flux near Earth.

A Surrogate Model for Studying Solar Energetic Particle Transport and the Seed Population

Atilim Guneş **Baydin**, Bala Poduval, Nathan A. Schwadron

Space Weather Volume21, Issue12 December **2023** e2023SW003593

https://doi.org/10.1029/2023SW003593

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003593

The high energy particles originating from the Sun, known as solar energetic particles (SEPs), contribute significantly to the space radiation environment, posing serious threats to astronauts and scientific instruments on board spacecraft. The mechanism that accelerates the SEPs to the observed energy ranges, their transport in the inner heliosphere, and the influence of suprathermal seed particle spectrum are open questions in heliophysics. Accurate predictions of the occurrences of SEP events well in advance are necessary to mitigate their adverse effects but prediction based on first principle models still remains a challenge. In this scenario, adopting a machine learning approach to SEP modeling and prediction is desirable. However, the lack of a balanced database of SEP events restrains this approach. We addressed this limitation by generating large data sets of synthetic SEP events sampled from the physics-based model, Energetic Particle Radiation Environment Module (EPREM). Using this data, we developed neural networks-based surrogate models to study the seed population parameter space. Our models, EPREM-S, run thousands to millions of times faster (depending on computer hardware), making simulation-based inference workflows practicable in SEP studies while providing predictive uncertainty estimates using a deep ensemble approach.

Comprehensive Characterization of Solar Eruptions With Remote and In-Situ Observations, and Modeling: The Major Solar Events on 4 November 2015

Iver H. **Cairns**, Kamen A. Kozarev, Nariaki V. Nitta, Neus Agueda, Markus Battarbee, Eoin P. Carley, Nina Dresing, Raul Gomez-Herrero, Karl-Ludwig Klein, David Lario, Jens Pomoell, Carolina Salas-Matamoros, Astrid M. Veronig, Bo Li, Patrick McCauley

Solar Phys. **2019**

https://arxiv.org/pdf/1910.03319.pdf

Solar energetic particles (SEPs) are an important product of solar activity. They are connected to solar active regions and flares, coronal mass ejections (CMEs), EUV waves, shocks, Type II and III radio emissions, and X-ray bursts. These phenomena are major probes of the partition of energy in solar eruptions, as well as for the organization, dynamics, and relaxation of coronal and interplanetary magnetic fields. Many of these phenomena cause terrestrial space weather, posing multiple hazards for humans and their technology from space to the ground. Since particular flares, shocks, CMEs, and EUV waves produce SEP events but others do not, since propagation effects from the low corona to 1 AU appear important for some events but not others, and since Type II and III radio emissions and X-ray bursts are sometimes produced by energetic particles leaving these acceleration sites, it is necessary to study the whole system with a multi-frequency and multi-instrument perspective that combines both in-situ and remote observations with detailed modelling of phenomena. This article demonstrates this comprehensive approach, and shows its necessity, by analysing a trio of unusual and striking solar eruptions, radio and X-ray bursts, and SEP events that occurred on 4 November 2015. These events show both strong similarities and differences from standard events and each other, despite having very similar interplanetary conditions and only two are sites and CME genesis regions. They are therefore major targets for further in-depth observational studies, and for testing both existing and new theories and models. Based on the very limited modelling available we identify the aspects that are and are not understood, and we discuss ideas that may lead to improved understanding of the SEP, radio, and space-weather events.

A study of solar energetic particle events of 1997–2006: Their composition and associations,

Cane, H. V., I. G. Richardson, and T. T. von Rosenvinge

J. Geophys. Res., 115, A08101, doi:10.1029/2009JA014848, (**2010**). **File**

sci-hub.si/10.1029/2009JA014848

We examined the properties and associations of 280 solar proton events that extended above 25 MeV and occurred in the years 1997–2006. The properties include early peak intensities of five species over several energy ranges and the intensity-time profiles. Solar event associations were made for as many events as possible. The solar parameters determined include coronal mass ejection and flare properties and radio emissions from a wavelength range of meters to kilometers. The events were divided into five representative types based on the relative abundances and particle profiles to more easily illustrate how particle characteristics vary with the solar parameters. We find a continuum of event properties with no indication of specific parameters that clearly separate out groups of events. There is, however, a reasonable separation of events based on the timing of the associated type III emissions relative to the H α flare. Type III bursts indicate the presence of flare particles that escape to the interplanetary medium. The least intense, relatively short-lived, proton events that are electron-rich (and generally Fe-rich and He-rich) have associated type III bursts that occur at the start of the flare (i.e., in the impulsive phase), indicating rapid acceleration and escape of particles. In the largest events the type III emissions occur after the impulsive phase. It is likely that this late acceleration and/or release of particles results in a composition different from that of impulsive acceleration and release. A scenario in which concomitant flare processes contribute particles in the majority of solar energetic particle events is consistent with the observations.

Comparing Small and Large SEP Events and the Role of Flares and Shocks

H. V. **CANE**, I. G. RICHARDSON, T. T. VON ROSENVINGE

30TH INTERNATIONAL COSMIC RAY CONFERENCE, **2007, File**

We have surveyed the properties and solar associations of the ~300 >20 MeV proton events that were observed near Earth in 1997-2005. About 20% have the properties of so-called "impulsive" events that are considered to arise from acceleration in flares. Another 31% of the events are the large, well studied, "gradual" events, that are considered to comprise only shock accelerated particles. The remaining events are often ignored but comprise ~50% of the events. We find that these events have intermediate properties such that there is a continuum of properties from the smallest to the largest events. It thus seems unlikely that there are two classes of fundamentally different events. Rather, there are two processes, one related to flares and one to coronal mass ejection shocks. As solar events become more energetic, shock acceleration becomes more important because of increasing CME energy. However, the flare characteristics also change so that flare particles in energetic events have different abundances from those in small events. We illustrate this for an impulsive event and another small event.

AN INTRODUCTION TO CMES AND ENERGETIC PARTICLES **Review**

H. V. **CANE**1,* and D. LARIO2

Space Science Reviews (**2006)** 123: 45–56; **File**

Energetic particle observations in the interplanetary medium provide fundamental information about the origin, development and structure of coronal mass ejections. This paper reviews the status of our understanding of the ways in which particles are energised at the Sun in association with CMEs. This understanding will remain incomplete until the relationship between CMEs and flares is determined and we know the topology of the associated magnetic fields. The paper also discusses the characteristics of interplanetary CMEs that may be probed using particle observations.

Role of flares and shocks in determining solar energetic particle abundances
Cane, H. V.; Mewaldt, R. A.; Cohen, C. M. S.; von Rosenvinge, T. T.
Journal of Geophysical Research, Volume 111, Issue A6, CiteID A06S90, **2006**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2005JA011071
We examine solar energetic particle (SEP) event-averaged abundances of Fe relative to O and intensity versus time profiles at energies above 25 MeV/nucleon using the SIS instrument on ACE. These data are compared with solar wind conditions during each event and with estimates of the strength of the associated shock based on average travel times to 1 AU. We find that the majority of events with an Fe to O abundance ratio greater than two times the average 5-12 MeV/nuc value for large SEP events (0.134) occur in the western hemisphere. Furthermore, in most of these Fe-rich events the profiles peak within 12 hours of the associated flare, suggesting that some of the observed interplanetary particles are accelerated in these flares. The vast majority of events with Fe/O below 0.134 are influenced by interplanetary shock acceleration. We suggest that variations in elemental composition in SEP events mainly arise from the combination of flare particles and shock acceleration of these particles and/or the ambient medium.
Table 1.GOES SEP Events (1997–2005)

Two components in major solar particle events
H. V. **Cane**, T. T. von Rosenvinge , C. M. S. Cohen , R. A. Mewaldt
JGR Volume30, Issue12 June **2003**, 8017
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2002GL016580
A study has been made of 29 intense, solar particle events observed in the energy range 25–80 MeV/nuc near Earth in the years 1997 through 2001. It is found that the majority of the events (19/29) had Fe/O ratios that were reasonably constant with time and energy, and with values above coronal. These all originated on the Sun's western hemisphere and most had intensities that rose rapidly at the time of an associated flare (and coronal mass ejection). Interplanetary shocks observed near Earth had little effect on particle intensities during these events. The remaining 10 events had different intensity-time profiles and Fe/O ratios that varied with time and energy with event-averaged values at or below coronal. Most of these originated near central meridian and 6 had strong interplanetary shocks that were observed near Earth. There were four events with two peaks in the intensity-time profiles, the first near the time of the associated flare (with high Fe/O) and the other at shock passage (with a lower Fe/O) suggesting that solar particle events have two components. At high rigidities the first component (probably flare generated) usually dominates and interplanetary shock-accelerated particles (forming the second component) make a minor contribution except in the case of unusually fast shocks.
Table 1. High Energy SEP Events in 1997 – 2001

Solar flares, type III radio bursts, coronal mass ejections and energetic particles.
Cane, H..V., Erickson, W..C., Prestage, N..P.:
2002, J. Geophys. Res. 107, 1315.
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2001JA000320
In this correlative study between >20 MeV solar proton events, coronal mass ejections (CMEs), flares, and radio bursts it is found that essentially all of the proton events are preceded by groups of type III bursts and all are preceded by CMEs. These type III bursts (that are a flare phenomenon) usually are long-lasting, intense bursts seen in the low-frequency observations made from space. They are caused by streams of electrons traveling from close to the solar surface out to 1 AU. In most events the type III emissions extend into, or originate at, the time when type II and type IV bursts are reported (some 5 to 10 minutes after the start of the associated soft X-ray flare) and have starting frequencies in the 500 to ˜100 MHz range that often get lower as a function of time. These later type III emissions are often not reported by ground-based observers, probably because of undue attention to type II bursts. It is suggested to call them type III-l. Type III-l bursts have previously been called shock accelerated (SA) events, but an examination of radio dynamic spectra over an extended frequency range shows that the type III-l bursts usually start at frequencies above any type II burst that may be present. The bursts sometimes continue beyond the time when type II emission is seen and, furthermore, sometimes occur in the absence of any type II emission. Thus the causative electrons are unlikely to be shock accelerated and probably originate in the reconnection regions below fast CMEs. A search did not find any type III-l bursts that were not associated with CMEs. The existence of low-frequency type III bursts proves that open field lines extend from within 0.5 radius of the Sun into the interplanetary medium (the bursts start above 100 MHz, and such emission originates within 0.5 solar radius of the solar surface). Thus it is not valid to assume that only closed field lines exist in the flaring regions associated with CMEs and some interplanetary particles originating in such flare regions might be expected in all solar particle events. **1997-05-12, 1997-11-04, 1999-12-28, 2000-02-12, 2000-11-08, 2001-04-18, 2000-11-24, 2001-03-10, 2001-04-10, 2001-04-18**
Table 1.Solar Energetic Particle Events, 1997–2001

Coronal mass ejections and forbush decreases. **Review**
Cane, H.V.

Space Sci. Rev. 93, 55–77, **2000; File**.
Coronal Mass Ejections (CMEs) are plasma eruptions from the solar atmosphere involving previously closed field regions which are expelled into the interplanetary medium. Such regions, and the shocks which they may generate, have pronounced effects on cosmic ray densities both locally and at some distance away. These energetic particle effects can often be used to identify CMEs in the interplanetary medium, where they are usually called `ejecta'. When both the ejecta and shock effects are present the resulting cosmic ray event is called a `classical, two-step' Forbush decrease. This paper will summarize the characteristics of CMEs, their effects on particles and the present understanding of the mechanisms involved which cause the particle effects. The role of CMEs in long term modulation will also be discussed.

Two Classes of Solar Energetic Particle Events Associated with Impulsive and Long-Duration Soft X-Ray Flares

Cane, H. V.; McGuire, R. E.; von Rosenvinge, T. T.
1986 ApJ...301..448–459C
http://articles.adsabs.harvard.edu/pdf/1986ApJ...301..448C
For the period 1978 September to 1983 December we have identified 67 solar particle events for which our instruments detected electrons above 3 MeV and for which there are soft X-ray observations. On the basis of their signature in soft X-rays, we have divided the events into two classes, impulsive and long duration, and find that they have different properties. The events originating with impulsive flares are associated with intense meter-wavelength type III bursts with associated type V continuum. The impulsive events are nearly all well connected, have high electron-to-proton ratios, and are almost never associated with interplanetary shocks. In contrast, the events associated with long-duration flares can originate anywhere on the solar disk, extend to much higher proton energies, and are well associated with coronal and interplanetary shocks. For about half of the long-duration events, the associated meter-wavelength events do not include type III bursts. We deduce that the two classes of particle events arise because different acceleration processes operate preferentially for the two classes of flares. In impulsive flares the acceleration is rapid. In some energetic events relativistic electrons are accelerated along with the lower energy electrons that are responsible for type III emission and other impulsive phenomena. The reported correlation of so-called electron-rich events with y-ray events is consistent with this suggestion. In long-duration flares the acceleration is more gradual, and we assume that acceleration takes place at extended shocks. These differences are attributed to the fact that impulsive flares occur low in the corona, are compact, and have high-energy densities, whereas long-duration flares occur high in the corona in extended regions. We find that occasionally a single flare event exhibits strong impulsive acceleration and also generates strong coronal and interplanetary shocks with their associated large fluxes of protons.

Quasiperiodic acceleration of electrons by a plasmoid-driven shock in the solar atmosphere

Eoin P. **Carley**, David M. Long, Jason P. Byrne, Pietro Zucca, D. Shaun Bloomfield, Joseph McCauley, Peter T. Gallagher
(**2013**). Nature Physics, 9, 811-816
http://arxiv.org/pdf/1406.0743v1.pdf ; **File** (**2014**)
Cosmic rays and solar energetic particles may be accelerated to relativistic energies by shock waves in astrophysical plasmas. On the Sun, shocks and particle acceleration are often associated with the eruption of magnetized plasmoids, called coronal mass ejections (CMEs). However, the physical relationship between CMEs and shock particle acceleration is not well understood. Here, we use extreme ultraviolet, radio and white-light imaging of a solar eruptive event on **22 September 2011** to show that a CME-induced shock (Alfv\'en Mach number 2.4+0.7−0.8) was coincident with a coronal wave and an intense metric radio burst generated by intermittent acceleration of electrons to kinetic energies of 2-46 keV (0.1-0.4 c). Our observations show that plasmoid-driven quasi-perpendicular shocks are capable of producing quasi-periodic acceleration of electrons, an effect consistent with a turbulent or rippled plasma shock surface.

Cross Calibration of the GPS Constellation CXD Proton Data With GOES EPS

Matthew R. **Carver**, John P. Sullivan, Steven K. Morley, Juan V. Rodriguez
Space Weather, v.16, no. 3, Pages: 273-288, March **2018**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001750
Accurate proton flux measurements of the near-Earth environment are essential to the understanding of many phenomena which have a direct impact on our lives. Currently, there is only a small set of satellites capable of performing these measurements which makes certain studies and analyses difficult. This paper details the capabilities of the Combined X-ray Dosimeter (CXD), flown on 21 satellites of the Global Positioning System constellation, as it relates to proton measurements. We present a cross calibration of the CXD with the Energetic

Particle Sensor (EPS) onboard the Geostationary Operational Environmental Satellite operated by the National Oceanic and Atmospheric Administration. By utilizing Solar Energetic Particle Events when both sets of satellites were operational we have orders of magnitude in flux and energy to compare against. Robust statistical analyses show that the CXD and Geostationary Operational Environmental Satellite flux calculations are similar and that for proton energies >30 MeV the CXD fluxes are on average within 20% of EPS. Although the CXD has a response to protons as low as 6 MeV, the sensitivity at energies below 20 MeV is reduced and so flux comparisons of these are generally worse. Integral flux values >10 MeV are typically within 40% of EPS. These calibrated CXD data sets will give researchers capabilities to study solar proton access to the inner magnetosphere down to L ~ 4 near the equatorial plane at high temporal cadence.

A catalog of solar radio bursts 1966-1976 having spectral characteristics predictive of proton activity.

Castelli, J.P., Barron, W.R.:

1977, *J. Geophys. Res.* **82**, 1275. DOI. ADS.

https://doi.org/10.1029/JA082i007p01275

A table of 81 distinctive solar radio outbursts occurring between January 1966 and July 1976 is presented. All of the bursts have the peak flux density U-shaped spectral signature found to be a reliable predictor of proton activity. These are the only events with this signature which occurred during the period. It has been confirmed that proton emission was indeed associated with 79 of the bursts; proton emission is probable for the remaining two events.

In situ evidence of ion acceleration between consecutive reconnection jet fronts

Filomena **Catapano**, Alessandro Retino, Gaetano Zimbardo, Alexandra Alexandrova, Ian J. Cohen, ….

ApJ **2020**

https://arxiv.org/pdf/2012.02641.pdf

Processes driven by unsteady reconnection can efficiently accelerate particles in many astrophysical plasmas. An example are the reconnection jet fronts in an outflow region. We present evidence of suprathermal ion acceleration between two consecutive reconnection jet fronts observed by the Magnetospheric Multiscale mission in the terrestrial magnetotail. An earthward propagating jet is approached by a second faster jet. Between the jets, the thermal ions are mostly perpendicular to magnetic field, are trapped and are gradually accelerated in the parallel direction up to 150 keV. Observations suggest that ions are predominantly accelerated by a Fermi-like mechanism in the contracting magnetic bottle formed between the two jet fronts. The ion acceleration mechanism is presumably efficient in other environments where jet fronts produced by variable rates of reconnection are common and where the interaction of multiple jet fronts can also develop a turbulent environment, e.g. in stellar and solar eruptions. **28 May 2017**

Solar Energetic Particle Events during the Rise Phases of Solar Cycles 23 and 24

R. **Chandra**, N. Gopalswamy, P. Mäkelä, H. Xie, S. Yashiro, S. Akiyama, W. Uddin, A.K. Srivastava, N.C. Joshi, R. Jain, A.K. Awasthi, P.K. Manoharan, K. Mahalakshmi, V.C. Dwivedi, D.P. Choudhary, N.V. Nitta

Advances in Space Research, **2013, File**

We present a comparative study of the properties of coronal mass ejections (CMEs) and flares associated with the solar energetic particle (SEP) events in the rising phases of solar cycles (SC) 23 (1996-1998) (22 events) and 24 (2009-2011) (20 events), which are associated with type II radio bursts. Based on the SEP intensity, we divided the events into three categories, i.e. weak (intensity <1 pfu), minor (1pfu <intensity <10 pfu) and major (intensity ⩾ 10 pfu) events. We used the GOES data for the minor and major SEP events and SOHO/ERNE data for the weak SEP event. We examine the correlation of SEP intensity with flare size and CME properties. We find that most of the major SEP events are associated with halo or partial halo CMEs originating close to the sun center and western-hemisphere. The fraction of halo CMEs in SC 24 is larger than the SC 23. For the minor SEP events one event in SC23 and one event in SC24 have widths < 120o and all other events are associated with halo or partial halo CMEs as in the case of major SEP events. In case of weak SEP events, majority (more than 60%) of events are associated with CME width < 120o. For both the SC the average CMEs speeds are similar. For major SEP events, average CME speeds are higher in comparison to minor and weak events. The SEP event intensity and GOES X-ray flare size are poorly correlated. During the rise phase of solar cycle 23 and 24, we find north-south asymmetry in the SEP event source locations: in cycle 23 most sources are located in the south, whereas during cycle 24 most sources are located in the north. This result is consistent with the asymmetry found with sunspot area and intense flares. **Tables**

MEMPSEP I : Forecasting the Probability of Solar Energetic Particle Event Occurrence using a Multivariate Ensemble of Convolutional Neural Networks

Subhamoy **Chatterjee**, Maher Dayeh, Andrés Muñoz-Jaramillo, Hazel M. Bain, Kimberly Moreland, Samuel Hart

Space Weather **Volume22, Issue9** September 2024 e2023SW003568
https://arxiv.org/pdf/2309.14570.pdf
https://doi.org/10.1029/2023SW003568
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003568
The Sun continuously affects the interplanetary environment through a host of interconnected and dynamic physical processes. Solar flares, Coronal Mass Ejections (CMEs), and Solar Energetic Particles (SEPs) are among the key drivers of space weather in the near-Earth environment and beyond. While some CMEs and flares are associated with intense SEPs, some show little to no SEP association. To date, robust long-term (hours-days) forecasting of SEP occurrence and associated properties (e.g., onset, peak intensities) does not effectively exist and the search for such development continues. Through an Operations-2-Research support, we developed a self-contained model that utilizes a comprehensive dataset and provides a probabilistic forecast for SEP event occurrence and its properties. The model is named Multivariate Ensemble of Models for Probabilistic Forecast of Solar Energetic Particles (MEMPSEP). MEMPSEP workhorse is an ensemble of Convolutional Neural Networks that ingests a comprehensive dataset (MEMPSEP III - (Moreland et al., 2023)) of full-disc magnetogram-sequences and in-situ data from different sources to forecast the occurrence (MEMPSEP I - this work) and properties (MEMPSEP II - Dayeh et al. (2023)) of a SEP event. This work focuses on estimating true SEP occurrence probabilities achieving a 2.5% improvement in reliability and a Brier score of 0.14. The outcome provides flexibility for the end-users to determine their own acceptable level of risk, rather than imposing a detection threshold that optimizes an arbitrary binary classification metric. Furthermore, the model-ensemble, trained to utilize the large class-imbalance between events and non-events, provides a clear measure of uncertainty in our forecast 28-30 Sep 2001

Study of Hysteresis Effect between Cosmic Ray Intensity and Solar Indices
D.M.L. **Chauhan** and M.K. Richharia
PoS(ICRC2019), id. 046, **2019**
https://pos.sissa.it/358/046/pdf
In order to perform the study of cosmic ray long-term modulation, we have used six monthly averaged cosmic ray data from Oulu (Rc = 0.78GV) and Rome (Rc = 6.32GV) neutron monitoring stations for three solar cycles. (21 - 23) with solar activity index (sunspot numbers). The detailed analysis of hysteresis effect between these two parameters has been done. The area of hysteresis loops and time lag with correlation coefficient between cosmic ray intensity and sunspot numbers have also been calculated and noticeable differences have been found during odd and even number solar cycles. Area of odd cycle loops is much larger than even cycle loop. Each hysteresis loop consists of a small secondary loop near solar maxima. Time lag between cosmic ray intensity and sunspot numbers is different in odd and even cycles. Implication and consequences of observed differences have been discussed in this paper.

Cosmic ray solar modulation and Forbush decrease analyses based on atmospheric neutron spectrometry at mountain altitude and GEANT4 simulations of extensive air showers
A. **Cheminet**1,2, G. Hubert1,*, V. Lacoste2, D. Maurin3, L. Derome
JGR, Volume 118, Issue 12, pages 7488–7496, December **2013**
A Bonner sphere spectrometer extended to high energies (HERMEIS) was set up at the summit of the Pic du Midi de Bigorre in the French Pyrenees (altitude: +2,885 m; geomagnetic cutoff: 5.6 GV) in May 2011. The spectral fluence rate distribution of the cosmic ray induced neutrons was continuously measured over a broad energy range from meV up to several GeV and with a 1 h time resolution. While the Sun's activity was increasing and reaching its 24th maximum in the 11 year solar cycle, some Forbush decreases were observed in the atmospheric secondary radiation at mountain altitude. We investigated the evolution of the cascade fluence rate (i.e., neutrons with energy greater than 20 MeV) during the **March 2012** events with a series of strong coronal mass ejections hitting the Earth's magnetosphere. The amplitude of the greatest Forbush decrease peaked at 10%. Then, a simulation work based on the GEANT4 toolkit was carried out to quantify the solar modulation induced on the galactic cosmic ray transportation during these events. We performed calculations of extensive air showers generated by monoenergetic primaries (Hydrogen and Helium nuclei) for several zenith incidences. Hence, a complete database was built and validated. We derived an analytical model to estimate the atmospheric neutron spectrum at the Pic du Midi according to primary spectra which only depend on the solar modulation potential (force field approximation). We compared the solar modulation potentials obtained in March 2012 with the ones derived by the neutron monitor yield method. Finally, a satisfying agreement was found.

Three-stage Acceleration of Solar Energetic Particles Detected by Parker Solar Probe
Xiaomin **Chen**, Chuan Li
ApJL 967 L33 **2024**
https://arxiv.org/pdf/2405.19680
https://iopscience.iop.org/article/10.3847/2041-8213/ad4a79/pdf

Coronal mass ejections (CMEs) drive powerful shocks and thereby accelerate solar energetic particles (SEPs) as they propagate from the corona into interplanetary space. Here we present the processes of three-stage particle acceleration by a CME-driven shock detected by the in situ spacecraft--Parker Solar Probe (PSP) on **2022 August 27**. The onset of SEPs is produced by a fast CME with a speed of 1284 km/s when it propagates to ∼2.85 Rs. The second stage of particle acceleration occurs when the fast CME catches up and interacts with a preceding slow one in interplanetary space at ∼40 Rs (∼0.19 au). The CME interaction is accompanied by an intense interplanetary type II radio enhancement. Such direct measurement of particle acceleration during interplanetary CME interaction/radio enhancement is rarely recorded in previous studies. The third stage of energetic storm particles is associated with the CME-driven shock passage of the PSP at ∼0.38 au. Obviously, harder particle spectra are found in the latter two stages than the first one, which can arise from a stronger shock produced by the CME interaction and the enriched seed particles inside the preceding CME.

Solar Energetic Particle Acceleration at a Spherical Shock with the Shock Normal Angle θBn Evolving in Space and Time

Xiaohang **Chen**, Joe Giacalone, Fan Guo

ApJ **941** 23 **2022**

https://arxiv.org/pdf/2211.05366.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac9f43/pdf

We present a 2D kinematic model to study the acceleration of solar energetic particles (SEPs) at a shock driven by a coronal mass ejection. The shock is assumed to be spherical about an origin that is offset from the center of the Sun. This leads to a spatial and temporal evolution of the angle between the magnetic field and shock normal direction (θBn) as it propagates through the Parker spiral magnetic field from the lower corona to 1 AU. We find that the high-energy SEP intensity varies significantly along the shock front due to the evolution of θBn. Generally, the west flank of the shock preferentially accelerates particles to high energies compared to the east flank and shock nose. This can be understood in terms of the rate of acceleration, which is higher at the west flank. Double power-law energy spectra are reproduced in our model as a consequence of the local acceleration and transport effects. These results will help better understand the evolution of SEP acceleration and provide new insights into large SEP events observed by multi-spacecraft, especially those close to the Sun, such as Parker Solar Probe and Solar Orbiter.

Global Prompt Proton Sensor Network: Monitoring Solar Energetic Protons Based on GPS Satellite Constellation

Yue **Chen** , Steven K. Morley , Matthew R. Carver

JGR Volume125, Issue3 March **2020** e2019JA027679

https://doi.org/10.1029/2019JA027679

sci-hub.tw/10.1029/2019JA027679

Energetic particle instruments on board Global Positioning System (GPS) satellites form a powerful global prompt proton sensor network (GPPSn) that provides an unprecedented opportunity to monitor and characterize solar energetic protons targeting the Earth. The medium-Earth orbits of the GPS constellation have the unique advantage of allowing solar energetic protons to be simultaneously measured from multiple points in both open- and closed-field line regions. Examining two example intervals of solar proton events, we showcase in this study how GPS proton data are prepared, calibrated, and utilized to reveal important features of solar protons, including their source, acceleration/scattering by interplanetary shocks, the relative position of Earth when impinged by these shocks, the shape of solar particle fronts, the access of solar protons inside the dynamic geomagnetic field, and temporally varying proton distributions in both energy and space. By comparing to Van Allen Probes data, GPS proton observations are further demonstrated not only to be useful for qualitatively monitoring the dynamics of solar protons but also for quantitative scientific research including determining cutoff L-shells. Our results establish that this GPPSn can join forces with other existing solar proton monitors and contribute to observing, warning, understanding, and ultimately forecasting the incoming solar energetic proton events.

Temperature of source regions of 3He-rich impulsive solar energetic particle events

N.-H. **Chen**, R. Bučík, R.-S. Kim

Space Weather of the Heliosphere: Processes and Forecasts Proceedings IAU Symposium No. 335, 2017

2018 Proc. IAU Symosium 335

https://arxiv.org/pdf/1712.07285.pdf

Impulsive solar energetic particle (SEP) events originate from the energy dissipation process in small solar flares. Anomalous abundances in impulsive SEP events provide an evidence on unique, yet unclear, acceleration mechanism. The pattern of heavy-ion enhancements indicates that the temperature of the source plasma that is accelerated is low and not flare-like. We examine the solar source of the 3He-rich SEP event of **2012 November 20** using Solar Dynamics Observatory (SDO)/ Atmospheric Imaging Assembly (AIA) images and investigate its thermal variation. The examined event is associated with recurrent coronal jets. The Differential Emission Measure

(DEM) analysis is applied to study the temperature evolution/distribution of the source regions. Preliminary results show that the temperature of the associated solar source is ranged between 1.2-3.1 MK.

Case studies of multi-day 3He-rich solar energetic particle periods

Nai-hwa **Chen**, Radoslav. Bucik, Davina. E. Innes, Glenn. M. Mason

A&A 580, A16 **2015**

http://arxiv.org/pdf/1506.04369v1.pdf

http://www.aanda.org/articles/aa/pdf/2015/08/aa25618-15.pdf

Context. Impulsive solar energetic particle events in the inner heliosphere show the long-lasting enrichment of 3He. Aims. We study the source regions of long-lasting 3He-rich solar energetic particle (SEP) events Methods. We located the responsible open magnetic field regions, we combined potential field source surface extrapolations (PFSS) with the Parker spiral, and compared the magnetic field of the identified source regions with in situ magnetic fields. The candidate open field regions are active region plages. The activity was examined by using extreme ultraviolet (EUV) images from the Solar Dynamics Observatory (SDO) and STEREO together with radio observations from STEREO and WIND. Results. Multi-day periods of 3He-rich SEP events are associated with ion production in single active region. Small flares or coronal jets are their responsible solar sources. We also find that the 3He enrichment may depend on the occurrence rate of coronal jets. **2010 November 14-18 and 2012 November 18-21**

Magnetic reconnection configurations and particle acceleration in solar flares

P. F. **Chen**, W. J. Liu, & C. Fang

E-print **2008**, File;

Adv. Space Res., 39, 1421, **2007**

Numerical simulations of two types of flares indicate that magnetic reconnection can provide environments favorable for various particle acceleration mechanisms to work. This paper reviews recent test particle simulations of DC electric field mechanism, and discusses how the **flare particles can escape into the interplanetary space** under different magnetic configurations.

Simulation of solar energetic particle events originated from coronal mass ejection shocks with a data-driven physics-based transport model

Lei **Cheng**, Ming Zhang, Ryun Young Kwon, David Lario

ApJ **2024**

https://arxiv.org/pdf/2411.04095

Solar energetic particle (SEP) events are associated with coronal mass ejections (CMEs) and/or solar flares. SEPs travel through the corona and interplanetary space to reach Earth, posing a radiation hazard to spacecraft and astronauts working in space and the electronics on spacecraft. Due to the distinct magnetic field configuration and solar eruption kinematic properties associated with each event, the utilization of a data-driven model becomes essential for predicting SEP hazards. In this study, we use a developed model that utilizes photospheric magnetic field measurements and CME shock observations as inputs to simulate several historical SEP events associated with fast CME speeds (>700 km/s). The model includes an SEP source term aligned with the theory of diffusive shock acceleration by the CME shock. The performance of the model is accessed by comparing simulations and observations of SEP intensity time profiles at SOHO, ACE, STEREO-A and STEREO-B. The results generally matched observations well, particularly for protons below 40.0 MeV. However, discrepancies arose for higher-energy protons, notably for the events on **2011 March 7 and 2014 February 25**, where the simulation tended to overestimate the proton flux . At STEREO-A, the modeled proton intensities for the SEP events on **2013 April 11 and 2011 March 7** display a very different behavior compared to observations because of the efficient transport in longitude caused by the weak magnetic field.

Simulation of the Solar Energetic Particle Event on 2020 May 29 Observed by Parker Solar Probe

Lei **Cheng**, Ming Zhang, David Lario, Laura A. Balmaceda, Ryun Young Kwon, Christina Cohen

ApJ **943** 134 **2023**

https://arxiv.org/pdf/2209.02566.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/acac21/pdf

This paper presents a stochastic three-dimensional (3D) focused transport simulation of solar energetic particles (SEPs) produced by a data-driven coronal mass ejection (CME) shock propagating through a data-driven model of coronal and heliospheric magnetic fields. The injection of SEPs at the CME shock is treated using diffusive shock acceleration of post-shock superthermal solar wind ions. A time backward stochastic simulation is employed to solve the transport equation to obtain the SEP time-intensity profile at any location, energy, and pitch angle. The model is applied to a SEP event on **2020 May 29**, observed by STEREO-A close to 1 au and by Parker Solar Probe (PSP) when it was about 0.33 au away from the Sun. The SEP event was associated with a very slow CME with a plane-of-sky speed of 337 km/s at a height below 6 RS as reported in the SOHO/LASCO CME catalog. We compute the time profiles of particle flux at PSP and STEREO-A locations, and estimate both the spectral index of the proton energy spectrum for energies between 2 and 16 MeV and the equivalent path length of the magnetic field lines experienced by the first arriving SEPs. We found that the simulation results are well correlated with observations. The SEP event could be explained by the acceleration of particles by a weak CME shock in the low solar corona that is not magnetically connected to the observers.

On some features of the solar proton event on 2021 October 28 – GLE73

I.M. **Chertok**

MNRAS Volume 517, Issue 2, Pages 2709–2713, **2022**

https://arxiv.org/ftp/arxiv/papers/2210/2210.04238.pdf

https://doi.org/10.1093/mnras/stac2843

In addition to several recent articles devoted to the rare event of ground-level enhancement of the solar relativistic proton flux observed on 2021 October 28 – GLE73, we study the 10–100 MeV solar energetic particle (SEP) component of this event. Based on the GOES satellite data for 26 GLEs recorded since 1986, we have formed a scatter plot displaying the ratio of the peak fluxes of the >10 MeV ($J10$) and >100 MeV ($J100$) protons and their energy spectra. Two extreme characteristics of the prompt component of the SEP–GLE73 event were revealed: (1) very small $J10$ and $J100$ proton fluxes and (2) a very hard energetic spectrum in the 10–100 MeV range. There are only two events with these characteristics similar to SEP–GLE73 namely, GLE40 (1989 July 25) and GLE46 (1989 November 15). A correspondence was demonstrated between the hard frequency spectrum of microwave radio bursts of initiating flares and the hard SEP energy spectrum of these two and other GLEs. These results suggest that the flare magnetic reconnection both in the impulsive and post-eruption phases plays an important role in the acceleration of the SEP–GLE protons.

Diagnostic Analysis of the Solar Proton Flares of September 2017 by Their Radio Bursts

I. M. **Chertok**

Geomagnetism and Aeronomy July **2018**, Volume 58, Issue 4, pp 457–46

Russian Text: Geomagnetizm i Aeronomiya, **2018**, Vol. 58, No. 4, pp. 471–478.

DOI: https://doi.org/10.1134/S0016793218040035

http://sci-hub.tw/10.1134/S0016793218040035

https://arxiv.org/abs/1808.05021

The powerful solar flares that occurred on September 4–10, 2017 are analyzed based on a quantitative diagnostics method for proton flares developed at the Institute of Terrestrial Magnetism, the Ionosphere and Radio-Wave Propagation (IZMIRAN) in the 1970–1980s. We show that the fluxes and energy spectra of the protons reached the Earth with the energies of tens of MeV qualitatively and quantitatively correspond to the intensity and frequency spectra of the microwave radio bursts in the range of 2.7–15.4 GHz. Specifically, the flare of September 4 with a peak radio flux S ~ 2000 sfu at the frequency f ~ 3 GHz (i.e., with the soft radio spectrum) was accompanied by a significant proton flux J (>10 MeV) ~100 pfu and a soft energy spectrum with the index γ ~3.0, while the strong flare on September 10 with S ~ 21000 sfu at f ~ 15 GHz (i.e., with the hard radio spectrum) led to a very intense proton event with J (>10 MeV) ~1000 pfu with a hard spectrum (γ ~ 1.4), including the ground level enhancement (GLE72). This is further evidence that microwave radio data can be successfully used in diagnostics of proton flares independently of a specific source of particle acceleration at the Sun, in particular, with the IZMIRAN method.

Powerful Solar Flares of 2017 September: Correspondence between Parameters of Microwave Bursts and Proton Fluxes near Earth

Ilya M. **Chertok**

Res. Notes AAS **2** 20 **2018**

http://iopscience.iop.org/article/10.3847/2515-5172/aaaab7

https://doi.org/10.3847/2515-5172/aaaab7

https://arxiv.org/ftp/arxiv/papers/1802/1802.00191.pdf

In this note, we consider radio characteristics of three proton flares that caused discrete enhancements of solar energetic particles (SEPs) near Earth. The analysis confirmed that the flux density and frequency spectrum of microwave bursts, although the latter are generated by electrons propagating to the photosphere, reflect the number and energy spectrum of accelerated particles, including the 10-100 MeV protons coming to Earth.

On the Correlation between Spectra of Solar Microwave Bursts and Proton Fluxes near the Earth

M. **Chertok**1, V. V. Grechnev2, and N. S. Meshalkina2

Astronomy Reports, **2009**, Vol. 53, No. 11, pp. 1059–1069
Astronomicheskiˇı Zhurnal, **2009**, Vol. 86, No. 11, pp. 1133–1144.
Studies of the extreme solar proton event of January 20, 2005 intensified the contest over of a long-standing problem: are solar cosmic rays arriving at the Earth accelerated by solar flares or by shocks preceding rapidly moving coronal mass ejections? Among the most important questions is the relationship between the energy spectra of the solar cosmic rays and the frequency spectra of flare microwave bursts. Some studies of previous solar-activity cycles have shown that such a relationship does exist, in particular, for protons with energies of tens ofMeV. The presentwork analyzes this relation using data for 1987–2008. For flare events observed in the western half of the disk, there is a significant correlation between the index δ, which is equivalent to the power-law index of the integrated energy spectrum of 10–100 MeV protons detected near the Earth's orbit, and radio burst parameters such as a ratio of peak fluxes S at two frequencies (for example, at 9 and 15 GHz) and a microwave peak frequency fm. Proton fluxes with hard (flat) energy spectra ($\delta \leq 1.5$) correspond to hard microwave frequency spectra ($S9/S15 \leq 1$ and $fm \geq 15$ GHz), while flares with soft radio spectra ($S9/S15 \geq 1.5$ and $fm \leq 5$ GHz) result in proton fluxes with soft (steep) energy spectra ($\delta \geq 1.5-2$). It is also shown that powerful high-frequency bursts with the hardest radio spectra ($fm \approx 30$ GHz) can point at acceleration of significant proton fluxes in flares occurring in strong magnetic fields. These results argue that solar cosmic rays (or at least their initial impulses) are mainly accelerated in flares associated with impulsive and post-eruptive energy release, rather than in shocks driven by coronal mass ejections.
See file **2016**: **Nunez** M. A preliminary assessment of the failed and successful predictions of proton spectral hardness using microwave emission
See also: However, this hypothesis was recently tested and its applicability is under debate.6
https://www.hesperia.astro.noa.gr/WP2/Hesperia_task_2-2.pdf.

On the correlation between the solar gamma-ray line emission, radio bursts and proton fluxes in the interplanetary space.

Chertok, I.M.:
1990, Astron. Nachr. 311, Issue 6, 379 – 381.
http://cdsads.u-strasbg.fr/pdf/1990AN....311..379C
It is shown that the correlation takes place between the 4–7 MeV gamma–ray line flare fluence F4–7 and the intensity of the > 10 MeV proton flux in the interplanetary space as well as between F4–7and the peak flux density of microwave bursts. Besides, the energy spectral index of protons displays the definite dependence from parameters of the radio burst frequency spectrum. These testify that: a) there is a close physical association between the acceleration of electrons and protons in flares; b) protons, giving gamma–ray lines, and ones, registered in the interplanetary space, belong to the same population.

Estimates of the exponent of the energy spectrum of protons from data on solar microwave radio bursts.

Chertok, I. M.
Geomagnetizm i Aeronomiia, vol. 22, Mar.-Apr. **1982**, p. 182-186. In Russian
A method is developed for the short-term prediction of the energy spectrum exponent (gamma) of protons near the earth with energies of the order of tens of MeV; gamma is determined on the basis of the ratio of maximum intensities of solar radio bursts at frequencies of 9 and 15.4 GHz (S9/S15). Data on 35 proton events are used to determine the relationship between S9/S15 and gamma for flares on the western half of the disk, as well as the heliolongitudinal correction for protons arriving at the earth from eastern flares.

Magnetic Field Line Random Walk and Solar Energetic Particle Path Lengths: Stochastic Theory and PSP/ISoIS Observation

R. **Chhiber**, W. H. Matthaeus, C.M.S. Cohen, D. Ruffolo, W. Sonsrettee, P. Tooprakai, A. Seripienlert, P.Chuychai, A. V. Usmanov, M. L. Goldstein, D. J. McComas, R. A. Leske, E. R. Christian, R. A. Mewaldt, A.W. Labrador, J. R. Szalay, C. J. Joyce, J. Giacalone, N. A. Schwadron, D. G. Mitchell, M. E. Hill, M. E.Wiedenbeck, R. L. McNutt Jr., M. I. Desai
A&A **2020**
https://arxiv.org/pdf/2011.08329.pdf
Context:In 2020 May-June, six solar energetic ion events were observed by the Parker Solar Probe/ISoIS instrument suite at 0.35 AU from the Sun. From standard velocity-dispersion analysis, the apparent ion path length is 0.625 AU at the onset of each event. Aims:We develop a formalism for estimating the path length of random-walking magnetic field lines, to explain why the apparent ion pathlength at event onset greatly exceeds the radial distance from the Sun for these events. Methods:We developed analytical estimates of the average increase in pathlength of

random-walking magnetic field lines, relative to the unperturbed mean field. Monte Carlo simulations of fieldline and particle trajectories in a model of solar wind turbulence are used to validate the formalism and study the path lengths of particle guiding-center and full-orbital trajectories. The formalism is implemented in a global solar wind model, and results are compared with ion pathlengths inferred from ISoIS observations. Results:Both a simple estimate and a rigorous theoretical formulation are obtained for fieldlines' pathlength increase as a function of pathlength along the large-scale field. From simulated fieldline and particle trajectories, we find that particle guiding centers can have pathlengths somewhat shorter than the average fieldline pathlength, while particle orbits can have substantially larger pathlengths due to their gyromotion with a nonzero effective pitch angle. Conclusions:The long apparent path length during these solar energetic ion events can be explained by 1) a magnetic field line path length increase due to the field line random walk, and 2) particle transport about the guiding center with a nonzero effective pitch angle. Our formalism for computing the magnetic field line path length, accounting for turbulent fluctuations, may be useful for application to solar particle transport in general. **2020 May 21-June 3**

Random Walk and Trapping of Interplanetary Magnetic Field Lines: Global Simulation, Magnetic Connectivity, and Implications for Solar Energetic Particles

Rohit **Chhiber**, David Ruffolo, William H. Matthaeus, Arcadi V. Usmanov, Paisan Tooprakai, Piyanate Chuychai, Melvyn L. Goldstein

ApJ **908** 174 **2020**

https://arxiv.org/pdf/2011.06620.pdf

https://doi.org/10.3847/1538-4357/abd7f0

The random walk of magnetic field lines is an important ingredient in understanding how the connectivity of the magnetic field affects the spatial transport and diffusion of charged particles. As solar energetic particles (SEPs) propagate away from near-solar sources, they interact with the fluctuating magnetic field, which modifies their distributions. We develop a formalism in which the differential equation describing the field line random walk contains both effects due to localized magnetic displacements and a non-stochastic contribution from the large-scale expansion. We use this formalism together with a global magnetohydrodynamic simulation of the inner-heliospheric solar wind, which includes a turbulence transport model, to estimate the diffusive spreading of magnetic field lines that originate in different regions of the solar atmosphere. We first use this model to quantify field line spreading at 1 au, starting from a localized solar source region, and find rms angular spreads of about 20° - 60°. In the second instance, we use the model to estimate the size of the source regions from which field lines observed at 1 au may have originated, thus quantifying the uncertainty in calculations of magnetic connectivity; the angular uncertainty is estimated to be about 20°. Finally, we estimate the filamentation distance, i.e., the heliocentric distance up to which field lines originating in magnetic islands can remain strongly trapped in filamentary structures. We emphasize the key role of slab-like fluctuations in the transition from filamentary to more diffusive transport at greater heliocentric distances. **2012 May 12**

The Energetic Storm Particle events of 3 November 2021

Federica **Chiappetta**, Monica Laurenza, Fabio Lepreti, Fabio Lepreti, Simone Benella, Simone Benella, Giuseppe Consolini, and Maria Marcucci

Front. Astron. Space Sci. 10: 1209479 **2023**

https://www.frontiersin.org/articles/10.3389/fspas.2023.1209479/pdf

Observations of energetic particles at interplanetary shocks are important to study acceleration mechanisms and their connection with magnetohydrodynamic turbulence. Energetic storm particle (ESP) events are increases in proton fluxes that occur locally at the passage time of interplanetary shocks. These events are more dangerous when they are superimposed on the solar energetic particles (SEPs) produced by the eruption of flares and/or CME-driven shocks propagating from the corona to the interplanetary space. We considered ESP events occurring in association with SEPs on **3 November 2021**. We used proton fluxes provided by Solar Orbiter (located at 0.85 AU) in the energy range of 30 keV–82 MeV, by Wind at energies from 70 keV to 72 MeV, and ACE in the range from 40 keV to 5 MeV (both located at the Lagrangian point L1, close to 1 AU along the Sun-Earth direction). In order to broaden the range of analyzed energies (40 keV - 72 MeV), we combine these data with the proton fluxes from the SOHO spacecraft, also located at L1. We analyzed the ESP event and fitted the proton energy spectra at both locations with several distributions to shed light on the mechanisms leading to the acceleration of energetic particles. We also investigated the turbulent magnetic field fluctuations around the shock. The obtained ESP spectra, best reproduced by the so-called double power law function, the spectral differences at the two locations, and the shock features (quasi-parallel geometry, enhanced downstream turbulence) suggest that diffusive shock acceleration is responsible for acceleration of low energy particles, whereas stochastic acceleration contributes to the (re) acceleration of high energies ones.

Proton Energy Spectra of Energetic Storm Particle Events and Relation with Shock Parameters and Turbulence

Federica **Chiappetta**1, Monica Laurenza2, Fabio Lepreti1,3, and Giuseppe Consolini2
2021 ApJ 915 8
https://doi.org/10.3847/1538-4357/abfe09
https://iopscience.iop.org/article/10.3847/1538-4357/abfe09/pdf
The proton energy spectra of 23 energetic storm particle (ESP) events of various types, occurring either in association with (16 events) or in the absence of (7 events) solar energetic particles (SEPs), are investigated by using data from particle instruments aboard STEREO A in the energy range from 84.1 keV to 100 MeV. The obtained spectra were fitted with several known functions. Out of the 12 ESP events occurring in association with SEPs and quasi-perpendicular shocks, the Weibull distribution provides good fits to the spectra over the whole energy range in five cases. For the other seven events it fits the high energy tail, with lower energies explained by the power law predicted by the diffusive shock acceleration (DSA). Conversely, for the four SEP-associated ESPs at quasi-parallel shocks, a double power law better reproduces the observed spectra. Moreover, a significant correlation of the downstream turbulence level is found with the background subtracted Weibull parameters for quasi-perpendicular shocks, and with the proton peak value in the intermediate energy range of 4–6 MeV for all 16 considered shocks. Our results suggest that the downstream turbulence is a relevant factor in particle acceleration and that stochastic acceleration (SA) can be a plausible mechanism for reacceleration at interplanetary shocks. In the seven cases not associated with SEPs, an Ellison–Ramaty form fits the observed spectra, consistently with a DSA process, suggesting that a strong shock and/or a high energy particle background should be present for the SA to be at work.
2011 March 9 , 2011 November 28 , 2012 January 29, 2013 April 22,
Table 1 Parameters of the 23 Selected Shocks, Associated with Enhancements in the Proton Flux (2010-2016)

The SEVAN Worldwide network of particle detectors: 10 years of operation

A. **Chilingarian**, V. Babayan, T. Karapetyan, B. Mailyan, B. Sargsyan, M. Zazyan
Advances in Space Research, Volume 61, Issue 10, 15 May **2018**, Pages 2680-2696
http://sci-hub.tw/10.1016/j.asr.2018.02.030
The Space Environment Viewing and Analysis Network (SEVAN) aims to improve the fundamental research on particle acceleration in the vicinity of the sun, on space weather effects and on high-energy physics in the atmosphere and lightning initiation. This new type of a particle detector setup simultaneously measures fluxes of most species of secondary cosmic rays, thus being a powerful integrated device for exploration of solar modulation effects and electron acceleration in the thunderstormatmosphere. The SEVAN modules are operating at the Aragats Space Environmental Center (ASEC) in Armenia, in Croatia, Bulgaria, Slovakia, the Czech Republic (from 2017) and in India. In this paper, we present the most interesting results of the SEVAN network operation during the last decade. We present this review on the occasion of the 10th anniversary of the International Heliophysical Year in 2007. **4 October 2010 , 16-20 February, 2011, 23-25 Jan 2012,**

On the relation of the Forbush decreases detected by ASEC monitors during the 23rd solar activity cycle with ICME parameters

A. **Chilingariana** and N. Bostanjyan, a,
Advances in Space Research
Volume 45, Issue 5, 1 March **2010**, Pages 614-621
To improve the physical understanding of the Forbush decreases (FD) and to explore the Space Weather drivers, we need to measure as much geospace parameter as possible, including the changing fluxes of secondary cosmic rays. At the Aragats Space Environmental Center (ASEC) are routinely measured the neutral and charged fluxes of secondary cosmic rays. Each of species has different most probable energy of primary “parent” proton/nuclei. Therefore, the energy range of the Galactic Cosmic Rays (GCR) affected by Interplanetary Coronal Mass Ejection (ICME) can be effectively estimated using data of the ASEC monitors. We presented relations of the magnitude of FD observed in different secondary particle fluxes to the most probable energy of the primary protons. We investigate the correlations between the magnitude of FD with the size, speed, density and magnetic field of the ICME. We demonstrate that the attenuation of the GCR flux incident on the Earth’s atmosphere due to passing of the ICME is dependent on the speed and size of the ICME and the magnetic field strength.

Heliospheric Transport of Neutron-Decay Protons

E. E. **Chollet**, R. A. Mewaldt
Solar Physics, November **2012**, Volume 281, Issue 1, pp 449-459
We report on new simulations of the transport of energetic protons originating from the decay of energetic neutrons produced in solar flares. Because the neutrons are fast-moving but insensitive to the solar wind magnetic field, the decay protons are produced over a wide region of space, and they should be detectable by current instruments over a broad range of longitudes for many hours after a sufficiently large gamma-ray flare. Spacecraft closer to the Sun are expected to see orders-of-magnitude higher intensities than those at the Earth-Sun distance. The current solar cycle

should present an excellent opportunity to observe neutron-decay protons with multiple spacecraft over different heliographic longitudes and distances from the Sun.

EVIDENCE OF CONFINEMENT OF SOLAR-ENERGETIC PARTICLES TO INTERPLANETARY MAGNETIC FIELD LINES

E. E. **Chollet**[1,2] and J. Giacalone[2]

Astrophysical Journal, 728:64 (4pp), **2011** February

We present new observations of solar-energetic particles (SEPs) associated with impulsive solar flares that show evidence for their confinement to interplanetary magnetic field lines. Some SEP events exhibit intermittent intensity dropouts becausemagnetic field lines filledwith and empty of particle flux mix together. The edges of these dropouts are observed to be very sharp, suggesting that particles cannot easily move from a filled to an empty field line in the time available during their transport from the Sun. In this paper, we perform high time-resolution observations of intensity fall-off at the edges of observed SEP dropouts in order to look for signatures of particle motion off field lines. However, the statistical study is dominated by one particularly intense event. The inferred length scale of the intensity decay is comparable to the gyroradii of the particles, suggesting that particles only rarely scatter off magnetic field lines during interplanetary transport.

Multipoint connectivity analysis of the May 2007 solar energetic particle events

Chollet, E. E.; Mewaldt, R. A.; Cummings, A. C.; Gosling, J. T.; Haggerty, D. K.; Hu, Q.; Larson, D.; Lavraud, B.; Leske, R. A.; Opitz, A.; Roelof, E. C.; Russell, C. T.; Sauvaud, J.-A.

J. Geophys. Res., Vol. 115, No. A12, A12106, **2010**

http://dx.doi.org/10.1029/2010JA015552

In May of **2007**, the STEREO Ahead and Behind spacecraft, along with the ACE spacecraft situated between the two STEREO spacecraft, observed two small solar energetic particle (SEP) events. STEREO-A and -B observed nearly identical time profiles in the **19 May** event, but in the **23 May** event, the protons arrived significantly earlier at STEREO-A than at STEREO-B and the time-intensity profiles were markedly different. We present SEP anisotropy, suprathermal electron pitch angle and solar wind data to demonstrate distortion in the magnetic field topology produced by the passage of multiple interplanetary coronal mass ejections on 22 and 23 May, causing the two spacecraft to magnetically connect to different points back at the Sun. This pair of events illustrates the power of multipoint observations in detailed interpretation of complex events, since only a small shift in observer location results in different magnetic field line connections and different SEP time-intensity profiles.

Intermediate-term periodicities in relativistic solar electron fluences during solar cycles 22 and 23

Partha **Chowdhury**, Manoranjan Khan, P.C. Ray

Advances in Space Research, Volume 43, Issue 2, 15 January **2009**, Pages 297-307

In this paper, we have investigated the intermediate-term periodicities of the relativistic (E > 10 MeV) solar electron flares measured by IMP-8 satellite of NASA for the time period of 1986–2001. This period of investigation includes the entire solar cycle 22; ascending, maximum and a part of descending phase of the current solar cycle 23. To determine accurately the occurrence rate of electron flux, we have employed three different spectral decomposition techniques, viz. fast Fourier transformation (FFT); maximum entropy method (MEM) and Lomb–Scargle periodogram analysis method. For solar cycle 22, in the low frequency range, power spectrum analysis exhibits statistically significant periodicities at ∼706, ∼504 and ∼392 days. In the intermediate frequency range, we have found a series of significant periodicities ∼294, ∼221, ∼153, ∼86, ∼73 and ∼66 days. For short term, periodicities of ∼21–23, ∼31 and ∼37 days were found in power spectrum. When solar cycle 23 is considered the significant periodicities are ∼20, ∼23, ∼29, ∼39, ∼54, ∼63, ∼118, ∼133 and ∼154 days. These results provide evidence that the best known Rieger period (∼153 days), appeared in the high energetic electron flux data for cycle 22 and also likely during maxima of cycle 23. The existence of these periodicities has been discussed in the light of earlier results.

Extreme solar events **Review**

Edward W. **Cliver**, Carolus J. Schrijver, Kazunari Shibata & Ilya G. Usoskin

Living Reviews in Solar Physics volume 19, Article number: 2 (**2022**)

https://link.springer.com/content/pdf/10.1007/s41116-022-00033-8.pdf **File**

We trace the evolution of research on extreme solar and solar-terrestrial events from the 1859 Carrington event to the rapid development of the last twenty years. Our focus is on the largest observed/inferred/theoretical cases of sunspot groups, flares on the Sun and Sun-like stars, coronal mass ejections, solar proton events, and geomagnetic storms. The reviewed studies are based on modern observations, historical or long-term data including the auroral and cosmogenic radionuclide record, and Kepler observations of Sun-like stars. We compile a table of 100- and 1000-year events based on occurrence frequency distributions for the space weather phenomena listed above. Questions considered include the Sun-like nature of superflare stars and the existence of impactful but unpredictable solar "black swans" and extreme "dragon king" solar phenomena that can involve different physics from that operating in events which are merely large. **774 AD, 17 Sep 1770, 1 September 1859, 4 Feb 1872, 14-15 May 1921, 28 Feb 1942, 5 April 1947, 23 May 1967, 2–11 August 1972 , 29 Apr 1973, 21 Apr 2002, 28 October 2003; 6, 13, 14 Dec 2006, 9 Nov 2011, 28 Oct 2013, 4 Nov 2015**
Table 5 Historical fast transit ICME events
Table 8 Largest SEP events during the space age, rank ordered for F30, F200, and FGLE

On the Size of the Flare Associated with the Solar Proton Event in 774 AD

E. W. **Cliver**1,2, H. Hayakawa3,4,5,6, Jeffrey J. Love7, and D. F. Neidig8,9
2020 ApJ 903 41
https://doi.org/10.3847/1538-4357/abad93
The 774 AD solar proton event (SPE) detected in cosmogenic nuclides had an inferred >1 GV (>430 MeV) fluence estimated to have been ~30–70 times larger than that of the 1956 February 23 ground level event (GLE). The 1956 GLE was itself ~2.5 times larger at >430 MeV than the episode of strong GLE activity from 1989 August–October. We use an inferred soft X-ray (SXR) class of X20 ± 10 for the 1956 February 23 eruptive flare as a bridge to the source flare for the 774 SPE. A correlation of the >200 MeV proton fluences of hard-spectra post-1975 GLEs with the SXR peak fluxes of their associated flares yields an **SXR flare class of X285 ± 140** (bolometric energy of ~(1.9 ± 0.7) × 1033 erg) for the 774 flare. This estimate is within theoretical determinations of the largest flare the Sun could produce based on the largest spot group yet observed. Assuming a single eruptive flare source for the 774 SPE, the above estimate indicates that the Sun can produce a threshold-level 1033 erg superflare. If the 774 event originated in two closely timed, equal-fluence SPEs, the inferred flare size drops to X180 ± 90 (~(1.4 ± 0.5) × 1033 erg). We speculate on favorable solar conditions that can lead to enhanced shock acceleration of high-energy protons in eruptive flares.

Solar Longitude Distribution of High-energy Proton Flares: Fluences and Spectra

E. W. **Cliver**1,2, F. Mekhaldi3, and R. Muscheler3
2020 ApJL 900 L11
https://doi.org/10.3847/2041-8213/abad44
https://iopscience.iop.org/article/10.3847/2041-8213/abad44/pdf **File**
The distribution of the longitudes of solar flares associated with the high-energy proton events called ground level events (GLEs) can be approximated by a Gaussian with a peak at ~W60, with a full range from ~E90 to ~W150. The longitudes of flares associated with the top third (24 of 72) of GLEs in terms of their >430 MeV fluences (F 430) are primarily distributed over E20–W100 with a skew toward disk center. This 120° span in longitude is comparable to the latitudinal spans of powerful coronal mass ejections (CMEs) from limb flares. Only 5 of 24 strong GLEs are located within the W40–80 zone of good magnetic connection to Earth. GLEs with hard spectra, i.e., a spectral index SI30/200(= log(F 30/F 200)) < 1.5, also tend to avoid W40–80 source regions. Three-fourths of such events (16 of 21) arise in flares outside this range. The above tendencies favor a CME-driven shock source over a flare-resident acceleration process for high-energy solar protons. GLE spectra show a trend, with broad scatter, from hard spectra for events originating in eruptive flares beyond the west limb to soft spectra for GLEs with sources near central meridian. This behavior can be explained in terms of: (1) dominant near-Sun quasi-perpendicular shock acceleration of protons for far western (>W100) GLEs; (2) quasi-parallel shock acceleration for well-connected (W40–80) GLEs, and (3) proton acceleration/trapping at CME-driven bow shocks from central meridian (E20–W20) that strike the Earth.
Table 1 Parameters of GLEs, 1942–2017

Particle acceleration at the Sun.

Cliver E.W.
In: Miyake F, Usoskin I, Poluianov S (eds) Extreme Solar particle storms. IOP Publishing, **2019** pp 3–14.
https://doi.org/10.1088/2514-3433/ab404a

The Disappearing Solar Filament of 2013 September 29 and Its Large Associated Proton Event: Implications for Particle Acceleration at the Sun
E. W. **Cliver**1, S. W. Kahler2, M. Kazachenko1,3,4, and M. Shimojo5,6
2019 ApJ 877 11
sci-hub.si/10.3847/1538-4357/ab0e03
https://iopscience.iop.org/article/10.3847/1538-4357/ab0e03/pdf
We present observations of a notable example of a disappearing solar filament (DSF) on **2013 September 29** that was associated with a large solar proton event (SPE) and discuss this event in the context of four recent studies that compare flare and SPE size parameters. The DSF-associated flare was characterized by weak radio and soft X-ray emissions and a low reconnection flux. It was accompanied by a fast coronal mass ejection (CME) and a decametric-hectometric type II burst. We assembled a list of eight such events that are outliers in plots of SPE versus flare size parameters. These events were characterized by weak magnetic field source regions (predominantly DSFs but including one case of a transequatorial loop and another of a decaying active region), fast CMEs, type II bursts with low starting frequencies, high proton yields (ratio of proton intensity to 1 MHz radio fluence), and low high-energy Fe/O ratios. The last of these attributes suggests quasi-parallel shock acceleration. The relationship between SPE and flare size parameters in large (gradual), well-connected proton events can be illustrated by a schematic diagram with three principal regions: (1) a DSF zone of weak flares and large SPEs, (2) a big flare syndrome main sequence of loosely correlated flare and SPE parameters, and (3) a zone of moderate to large flares with no SPEs. The existence of regions 1 and 3 argues against a significant role for flares in large proton events: region 1 implies that flares are not necessary for such SPEs, and region 3 indicates that they are not sufficient. **1998 Sep 30 , 2000 Apr 04 , 2000 Nov 08 , 2001 Nov 22 , 2002 May 22 , 2004 July 25, 2011 Nov 26, 2013 Sep 29**
Table 1 Flare, CME, Type II, and SEP Parameters for Events Plotted in Figure 4
Table 2 Flare and Particle Parameters for Eight Large SPEs That Originated in DSFs or Quasi-DSFs

Size Distributions of Solar Proton Events and Their Associated Soft X-Ray Flares: Application of the Maximum Likelihood Estimator
Edward W. **Cliver**1 and Elke D'Huys
2018 ApJ 864 48
http://sci-hub.tw/http://iopscience.iop.org/article/10.3847/1538-4357/aad043/meta
https://sci-hub.tw/10.3847/1538-4357/aad043
We use the maximum likelihood estimator to determine the slope (α) of the power-law size distribution of the peak proton fluxes of a subsampled set of 106 ~ 25 MeV solar energetic proton (SEP) events from 1997 to 2016 associated with western hemisphere soft X-ray (SXR) flares: α = 1.28 ± 0.03. For the peak SXR fluxes of a subsample of 110 SEP-associated flares, we find α = 1.51 ± 0.05. In addition, we obtained a slope of 1.61 ± 0.05 for the peak SXR fluxes of a sample of 128 ≥M1 SXR flares from 1996 to 2005 that were associated with coronal mass ejections (CMEs) with speeds ≥1000 km s−1. The slopes of both of these SXR peak-flux distributions (~1.5 and ~1.6) are closer to that for proton events (~1.3) than to the α value of ~2.1 (2.09 ± 0.08) determined for a subsample of 177 western hemisphere ≥M1 SXR flares considered from 1996 to 2005. These results are consistent with those of a previous study, based on a less reliable method (for small samples), in which it was argued that the flatter size distribution generally found for SEP events versus those for flare electromagnetic emissions was due to the fact that SEP flares are an energetic subset of all flares, characterized by their ~100% association with fast/wide CMEs that drive coronal/interplanetary shock waves. Shock formation in the corona requires CMEs with speeds ≳400 km s−1, a threshold effect that further distinguishes SEP flares from the general population of all flares.
Table 2 ∼25 MeV Proton Events from 1997 to 2016 with Flare, CME, and Type II Burst Associations
Table 3 CMEs with Speeds □1000 km s−1 and Their Associated Flares, 1996–2005 (from Yashiro et al. 2006)
CESRA highlights #1971 Sept **2018** http://cesra.net/?p=1971

FLARE VERSUS SHOCK ACCELERATION OF HIGH-ENERGY PROTONS IN SOLAR ENERGETIC PARTICLE EVENTS
E. W. **Cliver**
2016 ApJ 832 128 **File**
http://sci-hub.si/10.3847/0004-637X/832/2/128
https://iopscience.iop.org/article/10.3847/0004-637X/832/2/128/pdf
Recent studies have presented evidence for a significant to dominant role for a flare-resident acceleration process for high-energy protons in large ("gradual") solar energetic particle (SEP) events, contrary to the more generally held view that such protons are primarily accelerated at shock waves driven by coronal mass ejections (CMEs). The new support for this flare-centric view is provided by correlations between the sizes of X-ray and/or microwave bursts and associated SEP events. For one such study that considered >100 MeV proton events, we present evidence based on CME speeds and widths, shock associations, and electron-to-proton ratios that indicates that events omitted from

that investigation's analysis should have been included. Inclusion of these outlying events reverses the study's qualitative result and supports shock acceleration of >100 MeV protons. Examination of the ratios of 0.5 MeV electron intensities to >100 MeV proton intensities for the **Grechnev et al.** event sample provides additional support for shock acceleration of high-energy protons. Simply scaling up a classic "impulsive" SEP event to produce a large >100 MeV proton event implies the existence of prompt 0.5 MeV electron events that are approximately two orders of magnitude larger than are observed. While classic "impulsive" SEP events attributed to flares have high electron-to-proton ratios (5 × 105) due to a near absence of >100 MeV protons, large poorly connected (≥W120) gradual SEP events, attributed to widespread shock acceleration, have electron-to-proton ratios of ~2 × 103, similar to those of comparably sized well-connected (W20–W90) SEP events.
Introduction

Flare vs. Shock Acceleration of >100 MeV Protons in Large Solar Particle Events

E. W. **Cliver**

American Astronomical Society, SPD meeting #47, id.6.06, May **2016**

Recently several studies have presented correlative evidence for a significant-to-dominant role for a flare-resident process in the acceleration of high-energy protons in large solar particle events. In one of these investigations, a high correlation between >100 MeV proton fluence and 35 GHz radio fluence is obtained by omitting large proton events associated with relatively weak flares; these outlying events are attributed to proton acceleration by shock waves driven by coronal mass ejections (CMEs). We argue that the strong CMEs and associated shocks observed for proton events on the main sequence of the scatter plot are equally likely to accelerate high-energy protons. In addition, we examine ratios of 0.5 MeV electron to >100 MeV proton intensities in large SEP events, associated with both well-connected and poorly-connected solar eruptions, to show that scaled-up versions of the small flares associated with classical impulsive SEP events are not significant accelerators of >100 MeV protons.

On a Solar Origin for the Cosmogenic Nuclide Event of 775 A.D.

E. W. **Cliver**1, A. J. Tylka2, W. F. Dietrich3, and A. G. Ling

2014 ApJ 781 32

We explore requirements for a solar particle event (SPE) and flare capable of producing the cosmogenic nuclide event of 775 A.D., and review solar circumstances at that time. A solar source for 775 would require a >1 GV spectrum ~45 times stronger than that of the intense high-energy SPE of 1956 February 23. This implies a >30 MeV proton fluence (F 30) of ~8 × 1010 proton cm–2, ~10 times larger than that of the strongest 3 month interval of SPE activity in the modern era. This inferred F 30 value for the 775 SPE is inconsistent with the occurrence probability distribution for >30 MeV solar proton events. The best guess value for the soft X-ray classification (total energy) of an associated flare is ~X230 (~9 × 1033 erg). For comparison, the flares on 2003 November 4 and 1859 September 1 had observed/inferred values of ~X35 (~1033 erg) and ~X45 (~2 × 1033 erg), respectively. The estimated size of the source active region for a ~1034 erg flare is ~2.5 times that of the largest region yet recorded. The 775 event occurred during a period of relatively low solar activity, with a peak smoothed amplitude about half that of the second half of the 20th century. The ~1945-1995 interval, the most active of the last ~2000 yr, failed to witness a SPE comparable to that required for the proposed solar event in 775. These considerations challenge a recent suggestion that the 775 event is likely of solar origin.

The 1859 space weather event revisited: limits of extreme activity

Edward W. **Cliver**1* and William F. Dietrich2

J. Space Weather Space Clim., Volume 3, **2013**, A31; **File**

The solar flare on **1 September 1859** and its associated geomagnetic storm remain the standard for an extreme solar-terrestrial event. The most recent estimates of the flare soft X-ray (SXR) peak intensity and Dst magnetic storm index for this event are: SXR class = X45 (±5) (vs. X35 (±5) for the 4 November 2003 flare) and minimum Dst = −900 (+50, −150) nT (vs. −825 to −900 nT for the great storm of May 1921). We have no direct evidence of an associated solar energetic proton (SEP) event but a correlation between >30 MeV SEP fluence (F30) and flare size based on modern data yields a best guess F30 value of ~1.1 × 1010 pr cm−2 (with the ±1σ uncertainty spanning a range from ~109–1011 pr cm−2) for a composite (multi-flare plus shock) 1859 event. This value is approximately twice that of estimates/measurements – ranging from ~5–7 × 109 pr cm−2 – for the largest SEP episodes (July 1959, November 1960, August 1972) in the modern era.

SIZE DISTRIBUTIONS OF SOLAR FLARES AND SOLAR ENERGETIC PARTICLE EVENTS

E. W. **Cliver**1, A. G. Ling2, A. Belov3, and S. Yashiro

2012 ApJ 756 L29   **File**

http://iopscience.iop.org/2041-8205/756/2/L29/pdf/apjl_756_2_29.pdf

We suggest that the flatter size distribution of solar energetic proton (SEP) events relative to that of flare soft X-ray (SXR) events is primarily due to the fact that SEP flares are an energetic subset of all flares. Flares associated with gradual SEP events are characteristically accompanied by fast (≥1000 km s–1) coronal mass ejections (CMEs) that drive coronal/interplanetary shock waves. For the 1996-2005 interval, the slopes (α values) of power-law size distributions of the peak 1-8 Å fluxes of SXR flares associated with (a) >10 MeV SEP events (with peak fluxes ≥1 pr cm–2 s–1 sr–1) and (b) fast CMEs were ~1.3-1.4 compared to ~1.2 for the peak proton fluxes of >10 MeV SEP events and ~2 for the peak 1-8 Å fluxes of all SXR flares. The difference of ~0.15 between the slopes of the distributions of SEP events and SEP SXR flares is consistent with the observed variation of SEP event peak flux with SXR peak flux.

Table: SEP Events with Peak Fluxes >1 pfu and associated soft X-ray flares (1996–2005)

LOW-FREQUENCY TYPE III BURSTS AND SOLAR ENERGETIC PARTICLE EVENTS

E. W. **Cliver**1 and A. G. Ling2

Astrophysical Journal, 690:598–609, **2009**, January; **File**

We compare the ~1 MHz type III bursts of flares associated with samples of "impulsive" and "gradual" solar energetic particle (SEP) events from cycle 23. While large gradual SEP events had much higher > 30 MeV proton intensities, the median-integrated intensities, peak intensities, and durations of the two groups of radio bursts were comparable. Thus, the median "proton yield" (peak > 30 MeV proton intensity of an SEP event divided by its associated integrated ~1 MHz intensity) of type III bursts associated with gradual SEP events was ~280 times larger than that for impulsive SEP events. A similar yield difference of ~250 was observed for 4.4 MeV electron events. Only for extrapolated electron energies ~5 keV, corresponding to the energy of the electrons that excite type III emission, does the median yield converge to the same value for both groups of events. The time profiles of ~1 MHz bursts associated with impulsive SEP events are characteristically shorter and simpler than those associated with the gradual SEP events, reflecting the development of the second stage of radio emission in large eruptive flares. The gradual SEP events were highly associated (96%) with decametric-hectometric (DH) type II bursts versus only a 5% association rate for the impulsive events. Large favorably located ~1 MHz type III bursts with associated DH type IIs had an ~60% association rate with large (_ 1 pfu) > 30 MeV SEP events versus ~5% for ~1 MHz bursts without accompanying DH II emission. These results are interpreted in terms of two distinct types of particle acceleration at the Sun, a flare-resident process that produces relatively few > 30 MeV protons and ~4 MeV electrons in space and a shock process that dominates the large gradual proton events.

History of research on solar energetic particle (SEP) events: the evolving paradigm,

Cliver E., **Review**.

Proc. IAU Symposium, Volume 257, p. 401-412 (**2009**). **File**

https://sci-hub.si/10.1017/S1743921309029639

Forbush initiated research on solar energetic particle (SEP) events in 1946 when he reported ionization chamber observations of the first three ground level events (GLEs). The next key development was the neutron monitor observation of the GLE of 23 February 1956. Meyer, Parker and Simpson attributed this high-energy SEP event to a short time-scale process associated with a solar flare and ascribed the much longer duration of the particle event to scattering in the interplanetary medium. Thus "flare particle" acceleration became the initial paradigm for SEP acceleration at the Sun. A more fully-developed picture was presented by the Australian radio astronomers Wild, Smerd, and Weiss in 1963. They identified two distinct SEP acceleration processes in flares: (1) the first phase accelerated primarily ~100 keV electrons that gave rise to fast-drift type III emission as they streamed outward through the solar atmosphere; (2) the second phase was produced by an outward moving (~1000 km s⁻1) magnetohydrodynamic shock, occurring in certain (generally larger) flares. The second phase, manifested by slow-drift metric type II emission, appeared to be required for substantial acceleration of protons and higher-energy electrons. This two-stage (or two-class) picture gained acceptance during the 1980s as composition and charge state measurements strengthened the evidence for two distinct types of particle events which were termed impulsive (attributed to flare-resident acceleration process(es)) and gradual (shock-associated). Reames championed the two-class picture and it is the commonly accepted paradigm today. A key error made in the establishment of this paradigm was revealed in the late 1990s by observations of SEP composition and charge states at higher energies (>10 MeV) than previously available. Specifically, some large and therefore presumably "gradual" SEP events looked "impulsive" at these energies. One group of researchers attributes these unusual events to acceleration of high-energy SEPs by flares and another school favors acceleration of flare seed particles by quasi-perpendicular shocks. A revised SEP classification scheme is proposed to accommodate the new observations and to include ideas on geometry and seed particle composition recently incorporated into models of shock acceleration of SEPs.

Electrons and Protons in Solar Energetic Particle Events

E. W. **Cliver** and A. G. Ling
The Astrophysical Journal, 658:1349-1356, **2007**
http://iopscience.iop.org/article/10.1086/511737/pdf
A plot of 0.5 MeV peak electron intensity versus >10 MeV peak proton intensity for well-connected solar energetic particle (SEP) events from 1997 to 2003 reveals two distinct populations: (1) a group of events with peak proton intensities <3 protons cm^{-2} s^{-1} sr^{-1} that have electron-to-proton (*e*/*p*) ratios ranging from ~10^2 to 2 × 10^4 and (2) a well-defined branch spanning peak proton intensities from ~3 to 10^4 protons cm^{-2} s^{-1} sr^{-1} with *e*/*p* ratios ranging from ~10^1 to 2 × 10^2. Events with strong abundance enhancements of trans-Fe elements form a prominent subset of "population 1" and are absent from "population 2." For a sample of poorly connected SEP events, population 1 largely disappears, and population 2 is observed to extend down to low (<10^{-1} protons cm^{-2} s^{-1} sr^{-1}) proton intensities. Plots of 0.5 MeV peak electron intensity versus >30 MeV peak proton intensity yield comparable results. The SEP events in population 2 are highly (~90%) associated with dekametric/hectometric (DH) type II bursts versus only a ~20% association rate for population 1 events. Population 2 events have flatter electron (0.5-4.4 MeV) and proton spectra (10-30 MeV) than those in population 1. Based on their high *e*/*p* ratios, trans-Fe enhancements, poor association with DH type IIs, and inferred small "emission cones," population 1 events are attributed to acceleration in solar flares. For population 2 events, evidence for a dominant shock process includes their flatter spectra, apparent widespread sources, and high association with DH type II bursts.

THE UNUSUAL RELATIVISTIC SOLAR PROTON EVENTS OF 1979 AUGUST 21 AND 1981 MAY 10
E. W. **Cliver**
Astrophysical Journal, 639:1206–1217, **2006, File**
http://iopscience.iop.org/article/10.1086/499765/pdf
Sixty-nine ground level events (GLEs) caused by relativistic solar protons have been observed from 1942 to 2005. GLEs are characteristically associated with intense solar flares [having peak _9 GHz flux densities S_P(9 GHz) **>**10_3 sfu] and fast (>1000 kms$_{_1}$) coronalmass ejections (CMEs). The small GLEs on 1979 August 21 and 1981 May 10 provide an exception to these rules of thumb. In comparison with other GLEs, they were associated with significantly weaker flares [S_P(9 GHz) **<** 30 sfu vs. a median value of _8000 sfu for all GLEs] and slower CMEs (plane-of-sky speeds _800 km s$_{_1}$ vs. a median of _1600 km s$_{_1}$). The sunspot groups in which these two events originated ranked near the bottom of GLE-parent regions in terms of sunspot area (_100 millionths of a solar hemisphere [msh] vs. a median of _850 msh). What enabled these two otherwise common place solar eruptions to accelerate protons to GeV energies? In both cases, intense, long-duration, metric type II bursts were observed. In addition, both of these GLEs occurred when the background _10 MeV proton intensity at 1 AU was >1000 times the normal background because of preceding SEP events originating in active regions that were located in each case _100_ east of the active region responsible for the GLE. We suggest that the relativistic solar protons observed in these two events resulted from CME-driven shock acceleration of an elevated coronal seed population, reflecting the enhanced background proton intensity at 1 AU. For this scenario, the timing onset of the relativistic protons in the two events indicates that the shocks had access to the energetic seed particles within _2–5 R_ of the solar surface. While an elevated _10 MeV proton background at Earth is a favorable/common condition for GLE occurrence, it is not a requirement.

CORONAL SHOCKS AND SOLAR ENERGETIC PROTON EVENTS
E. W. **Cliver,** S. W. Kahler, and D. V. Reames
Astrophysical Journal, 605,:902–910, **2004; File**
https://iopscience.iop.org/article/10.1086/382651/pdf
From1996 July through 2001 June, less than half (43/98) of all favorably located (from solar western hemisphere sources) metric type II radio bursts were associated with solar energetic proton (SEP) events observed at Earth. When western hemisphere metric type IIs were accompanied by decametric-hectometric (DH; 1–14 MHz) type II emission (observed by Wind/WAVES) during this period, their association with _20 MeV SEP events (with peak fluxes _10$_{_3}$ protons cm$_{_2}$ s$_{_1}$ sr$_{_1}$ MeV$_{_1}$) was 90% (26/29), versus only 25% (17/69) for metric IIs without a DH counterpart. Overall, 82% (63%) of all SEP events with visible disk origins were associated with metric (DH) type II bursts, with the percentage associations increasing with SEP event size to 88% (96%) for _20 MeV SEP events with peak intensities of _10$_{_1}$ protons cm$_{_2}$ s$_{_1}$ sr$_{_1}$ MeV$_{_1}$. Our results are consistent with the following possibilities (which are not mutually exclusive): (1) large _20 MeV SEP events result from strong shocks that are capable of persisting well beyond _3 R_ (the nominal 14 MHz plasma level); (2) shock acceleration is most efficient above _3 R_; and (3) shocks that survive beyond _3 R_ are more likely to have broad longitudinal extents, enabling less well connected shocks to intercept open field lines connecting to Earth

X-class soft X-ray bursts and major proton events during solar cycle 21,
Cliver, E., and H. V. Cane

(1989), in Solar Terrestrial Predictions Proceedings, edited by R. J. Thompson et al., Leura, Australia.
***Cliver and Cane* [1989]** discriminated impulsive from gradual soft X-ray flares by their e-folding decay time.

Solar flare nuclear gamma-rays and interplanetary proton events.
Cliver, E.W., Forrest, D.J., Cane, H.V., Reames, D.V., McGuire, R.E., von Rosenvinge, T.T., Kane, S.R., MacDowall, R.J.:
1989, Astrophys. J. 343, 953 – 970.
http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1989ApJ...343..953C&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf
Gamma-ray line (GRL) and solar energetic proton (SEP) events observed from February 1980 through January 1985 are compared in order to substantiate and better characterize the lack of correlation between GRL fluences and SEP event peak fluxes. The scatter plot of SEP event peak flux vs. GRL fluence is presented, and the ratio of 'solar' to 'interplanetary', about 10 MeV protons, is presented. It is shown that, while even large SEP events can originate in flares lacking detectable GRL emission, the converse case of flares with a significant GRL line fluence by lacking protons in space is rare. The ratio R of the number of about 10 MeV protons that produce GRL emission at the flare site to the number of about 10 MeV protons detected in space can vary from event to event by four orders of magnitude. There is a clear tendency for impulsive flares to have larger values of R than long-duration flares, where the flare time scale is given by the e-folding decay time of the associated soft X-ray emission.
TABLE 1 Solar Proton Events, 1980-1985

Solar proton flares with weak impulsive phases,
Cliver, E., S. W. Kahler, and P. S. McIntosh
(**1983**), Astrophys. J., 264, 699–707
http://articles.adsabs.harvard.edu/pdf/1983ApJ...264..699C
The current picture of a proton flare includes a well-defined impulsive phase characterized by a prominent hard X-ray (or microwave) peak. Lin and Hudson have argued that the correlation between intense flare hard X-ray bursts and large proton events is evidence that the second stage of particle acceleration is fueled by energy originally contained in flash phase 10-100 keV electrons. In their examination of large, prompt, proton events occurring between 1965-1979, however, the authors found several events that originated in flares with relatively weak impulsive phases. Various lines of evidence indicate that these flares were associated with mass ejection events which appear to have been magnetically driven.

Observations of the 2022 September 5 Solar Energetic Particle Event at 15 Solar Radii
C. M. S. **Cohen**1, R. A. Leske1, E. R. Christian2, A. C. Cummings1, G. A. de Nolfo2, M. I. Desai3,4, J. Giacalone5, M. E. Hill6, A. W. Labrador1, D. J. McComas7Show full author list
2024 ApJ 966 148
https://iopscience.iop.org/article/10.3847/1538-4357/ad37f8/pdf
On **2022 September 5**, Parker Solar Probe (Parker) observed a large solar energetic particle (SEP) event at the unprecedented distance of only 15 RS from the Sun. The observations from the Integrated Science Investigation of the Sun (IS⊙IS) obtained over the course of this event are remarkably rich, and an overview is presented here. IS⊙IS is capable of measuring ions from 20 keV to over 100 MeV nuc−1 and electrons from 30 keV to 6 MeV; here, we primarily focus on the proton and helium measurements above 80 keV. Among the surprising results are evidence of inverse velocity dispersion at energies above 1 MeV during the onset of the event, a sharp decrease in the energetic particle intensities at all energies at the interplanetary shock crossing, and repeated short durations of highly anisotropic sunward flow. Many changes in the SEP intensities, anisotropy, and spectral steepness are coincident with solar wind structure boundaries identified using the Parker solar wind magnetic field and plasma data. However, there are significant changes that are not correlated with any clearly visible solar wind variation. The observations presented here serve as an introduction to a complex event with numerous opportunities for future, more in-depth studies.

Energetic Neutral Atoms Detected in the 2022 February 15 Solar Energetic Particle Event
C. M. S. **Cohen**1, R. A. Leske1, O. C. St. Cyr4,2, and G. M. Mason3
2024 ApJL 966 L19
https://iopscience.iop.org/article/10.3847/2041-8213/ad4038/pdf
Energetic neutral atoms (ENAs) are expected to be produced near the Sun during large solar energetic particle (SEP) events. However, their detection by SEP instruments near 1 au has been limited. The clearest reported measurement

has been from the Solar Terrestrial Relations Observatory (STEREO) during the 2006 December 5 SEP event. Additional evidence of ENAs has been found through reanalysis of observations by the Solar Anomalous and Magnetospheric Particle Explorer obtained near the equator in low Earth orbit and associated with several large X-ray flares and fast coronal mass ejections (CMEs). Here we describe another detection of ENAs from the STEREO Low Energy Telescope associated with the large **2022 February 15** SEP event. Given the timing and spectrum of the ENAs and the location of the source region (behind the east limb from STEREO's viewpoint), these ENAs are most likely a result of acceleration by a CME-driven shock when the CME was at approximately 2–3 RS. The possibility of a postflare loop origin is considered unlikely.

Parker Solar Probe observations of He/H abundance variations in SEP events inside 0.5 au

C. M. S. **Cohen**1, E. R. Christian2, A. C. Cummings1, A. J. Davis1, M. I. Desai3, G. A. de Nolfo2, J. Giacalone4, M. E. Hill5, C. J. Joyce6, A. W. Labrador1, R. A. Leske1, W. H. Matthaeus7, D. J. McComas6, R. L. McNutt Jr.5, R. A. Mewaldt1, D. G. Mitchell5, J. G. Mitchell2,8, J. S. Rankin6, E. C. Roelof5, N. A. Schwadron9, E. C. Stone1, J. R. Szalay6, M. E. Wiedenbeck10, A. Vourlidas5, S. D. Bale11, M. Pulupa12 and R. J. MacDowall2
A&A 650, A23 (**2021**)
https://www.aanda.org/articles/aa/pdf/2021/06/aa39299-20.pdf
https://doi.org/10.1051/0004-6361/202039299
Aims. The Parker Solar Probe (PSP) orbit provides an opportunity to study the inner heliosphere at distances closer to the Sun than previously possible. Due to the solar minimum conditions, the initial orbits of PSP yielded only a few solar energetic particle (SEP) events for study. Recently during the fifth orbit, at distances from 0.45 to 0.3 au, the energetic particle suite on PSP, Integrated Science Investigation of the Sun (IS⨀IS), observed a series of six SEP events, adding to the limited number of SEP events studied inside of 0.5 au. Variations in the H and He spectra and the He/H abundance ratio are examined and discussed in relation to the identified solar source regions and activity.
Methods. IS⨀IS measures the energetic particle environment from ~20 keV to >100 MeV/nuc. Six events were selected using the ~1 MeV proton intensities, and while small, they were sufficient to calculate proton and helium spectra from ~1 to ~10 MeV/nuc. For the three larger events, the He/H ratio as a function of energy was determined. Using the timing of the associated radio bursts, solar sources were identified for each event and the eruptions were examined in extreme ultraviolet emission.
Results. The largest of the selected events has peak ~1 MeV proton intensities of 3.75 (cm2 sr s MeV)−1. Within uncertainties, the He and H spectra have similar power law forms with indices ranging from −2.3 to −3.3. For the three largest events, the He/H ratios are found to be relatively energy independent; however, the ratios differ substantially with values of 0.0033 ± 0.0013, 0.177 ± 0.047, and 0.016 ± 0.009. An additional compositional variation is evident in both the 3He and electron signatures. These variations are particularly interesting as the three larger events are likely a result of similar eruptions from the same active region.

Energetic Particle Increases Associated with Stream Interaction Regions

C. M. S. **Cohen**, E. R. Christian, A. C. Cummings, A. J. Davis, M. I. Desai, ...
2020 *ApJS* **246** 20
https://arxiv.org/ftp/arxiv/papers/1912/1912.08244.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/ab4c38/pdf
The **Parker Solar Probe** was launched on 2018 August 12 and completed its second orbit on **2019 June 19** with perihelion of 35.7 solar radii. During this time, the Energetic particle Instrument-Hi (EPI-Hi, one of the two energetic particle instruments comprising the Integrated Science Investigation of the Sun, ISOIS) measured seven proton intensity increases associated with stream interaction regions (SIRs), two of which appear to be occurring in the same region corotating with the Sun. The events are relatively weak, with observed proton spectra extending to only a few MeV and lasting for a few days. The proton spectra are best characterized by power laws with indices ranging from -4.3 to -6.5, generally softer than events associated with SIRs observed at 1 au and beyond. Helium spectra were also obtained with similar indices, allowing He/H abundance ratios to be calculated for each event. We find values of 0.016-0.031, which are consistent with ratios obtained previously for corotating interaction region events with fast solar wind < 600 km s-1. Using the observed solar wind data combined with solar wind simulations, we study the solar wind structures associated with these events and identify additional spacecraft near 1 au appropriately positioned to observe the same structures after some corotation. Examination of the energetic particle observations from these spacecraft yields two events that may correspond to the energetic particle increases seen by EPI-Hi earlier.

The Ground Level Enhancement Event of September 2017 and Other Large Solar Energetic Particle Events of Cycle 24

C. M. S. **Cohen**, R. A. Mewaldt
Space Weather Volume16, Issue10 Pages 1616-1623 **2018**
https://doi.org/10.1029/2018SW002006
sci-hub.tw/10.1029/2018SW002006
The **10 September 2017** solar energetic particle (SEP) event was the largest since June 2015 and one of only two ground level enhancement (GLE) events of solar cycle 24. GLE events are subset of large SEP events (~15% of events identified by Space Weather Prediction Center) with particularly hard spectra, making them a substantial space weather hazard to space-based instrumentation and exposed astronauts. We present analysis of the 10 September 2017 event and compare it to the other cycle 24 GLE events, to those of cycle 23, and also to two extreme SEP events observed by STEREO. We find the 10 September 2017 event had a broken power-law spectrum typical of GLE events, but was softer than average at high energies. However, it was hard at low energies with a relatively high break energy which led to 100 MeV proton fluences within a factor of 4.5 of the largest cycle 23 GLE events. The composition was nominal, except for a low Fe/O ratio, which has also been seen in large SEP events this cycle, but is somewhat atypical of the cycle 23 GLE events. The extreme events seen by STEREO exhibited very hard high-energy spectra, with one event producing ~80 MeV proton fluences larger than the largest cycle 23 GLE event. However, even including STEREO events, the top ten largest cycle 24 events are, on average, 2.4 times smaller than the top ten of cycle 23 based on >10 MeV proton fluences. **6 May 1998, 14 July 2000 and 28 October 2003, 13 December 2006, 7 March 2012, 17 May 2012, 23 July 2012, 1 September 2014**

Searching for Extreme SEP Events with STEREO,

Cohen, C. M. S., J. G. Luhmann, R. A. Mewaldt, M. L. Mays, H. M. Bain, Y. Li, and C. O. Lee
(**2017**), Proceedings of 35th ICRC Conference, PoS(ICRC2017), id.134, 1–8.
https://pos.sissa.it/301/134/pdf
Ground Level Enhancement (GLE) events are a particular class of solar energetic particle (SEP) events in which the particle spectrum is hard enough to produce effects on the Earth's surface. Historically a GLE had to be observed by two separate ground-based monitors to be added to the informal 'GLE list' (http://neutronm.bartol.udel.edu/~pyle/GLE_List.txt). As these events are among the most energetic of SEP events, they are a clear space weather concern and understanding the conditions under which they occur and the processes that create them is critical for improving our predictive capabilities. By their very definition, GLEs cannot be identified with only space-based instrumentation or at locations far from Earth, yet as we increasingly send instrumentation to distant locations, our need for predicting space weather throughout the heliosphere becomes more urgent.
Using the 13-100 MeV proton intensities observed during the **13 Dec 2006** GLE by the STEREO-B spacecraft (when it was still close to Earth) as a guide, we have identified several SEP events observed by STEREO of similar or larger intensity. None of these events were strong enough at Earth to register as a GLE, but had Earth been in the STEREO location, they might have been. We have calculated the eventintegrated proton spectra for these events and found they fell into two categories: those with hard spectra and those with soft spectra above a few tens of MeV. Extrapolation of the hard spectra to higher energies indicates that these events had >500 MeV fluences that exceeded those of the **13 Dec 2006** and **17 May 2012** GLE events by factors of ~4 to 500, suggesting that they would have caused GLEs had the Earth been suitably positioned. The spectral indices of these events are consistent with those found in previous studies of GLE events. Simulations using the WSA-ENLIL+Cone model indicate that the observing spacecraft was magnetically connected to both the event coronal mass ejection (CME) and a preceding CME during the hard spectrum events. This may suggest a favorable configuration for the generation of extreme SEP events and/or GLEs. **4 Jun 2011, 7 Mar 2012, 23 Jul 2012, 1 Sep 2014, 14 Dec 2014**

Characteristics of Solar Energetic Ions as a Function of Longitude

C. M. S. **Cohen**1, G. M. Mason2, and R. A. Mewaldt
2017 ApJ 843 132
http://sci-hub.cc/10.3847/1538-4357/aa7513
Since the 2006 launch of STEREO, multi-spacecraft studies have yielded several surprising results regarding the spread of solar energetic particles (SEPs) within the inner heliosphere. We have investigated the role of energy and ridigity, using ACE and STEREO 10 MeV n^{-1} oxygen data to identify 41 large SEP events observed by two or three spacecraft. We calculated fluence spectra from ~0.1 to >10 MeV n^{-1} for H, He, O, and Fe for each event at the observing spacecraft (including SOHO and GOES). The particle fluences at 0.3, 1, and 10 MeV n^{-1} were examined as a function of the distance between the associated solar flare longitude and the spacecraft magnetic footpoints at the Sun to determine the longitudinal spread of particles and study how the distribution centers and widths depend on energy and charge-to-mass (Q/M) for the first time. On average, the three-spacecraft event distributions were centered at 22 ± 4° west of the flare site and were 43 ± 1° wide, though there was substantial variability, while the fit to the aggregate of the two-spacecraft event fluences yielded significantly wider distributions at 0.3 and 1 MeV n^{-1}. The widths derived from both the three- and two-spacecraft events show an energy dependence with distributions narrowing with increasing energy, consistent with lower energy ions

experiencing more field line co-rotation, or being accelerated over a larger portion of the CME-driven shock or for longer times as the shock expands. Surprisingly, no clear evidence was found for a Q/M dependence to the widths or centers suggesting that rigidity-related processes are not the dominant means of spreading particles in longitude.
Table 1 List of Selected Events

The Longitudinal Dependence of Heavy-ion Composition in the 2013 April 11 Solar Energetic Particle Event

C. M. S. **Cohen**1, G. M. Mason2, R. A. Mewaldt1, and M. E. Wiedenbeck
2014 ApJ 793 35

On **2013 April 11** active region 11719 was centered just west of the central meridian; at 06:55 UT, it erupted with an M6.5 X-ray flare and a moderately fast (~800 km s–1) coronal mass ejection. This solar activity resulted in the acceleration of energetic ions to produce a solar energetic particle (SEP) event that was subsequently observed in energetic protons by both ACE and the two STEREO spacecraft. Heavy ions at energies ≥10 MeV nucleon–1 were well measured by SEP sensors on ACE and STEREO-B, allowing the longitudinal dependence of the event composition to be studied. Both spacecraft observed significant enhancements in the Fe/O ratio at 12-33 MeV nucleon–1, with the STEREO-B abundance ratio (Fe/O = 0.69) being similar to that of the large, Fe-rich SEP events observed in solar cycle 23. The footpoint of the magnetic field line connected to the ACE spacecraft was longitudinally farther from the flare site (77° versus 58°), and the measured Fe/O ratio at ACE was 0.48, 44% lower than at STEREO-B but still enhanced by more than a factor of 3.5 over average SEP abundances. Only upper limits were obtained for the 3He/4He abundance ratio at both spacecraft. Low upper limits of 0.07% and 1% were obtained from the ACE sensors at 0.5-2 and 6.5-11.3 MeV nucleon–1, respectively, whereas the STEREO-B sensor provided an upper limit of 4%. These characteristics of high, but longitudinally variable, Fe/O ratios and low 3He/4He ratios are not expected from either the direct flare contribution scenario or the remnant flare suprathermal material theory put forth to explain the Fe-rich SEP events of cycle 23.

Solar energetic particle characteristics and their dependence on longitude in solar cycle 24

Cohen, C. M. S.; Mason, G. M.; Mewaldt, R. A.; von Rosenvinge, T. T.
SOLAR WIND 13: Proceedings of the Thirteenth International Solar Wind Conference. AIP Conference Proceedings, Volume 1539, pp. 151-154 (**2013**)

In previous solar cycles, most studies examining the longitude dependence of solar energetic particle (SEP) event characteristics (such as composition and spectral hardness) have involved statistical analysis of single-point measurements. With the significant separation between the two STEREO and near-Earth spacecraft during solar cycle 24, these SEP characteristics can be examined simultaneously from multiple vantage points. Using SEP measurements from sensors on STEREO and ACE, we have examined the longitude dependence of the Fe/O abundance ratio at 10 MeV/nuc and the oxygen spectral index for energies above 10 MeV/nuc. Longitudinal patterns were sought that support or refute the scenarios put forth by Tylka et al. and Cane et al. to explain the Fe-enriched large SEP events of cycle 23. Unfortunately few Fe-enriched events have occurred in cycle 24 and their longitudinal behavior is not entirely consistent with either of the proposed scenarios.

Energetic particle contamination in STIX during Solar Orbiter's passage through Earth's radiation belts and an interplanetary shock

Hannah **Collier**, Olivier Limousin, Hualin Xiao, Arnaud Claret, Frederic Schuller, Nina Dresing, Saku Valkila, Francisco Espinosa Lara, Annamaria Fedeli, Simon Foucambert, Säm Krucker
IEEE TRANSACTIONS ON NUCLEAR SCIENCE **2024**
https://arxiv.org/pdf/2402.03816.pdf

The Spectrometer/Telescope for Imaging X-rays (STIX) is a hard X-ray imaging spectrometer on board the ESA and NASA heliospheric mission Solar Orbiter. STIX has been operational for three years and has observed X-ray emission from ~35,000 solar flares. Throughout its lifetime, Solar Orbiter has been frequently struck by a high flux of energetic particles usually of flare origin, or from coronal mass ejection shocks. These Solar Energetic Particles (SEPs) are detected on board by the purpose-built energetic particle detector instrument suite. During SEP events, the X-ray signal is also contaminated in STIX. This work investigates the effect of these particles on the STIX instrument for two events. The first event occurred during an interplanetary shock crossing and the second event occurred when Solar Orbiter passed through Earth's radiation belts while performing a gravity assist maneuver. The induced spectra consist of tungsten fluorescence emission lines and secondary Bremsstrahlung emission produced by incident particles interacting with spacecraft components. For these two events, we identify > 100 keV electrons as significant contributors to the contamination via Bremsstrahlung emission and tungsten fluorescence. **2021-11-27, July 25th, 2022**

Solar Cosmic Ray Dose Rate Assessments During GLE 72 Using MIRA and PANDOCA

Kyle **Copeland**, Daniel Matthiä, Matthias M. Meier
Space Weather **2018**
http://sci-hub.tw/10.1029/2018SW001917
Ground level enhancement (GLE) 72, which occurred **10 September 2017**, is the most recent of two solar particle-induced enhancements in ground level measurements of cosmic radiation secondary neutrons in solar cycle 24. GLEs have been unusually rare in this solar cycle. GLEs can significantly increase ionizing radiation dose rates at aviation altitudes for hours to days, leading to concern among crewmembers. Real-time monitoring and preliminary evaluation of solar proton events, including GLEs, in regard to effective dose rates at aviation altitudes has been ongoing since the U.S. Federal Aviation Administration began operating its Solar Radiation Alert System (SRAS) in 2002. Since then, SRAS has been revised multiple times. In this report, model calculations of dose rates during GLE 72 from Maps of Ionizing Radiation in the Atmosphere (MIRA), the latest SRAS software based on CARI-7A, are compared with those from the model Professional Aviation Dose Calculator (PANDOCA) developed by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt). At very low cutoff rigidities model calculations agree within 40% and indicate no significant increase in radiation exposures at commercial aviation altitudes. The larger than expected differences at very low cutoff rigidities indicate Geostationary Orbiting Environmental Satellite particle flux data alone that are insufficient to produce consistent solar particle dose estimates.

Very High Energy Solar Energetic Particle Events and Ground Level Enhancement Events: Forecasting and Alerts **Review**

N. **Crosby**, H. Mavromichalaki, O. Malandraki, M. Gerontidou, M. Karavolos, D. Lingri, P. Makrantoni, M. Papailiou, P. Paschalis, A. Tezari
Space Weather Volume22, Issue9 e2023SW003839 **2024**
https://doi.org/10.1029/2023SW003839
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003839
A Ground Level Enhancement (GLE) event can be observed as an increase in the background of ground-based neutron monitor observations and is often associated with an increase of >500 MeV space-based proton flux measurements. GLE events begin as very high-energy SEP events associated with GeV protons. For such events to be detected at sea level, proton energies must exceed about 433 MeV. Since the increased flux of such particles can be a major problem to technology in space and on Earth and pose a threat for human health, developing real time warning systems is of great importance. GLE Alert++ is a product, built by the Athens Cosmic Ray Group of the National and Kapodistrian University of Athens, that issues alerts when a GLE event starts to register and is based on ground-based neutron monitor observations. From the space-based approach, the HESPERIA UMASEP-500 product, jointly developed within the framework of the EU HORIZON2020 HESPERIA project by the Universidad de Malaga, Spain and National Observatory of Athens, Greece, provides forecasts of GLE events and >500 MeV protons relying on GOES satellite Soft X-Ray and high energy proton observations. These two products are fully integrated as federated products on the ESA SWE Portal and are provided as part of the ESA Space Safety Program Space Weather Service Network. In this paper we present how the products were built, provide examples of their outputs as seen on the ESA SWE Portal, and show how the products complement each other and how using them together can in some instances provide more information for users of these services. **14 July 2000, 28 Oct 2003, 10 Sep 2017, 28 Oct 2021**
Table 1 Covering 2000 to 2022, the GLE Event Date, Associated Solar Flare, GLE Alert Plus Onset Time and GLE Alert++ OnsetTime are Listed
Table A1 GLE Event List Based on The NEST Neutron Monitor DataBase (NMDB, https://www.nmdb.eu/nest/)

Galactic Cosmic Rays and Solar Energetic Particles in Cis-Lunar Space: Need for contextual energetic particle measurements at Earth and supporting distributed observations **Review**

Claudio **Corti** , Kathryn Whitman , Ravindra Desai , Jamie Rankin , Du Toit Strauss , Nariaki Nitta , Drew Turner , Thomas Y Chen
White Paper submitted to Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033
2022
https://arxiv.org/ftp/arxiv/papers/2209/2209.03635.pdf
The particle and radiation environment in cis-lunar space is becoming increasingly important as more hardware and human assets occupy various orbits around the Earth and space exploration efforts turn to the Moon and beyond. Since 2020, the total number of satellites in orbit has approximately doubled, highlighting the growing dependence on space-based resources. Through NASA's upcoming Artemis missions, humans will spend more time in cis-lunar space than ever before supported by the expansive infrastructure required for extended missions to the Moon, including a surface habitat, a communications network, and the Lunar Gateway. This paper focuses on galactic cosmic rays (GCRs) and solar energetic

particles (SEPs) that create a dynamic and varying radiation environment within these regions. GCRs are particles of hundreds of MeV/nucleon (MeV/n) and above generated in highly energetic astrophysical environments in the Milky Way Galaxy, such as supernovae and pulsars, and beyond. These particles impinge isotropically on the heliosphere and are filtered down to 1 AU, experiencing modulation in energy and intensity on multiple timescales, from hours to decades, due to the solar magnetic cycle and other transient phenomena. SEPs are particles with energies up to thousands of MeV/n that are accelerated in eruptive events on the Sun and flood the inner heliosphere causing sudden and drastic increases in the particle environment on timescales of minutes to days. This paper highlights a current and prospective future gap in energetic particle measurements in the hundreds of MeV/n. We recommend key observations near Earth to act as a baseline as well as distributed measurements in the heliosphere, magnetosphere, and lunar surface to improve the scientific understanding of these particle populations and sources.

SEPEM: A tool for statistical modeling the solar energetic particle environment

Norma **Crosby**, Daniel Heynderickx, Piers Jiggens, et al.

Space Weather, Volume 13, Issue 7 July **2015** Pages 406–426

Solar energetic particle (SEP) events are a serious radiation hazard for spacecraft as well as a severe health risk to humans traveling in space. Indeed, accurate modeling of the SEP environment constitutes a priority requirement for astrophysics and solar system missions and for human exploration in space. The European Space Agency's Solar Energetic Particle Environment Modelling (SEPEM) application server is a World Wide Web interface to a complete set of cross-calibrated data ranging from 1973 to 2013 as well as new SEP engineering models and tools. Both statistical and physical modeling techniques have been included, in order to cover the environment not only at 1 AU but also in the inner heliosphere ranging from 0.2 AU to 1.6 AU using a newly developed physics-based shock-and-particle model to simulate particle flux profiles of gradual SEP events. With SEPEM, SEP peak flux and integrated fluence statistics can be studied, as well as durations of high SEP flux periods. Furthermore, effects tools are also included to allow calculation of single event upset rate and radiation doses for a variety of engineering scenarios.

Observations of Kappa Distributions in Solar Energetic Protons and Derived Thermodynamic Properties

M. E. **Cuesta**, A. T. Cummings, G. Livadiotis, D. J. McComas, C. M. S. Cohen, L. Y. Khoo, T. Sharma, M. M. Shen, R. Bandyopadhyay, J. S. Rankin, J. R. Szalay, H. A. Farooki, Z. Xu, G. D. Muro, M. L. Stevens, S. D. Bale

2024 *ApJ* **973** 76

https://arxiv.org/pdf/2407.20343

https://iopscience.iop.org/article/10.3847/1538-4357/ad68fd/pdf

In this paper we model the high-energy tail of observed solar energetic proton energy distributions with a kappa distribution function. We employ a technique for deriving the thermodynamic parameters of solar energetic proton populations measured by the Parker Solar Probe (PSP) Integrated Science Investigation of the Sun (IS⊙IS) EPI-Hi high energy telescope (HET), over energies from 10 - 60 MeV. With this technique we explore, for the first time, the characteristic thermodynamic properties of the solar energetic protons associated with an interplanetary coronal mass ejection (ICME) and its driven shock. We find that (1) the spectral index, or equivalently, the thermodynamic parameter kappa of solar energetic protons (κ_{EP}) gradually increases starting from the pre-ICME region (upstream of the CME-driven shock), reaching a maximum in the CME ejecta ($\kappa_{EP} \approx 3.5$), followed by a gradual decrease throughout the trailing portion of the CME; (2) solar energetic proton temperature and density (T_{EP} and n_{EP}) appear anti-correlated, a behavior consistent to sub-isothermal polytropic processes; and (3) values of T_{EP} and κ_{EP} appear are positively correlated, indicating an increasing entropy with time. Therefore, these proton populations are characterized by a complex and evolving thermodynamic behavior, consisting of multiple sub-isothermal polytropic processes, and a large-scale trend of increasing temperature, kappa, and entropy. This study and its companion study by Livadiotis et al. (2024) open a new set of procedures for investigating the thermodynamic behavior of energetic particles and their shared thermal properties. **15 Feb 2022**

Correlation of Coronal Mass Ejection Shock Temperature with Solar Energetic Particle Intensity

Manuel Enrique **Cuesta**, D. J. McComas, L. Y. Khoo, R. Bandyopadhyay, T. Sharma, +++

ApJ **964** 114 **2024**

https://arxiv.org/pdf/2402.00210.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ad245d/pdf

Solar energetic particle (SEP) events have been observed by the Parker Solar Probe (PSP) spacecraft since its launch in 2018. These events include sources from solar flares and coronal mass ejections (CMEs). Onboard PSP is the IS\(\odot\)IS instrument suite measuring ions over energies from ~ 20 keV/nucleon to 200 MeV/nucleon and electrons from ~ 20 keV to 6 MeV. Previous studies sought to group CME characteristics based on their plasma conditions and arrived at general descriptions with large statistical errors, leaving open questions on how to properly group CMEs based solely on their plasma conditions. To help resolve these open questions, plasma properties of CMEs have been examined in relation to SEPs. Here we reexamine one plasma property, the solar wind proton temperature, and compare it to the proton SEP intensity in a region immediately downstream of a CME-driven shock for seven CMEs observed at radial distances within 1 au. We find a statistically strong correlation between proton SEP intensity and bulk proton temperature, indicating a clear relationship between SEPs and the conditions in the solar wind. Furthermore, we propose that an indirect coupling of SEP intensity to the level of turbulence and the amount of energy dissipation that results is mainly responsible for the observed correlation between SEP intensity and proton temperature. These results are key to understanding the interaction of SEPs with the bulk solar wind in CME-driven shocks and will improve our ability to model the interplay of shock evolution and particle acceleration. **29 Nov 2020, 28 May 2021, 15-16 Feb 2022, 21 Mar 2022, 9 Jul 2022, 28 Aug 2022, 3 Jan 2023**

Solar and Galactic Cosmic Rays observed by SOHO

Werner **Curdt**, Bernhard Fleck

Cent. Eur. Astrophys. Bull **2015**

http://arxiv.org/pdf/1505.07952v1.pdf

Both the Cosmic Ray Flux (CRF) and Solar Energetic Particles (SEPs) have left an imprint on SOHO technical systems. While the solar array efficiency degraded irreversibly down to ~77% of its original level over roughly 1 1/2 solar cycles, Single Event Upsets (SEUs) in the solid state recorder (SSR) have been reversed by the memory protection mechanism. We compare the daily CRF observed by the Oulu station with the daily SOHO SEU rate and with the Degradation curve of the solar arrays. The Oulu CRF and the SOHO SSR SEU rate are both modulated by the solar cycle and are highly correlated, except for sharp spikes in the SEU rate, caused by isolated SEP events, which also show up as discontinuities in the otherwise slowly decreasing solar ray efficiency. This allows to discriminate between effects with solar and non-solar origin and to compare the relative strength of both. We find that during solar cycle 23 (1996 Apr 1 -- 2008 Aug 31) only 6% of the total number of SSR SEUs were caused by SEPs; the remaining 94% were due to galactic cosmic rays. During the maximum period of cycle 23 (2000 Jan 1 -- 2003 Dec 31), the SEP contribution increased to 22%, and during 2001, the year with the highest SEP rate, to 30%. About 40% of the total solar array degradation during the 17 years from Jan 1996 through Feb 2013 can be attributed to proton events, i.e. the effect of a series of short-lived, violent SEP events is comparable to the cycle-integrated damage by cosmic rays.

Solar energetic particle warnings from a coronagraph

O. C. St. **Cyr**, A. Posner, J. T. Burkepile

Space Weather Volume 15, Issue 1 January **2017** Pages 240–257 **File**

http://sci-hub.cc/10.1002/2016SW001545

We report here the concept of using near-real time observations from a coronagraph to provide early warning of a fast coronal mass ejection (CME) and the possible onset of a solar energetic particle (SEP) event. The **1 January 2016**, fast CME, and its associated SEP event are cited as an example. The CME was detected by the ground-based K-Cor coronagraph at Mauna Loa Solar Observatory and by the SOHO Large Angle and Spectrometric Coronagraph. The near-real-time availability of the high-cadence K-Cor observations in the low corona leads to an obvious question: "Why has no one attempted to use a coronagraph as an early warning device for SEP events?" The answer is that the low image cadence and the long latency of existing spaceborne coronagraphs make them valid for archival studies but typically unsuitable for near-real-time forecasting. The January 2016 event provided favorable CME viewing geometry and demonstrated that the primary component of a prototype ground-based system for SEP warnings is available several hours on most days. We discuss how a conceptual CME-based warning system relates to other techniques, including an estimate of the relative SEP warning times, and how such a system might be realized.

2. Existing SEP Forecasting Techniques

Forecasting Shock-associated Energetic Particle Intensities in the Inner Heliosphere: A Proof-of-Concept Capability for the PUNCH Mission

Maher A. **Dayeh**, Michael J. Starkey, Heather A. Elliott, Raphael Attie, Craig E. DeForest, Radoslav Bučik, Mihir I. Desai

Solar Phys. **2024**

https://arxiv.org/pdf/2411.16510

Solar energetic particles (SEPs) associated with shocks driven by fast coronal mass ejections (CMEs) or shocks developed by corotating interaction regions (CIRs) often extend to high energies, and are thus key elements of space weather. The PUNCH mission, set to be launched in 2025, is equipped with photometric that enables 3D tracking of solar wind structures in the interplanetary space through polarized light. Tracking techniques are used to estimate speeds and speed gradients of solar structures, including speed jumps at fast shocks. We report on a strong and a robust relation between the shock speed jump magnitude at CME and CIR shocks and the peak fluxes of associated energetic particles from the analysis of 59 CME-driven shocks and 74 CIRs observed by Wind/STEP between 1997-2023. We demonstrate that this relation, along with PUNCH anticipated observations of solar structures can be used to forecast shock-associated particle events close to the Sun; thus, advancing and providing a crucial input to forecasting of SEP fluxes in the heliosphere. **2014-04-14**

Solar energetic particle events from solar flares with weak impulsive phases of microwave emission. –

Daibog E.I., Melnikov V.F., Stolpovskii V.G..

Solar Physics, **1993**, V.144, pp.361-372., **File**

In some solar energetic particle events relatively intense proton fluxes are accompanied by disproportionately weak intensity of/z-burst. A possible reason for such a situation is discussed in this paper. We use the idea that the dynamics of particles in flare loops strongly influences the efficiency of their escape into interplanetary space. It is proposed that in events with weak impulsive phase flare loops are large sized and stretched high into the corona, the magnetic field is weak, and the level of excited turbulence is rather low. All this leads to the weak diffusion of protons into the loss cone, a large lifetime of a particle in the loop (~ 103 s) and, hence, to the relatively high efficiency of their escape into interplanetary space.

Microwave bursts and the relative abundance of electrons and protons in cosmic-rays from solar flares.

Daibog, E.I., Stolpovskii, V.G., Melnikov, V.F., Podstrigach, T.S.:

1989, Soviet Astron. Lett. 15, 432 – 436.

Solar cosmic ray events with low and high p-ratios: comparison with X-ray and radio emission data.

Daibog, E.I., Kurt, V.G., Logachev, Y.I., Stolpovsky, V.G.:

1987, In: Proc. 20th Int. Cosmic Ray Conf. 3, 45 – 48.

Detection asymmetry in solar energetic particle events

S. **Dalla**, A. Hutchinson, R.A. Hyndman, K. Kihara, N. Nitta, L. Rodriguez-Garcia, T. Laitinen, C.O.G. Waterfall, D.S. Brown

A&A **2024**

https://arxiv.org/pdf/2411.08211

Context. Solar energetic particles (SEPs) are detected in interplanetary space in association with flares and coronal mass ejections (CMEs) at the Sun. The magnetic connection between the observing spacecraft and the solar active region (AR) source of the event is a key parameter in determining whether SEPs are observed and the properties of the particle event. Aims. We investigate whether an east-west asymmetry in the detection of SEP events is present in observations and discuss its possible link to corotation of magnetic flux tubes with the Sun. Methods. We used a published dataset of 239 CMEs recorded between 2006 and 2017 and having source regions both on the front side and far side of the Sun as seen from Earth. We produced distributions of occurrence of in-situ SEP intensity enhancements associated with the CME events, versus \Delta \phi, the separation in longitude between the source active region and the magnetic footpoint of the observing spacecraft based on the nominal Parker spiral. We focused on protons of energy >10 MeV measured by the STEREO A, STEREO B and GOES spacecraft at 1 au. We also considered the occurrence of 71-112 keV electron events detected by MESSENGER between 0.31 and 0.47 au. Results. We find an east-west asymmetry in the detection of >10 MeV proton events and of 71-112 keV electron events. For protons, observers for which the source AR is on the east side of the spacecraft footpoint and not well connected (-180 < \Delta \phi < -40) are 93% more likely to detect an SEP event compared to observers with +40 < \Delta \phi < +180. The asymmetry may be a signature of corotation of magnetic flux tubes with the Sun, given that for events with \Delta \phi < 0 corotation sweeps the particle-filled flux tubes towards the observing spacecraft, while for \Delta \phi > 0 it takes them away from it.

3D propagation of relativistic solar protons through interplanetary space

S. **Dalla**, G. De Nolfo, A. Bruno, J. Giacalone, T. Laitinen, S. Thomas, M. Battarbee, M.S. Marsh

A&A **639**, A105 **2020**

https://arxiv.org/pdf/2002.00929.pdf

https://www.aanda.org/articles/aa/pdf/2020/07/aa37338-19.pdf

Context. Solar Energetic Particles (SEPs) with energy in the GeV range can propagate to Earth from their acceleration region near the Sun and produce Ground Level Enhancements (GLEs). The traditional approach to interpreting and modelling GLE observations assumes particle propagation only parallel to the magnetic field lines of interplanetary space, i.e. it is spatially 1D. Recent measurements by PAMELA have characterised SEP properties at 1 AU for the ~100 MeV-1 GeV range at high spectral resolution. Aims. We model the transport of GLE-energy solar protons through the Interplanetary Magnetic Field (IMF) using a 3D approach, to assess the effect of the Heliospheric Current Sheet (HCS) and drifts associated to the gradient and curvature of the Parker spiral. The latter are influenced by the IMF polarity. We derive 1 AU observables and compare the simulation results with data from PAMELA. Methods. We use a 3D test particle model including a HCS. Monoenergetic populations are studied first to obtain a qualitative picture of propagation patterns and numbers of crossings of the 1 AU sphere. Simulations for power law injection are used to derive intensity profiles and fluence spectra at 1 AU. A simulation for a specific event, GLE 71, is used to compare with PAMELA data. Results. Spatial patterns of 1 AU crossings and the average number of crossings are strongly influenced by 3D effects, with significant differences between periods of A+ and A- polarities. The decay time constant of 1 AU intensity profiles varies depending on the polarity and position of the observer, and it is not a simple function of the mean free path as in 1D models. Energy dependent leakage from the injection flux tube is particularly important for GLE energy particles, in many cases resulting in a roll-over in the fluence spectrum. **May 17th, 2012**

Solar and Heliospheric Physics **Review**

Silvia **Dalla**
36th ICRC **2019**, id. 027
https://pos.sissa.it/358/027/pdf

This rapporteur report summarises contributions to the SH sessions at the 36th ICRC. Topics include energetic particles accelerated at/near the Sun and in interplanetary space, anomalous cosmic rays and galactic cosmic rays within the heliosphere. A review is presented of the main new findings in observational, theoretical and computational work on solar and heliospheric particle populations, their acceleration, transport and effects on the near-Earth environment. Finally future missions and new proposed instrumentation are discussed. **2012 May 17, 4-14 Sep 2017**

Solar Energetic Particle drifts and the energy dependence of 1 AU charge states

S. **Dalla**, M.S. Marsh, M. Battarbee
ApJ **834** 167 **2017**
https://arxiv.org/pdf/1610.05104v1.pdf
The event-averaged charge state of heavy ion Solar Energetic Particles (SEPs), measured at 1 AU from the Sun, typically increases with the ions' kinetic energy. The origin of this behaviour has been ascribed to processes taking place within the acceleration region. In this paper we study the propagation through interplanetary space of SEP Fe ions, injected near the Sun with a variety of charge states that are uniformly distributed in energy, by means of a 3D test particle model. In our simulations, due to gradient and curvature drifts associated with the Parker spiral magnetic field, ions of different charge propagate with very different efficiencies to an observer that is not magnetically well connected to the source region. As a result we find that, for many observer locations, the 1 AU event-averaged charge state <Q>, as obtained from our model, displays an increase with particle energy E, in qualitative agreement with spacecraft observations. We conclude that drift-associated propagation is a possible explanation for the observed distribution of <Q> versus E in SEP events, and that the distribution measured in interplanetary space cannot be taken to represent that at injection.

Time dependence of Fe/O ratio within a 3D Solar Energetic Particle propagation model including drift

S. **Dalla**, M.S. Marsh, P. Zelina, T. Laitinen
A&A 598, A73 **2017**
http://arxiv.org/pdf/1606.05612v1.pdf
Context. The intensity profiles of iron and oxygen in Solar Energetic Particle (SEP) events often display differences that result in a decreasing Fe/O ratio over time. The physical mechanisms behind this behaviour are not fully understood, but these observational signatures provide important tests of physical modelling efforts. Aims. In this paper we study the propagation of iron and oxygen SEP ions using a 3D model of propagation which includes the effect of guiding centre drift in a Parker spiral magnetic field. We derive time intensity profiles for a variety of observer locations and study the temporal evolution of the Fe/O ratio. Methods. We use a 3D full orbit test particle model which includes scattering. The configuration of the interplanetary magnetic field is a unipolar Parker spiral. Particles are released instantaneously from a compact region at 2 solar radii and allowed to propagate in 3D. Results. Both Fe and O experience significant transport across the magnetic field due to gradient and curvature drifts. We find that Fe ions drift more than O ions due to their larger mass-to-charge ratio, so that an observer that is not

magnetically well connected to the source region will observe Fe arriving before O, for particles within the same range in energy per nucleon. As a result, for the majority of observer locations, the Fe/O ratio displays a decrease in time. Conclusions. We conclude that propagation effects associated with drifts produce a decay over time of the Fe/O ratio, qualitatively reproducing that observed in SEP event profiles.

Drift-induced deceleration of Solar Energetic Particles

S. **Dalla**, M.S. Marsh, T. Laitinen
2015 *ApJ* **808** 62
http://arxiv.org/pdf/1506.04015v1.pdf
We investigate the deceleration of Solar Energetic Particles (SEPs) during their propagation from the Sun through interplanetary space, in the presence of weak to strong scattering in a Parker spiral configuration, using relativistic full orbit test particle simulations. The calculations retain all three spatial variables describing particles' trajectories, allowing to model any transport across the magnetic field. Large energy change is shown to occur for protons, due to the combined effect of standard adiabatic deceleration and a significant contribution from particle drift in the direction opposite to that of the solar wind electric field. The latter drift-induced deceleration is found to have a stronger effect for SEP energies than for galactic cosmic rays. The kinetic energy of protons injected at 1 MeV is found to be reduced by between 35 and 90% after four days, and for protons injected at 100 MeV by between 20 and 55%. The overall degree of deceleration is a weak function of the scattering mean free path, showing that, although adiabatic deceleration plays a role, a large contribution is due to particle drift. Current SEP transport models are found to account for drift-induced deceleration in an approximate way and their accuracy will need to be assessed in future work.

Solar Energetic Particle drifts in the Parker spiral

S. **Dalla**, M.S. Marsh, J. Kelly, T. Laitinen
E-print, July **2013**, JGR
Drifts in the Parker spiral interplanetary magnetic field are known to be an important component in the propagation of galactic cosmic rays, while they are thought to be negligible for Solar Energetic Particles (SEPs). As a result they have so far been ignored in SEP propagation modelling and data analysis. We examine drift velocities in the Parker spiral within single particle first-order adiabatic theory, in a local coordinate system with an axis parallel to the magnetic field. We show that, in the presence of scattering in interplanetary space, protons at the high end of the SEP energy range experience significant gradient and curvature drift. In the scatter-free case, drift due to magnetic field curvature is present. The magnitude of drift velocity increases by more than an order of magnitude at high heliographic latitudes compared to near the ecliptic; it has a strong dependence on radial distance r from the Sun, reaching a maximum at r~1 AU at low heliolatitudes and r~10 AU at high heliolatitudes. Due to the mass over charge dependence of drift velocities, the effect of drift for partially ionised SEP heavy ions is stronger than for protons. Drift is therefore likely to be a considerable source of cross field transport for high energy SEPs.

Role of latitude of source region in Solar Energetic Particle events,

Dalla, S., Agueda, N.
2010, in SOLAR WIND TEN. AIP Conference Proceedings, Volume 679, pp. 613-616

Properties of high heliolatitude solar energetic particle events and constraints on models of acceleration and propagation

S. **Dalla**, A. Balogh, S. Krucker, A. Posner, R. Müller-Mellin, J. D. Anglin, M. Y. Hofer, R. G. Marsden, T. R. Sanderson, C. Tranquille, B. Heber, M. Zhang, R. B. McKibben
Geophysical Research Letters VOL. 30, NO. 19, 8035, **2003**
https://doi.org/10.1029/2003GL017139
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2003GL017139
We analyse 9 large solar energetic particle (SEP) events detected by the Ulysses spacecraft at high heliolatitudes during the recent solar maximum polar passes. Properties of time intensity profiles from the Ulysses/COSPIN instrument are compared with those measured by SOHO/COSTEP and Wind/3DP near Earth. We find that onset times and times to maximum at high latitude are delayed compared to in-ecliptic values. We show that the parameter which best orders these characteristics of time profiles is the difference in latitude between the associated flare and the spacecraft. We find that the presence of a shock is not necessary for the establishing of near equal intensities at Ulysses and in the ecliptic during the decay phase. ***The model of SEP acceleration by coronal mass ejection driven shocks does not appear to account for our observations, which would more easily be explained by particle diffusion across the interplanetary magnetic field.*** **15 Aug 2001**

Table 1. SEP Events at High Latitudes 2000-2002

MEMPSEP II. -- Forecasting the Properties of Solar Energetic Particle Events using a Multivariate Ensemble Approach

Maher A. **Dayeh**, Subhamoy Chatterjee, Andres Munoz-Jaramillo, Kimberly Moreland, Hazel M. Bain, Samuel Hart

Space Weather **Volume22, Issue9** September 2024 e2023SW003697
https://arxiv.org/ftp/arxiv/papers/2309/2309.14503.pdf
https://doi.org/10.1029/2023SW003697
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003697

Solar Energetic Particles (SEPs) form a critical component of Space Weather. The complex, intertwined dynamics of SEP sources, acceleration, and transport make their forecasting very challenging. Yet, information about SEP arrival and their properties (e.g., peak flux) is crucial for space exploration on many fronts. We have recently introduced a novel probabilistic ensemble model called the Multivariate Ensemble of Models for Probabilistic Forecast of Solar Energetic Particles (MEMPSEP). Its primary aim is to forecast the occurrence and physical properties of SEPs. The occurrence forecasting, thoroughly discussed in a preceding paper (Chatterjee et al., 2023), is complemented by the work presented here, which focuses on forecasting the physical properties of SEPs. The MEMPSEP model relies on an ensemble of Convolutional Neural Networks, which leverage a multi-variate dataset comprising full-disc magnetogram sequences and numerous derived and in-situ data from various sources. Skill scores demonstrate that MEMPSEP exhibits improved predictions on SEP properties for the test set data with SEP occurrence probability above 50%, compared to those with a probability below 50%. Results present a promising approach to address the challenging task of forecasting SEP physical properties, thus improving our forecasting capabilities and advancing our understanding of the dominant parameters and processes that govern SEP production.

Modeling proton intensity gradients and radiation dose equivalents in the inner heliosphere using EMMREM: May 2003 solar events,

Dayeh, M. A., M. I. Desai, K. Kozarev, N. A. Schwadron, L. W. Townsend, M. PourArsalan, C. Zeitlin, and R. B. Hatcher

(**2010**), Space Weather, 8, S00E07, doi:10.1029/2009SW000566.

Solar energetic particles (SEPs) provide a significant radiation hazard for manned and unmanned interplanetary (IP) space missions. In order to estimate these hazards, it is essential to quantify the gradients of SEP intensities in the IP medium. The Earth-Moon-Mars Radiation Exposure Module (EMMREM) is a new project aimed at characterizing the time-dependent radiation exposure in IP space. In this paper, we utilize EMMREM to study the radial dependence of proton peak intensities, event fluences, and radiation dose equivalents of 27–31 May 2003 SEP events at eight different locations between 1 and 4.91 AU at energies between ~1.5 MeV and ~130 MeV. We have modeled onset times and intensity profiles of the SEP events at Mars and Ulysses and found very good agreement at different energies. We report observations of energetic particles at locations with magnetic field line footprints that are separated by ~90° in heliolongitude, possibly indicating very large coronal mass ejection sizes and/or high cross-field diffusion at large radial distances. Our results show that radial dependencies of proton peak intensities exhibit a broken power law between 1 to 2.5 AU and 2.5 to 4.91 AU, ranging between $R^{-2.52 \pm 0.42}$ and $R^{-5.97 \pm 0.32}$ for 25 MeV and between $R^{-2.13 \pm 0.36}$ and $R^{-5.21 \pm 0.29}$ for 52 MeV, where R is the radial distance from the Sun in units of AU. Event fluences exhibit a similar behavior but with a harder spectra. Radiation dose calculations show that these events did not pose a short-term radiation hazard to humans in the IP space.

The Solar Eruption of 2017 September 10: Wavy with a Chance of Protons

Curt A. **de Koning**[1,2], V. J. Pizzo[2], and Daniel B. Seaton[1,3]

2022 ApJ 924 106 **File**
https://iopscience.iop.org/article/10.3847/1538-4357/ac374d/pdf

High-resolution SUVI images reveal an interesting new picture of particle acceleration in powerful solar eruptions. Typically, powerful solar eruptions include a coronal wave component, as well the traditional CME and flare components. At low solar altitudes, coronal waves refract downward, toward the solar surface, because of the slower Alfvén speeds at the base of the corona. The refracted wave plus the shock wave ahead of an intense CME allow for a two-step shock acceleration process that can result in relativistic or GLE particles. This mechanism may be particularly applicable to the first-to-arrive, prompt relativistic particles measured by the Fort Smith neutron monitor during GLE # 72 on **2017 September 10**.

A good Review in Introduction

Long Duration Gamma-ray Flares and High Energy Solar Energetic Particles: Is there a Connection?

G.A. **de Nolfo**∗1 , A. Bruno1 , J.M. Ryan2 , S. Dalla3 , J. Giacalone4 , I.G. Richardson1,5 , E.R. Christian1 , On Behalf of the PAMELA Collaboration

36th International Cosmic Ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A. id. 1073

https://pos.sissa.it/358/1073/pdf

Long Duration Gamma-Ray Flares (LDGRFs) are characterized by delayed and long-duration gamma-ray emission above ∼50 MeV. Despite dozens of observations in the last decade with Fermi/LAT, the nature of this emission has been a challenge to explain. The highest energy emission has generally been attributed to the decay of pions produced by the interaction of highenergy protons with ambient solar material. The fact that the γ-ray emission is delayed from the onset of the initial eruption and that the emission is, in some cases, unusually long in duration suggests that particle acceleration occurs within large volumes extending to high altitudes, either by stochastic acceleration within large coronal loops or by back-precipitation from CME-driven shocks. We have tested these models by a making direct comparisons between the properties of the accelerated ion population at the flare derived from the observations of Fermi/LAT and those of solar energetic particles detected at Earth by PAMELA at comparable high energies. We investigated 27 high-energy gamma ray events (from [1]), and for 14 events we compare the two populations (SEPs in space and the interacting population at the Sun) and discuss the implications in terms of potential sources of the LDGRFs.

Table 1: List of SEP events with a proton signal in excess of 500 MeV, associated with LDGRF detected by Fermi/LAT above 100 MeV between 2008 August and 2014 September.

G. A. **de Nolfo**, A. Bruno, J. M. Ryan, S. Dalla, J. Giacalone, I. G. Richardson, E. R. Christian, S. J. Stochaj, G. A. Bazilevskaya, M. Boezio, M. Martucci, V. V. Mikhailov, R. Munini

ApJ **879** 90 **2019**

https://arxiv.org/pdf/1905.12878.pdf **File**

sci-hub.se/10.3847/1538-4357/ab258f

Little is known about the origin of the high-energy and sustained emission from solar Long-Duration Gamma-Ray Flares (LDGRFs), identified with the Compton Gamma Ray Observatory (CGRO), the Solar Maximum Mission (SMM), and now Fermi. Though Fermi/Large Area Space Telescope (LAT) has identified dozens of flares with LDGRF signature, the nature of this phenomenon has been a challenge to explain both due to the extreme energies and long durations. The highest-energy emission has generally been attributed to pion production from the interaction of >300 MeV protons with the ambient matter. The extended duration suggests that particle acceleration occurs over large volumes extending high in the corona, either from stochastic acceleration within large coronal loops or from back precipitation from coronal mass ejection driven shocks. It is possible to test these models by making direct comparison between the properties of the accelerated ion population producing the gamma-ray emission derived from the Fermi/LAT observations, and the characteristics of solar energetic particles (SEPs) measured by the Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics (PAMELA) spacecraft in the energy range corresponding to the pion-related emission detected with Fermi. For fourteen of these events we compare the two populations -- SEPs in space and the interacting particles at the Sun -- and discuss the implications in terms of potential sources. Our analysis shows that the two proton numbers are poorly correlated, with their ratio spanning more than five orders of magnitude, suggesting that the back precipitation of shock-acceleration particles is unlikely the source of the LDGRF emission. **2011 03/07, 2011 06/07, 2011 08/04, 2011 08/09, 2011 09/06, 2012 01/23, 2012 01/27, 2012 03/07 , 2012 March 13, 2012 05/17 , 2012 07/07 , 2012 July 8, 2013 04/11, 2013 05/13, 2013 05/15, 2013 10/28, 2014 01/06, 2014 01/07, 2014 02/25, 2014 09/01, 2014 09/10, 2015 06/21, 2015 06/25, 2017 09/06, 2017 09/10**

2011/06/02, 2011 09/07, 2011/09/24, 2012 03/05, 2012 06/03, 2012 06/03, 2012 11/27,, 2013 05/14, 2013 10/11, 2013 10/25

Table 1. List of SEP events with an associated LDGRF detected by Fermi/LAT above 100 MeV between 2008 August and 2017 September, based on (Share et al. 2018; Winter et al. 2018)

Table 2. List of LDGRFs detected by Fermi/LAT (Share et al. 2018), without a clearly observed associated SEP event at near-earth spacecraft.

Large gradual solar energetic particle events **Review**

Mihir **Desai**, Joe Giacalone

Living Reviews in Solar Physics, December **2016**, 13:3

http://solarphysics.livingreviews.org/

https://link.springer.com/content/pdf/10.1007%2Fs41116-016-0002-5.pdf

Solar energetic particles, or SEPs, from suprathermal (few keV) up to relativistic (∼few GeV) energies are accelerated near the Sun in at least two ways: (1) by magnetic reconnection-driven processes during solar flares resulting in impulsive SEPs, and (2) at fast coronal-mass-ejection-driven shock waves that produce large gradual SEP events. Large gradual SEP events are of particular interest because the accompanying high-energy (>10s MeV) protons pose serious radiation threats to human explorers living and working beyond low-Earth orbit and to technological assets such as communications and scientific satellites in space. However, a complete understanding of these large SEP events has eluded us primarily because their properties, as observed in Earth orbit, are smeared due to mixing and contributions from many important physical effects. This paper provides a comprehensive review of the current state of knowledge of these important phenomena, and summarizes some of the key questions that will be addressed by two upcoming missions—NASA's Solar Probe Plus and ESA's Solar Orbiter. Both of these missions are designed to directly and repeatedly sample the near-Sun environments where interplanetary scattering and transport effects are significantly reduced, allowing us to discriminate between different acceleration sites and mechanisms and to isolate the contributions of numerous physical processes occurring during large SEP events. **28-29 May 1980, 5 Dec 1981, 7 March 1982, 14 Aug 1982, 25-29 Dec 1982, 6 Nov 1997, 21-22 Apr 1998, 2 May 1998, 6 May 1998, 6 Aug 1998, 26 Aug 1998, 9-11 Jan 1999, 18 Feb 1999, 4 June 1999, 22-28 1999, 1 May 2000, 14 July 2000, 14 Apr 2001, 15 Apr 2001, 21 Apr 2001, 24 Sept 2001, 4-6 Nov 2001, 26 Dec 2001, 28 Oct 2003, 29 Oct 2003, 17 Jan 2005, 20 Jan 2005, 5 Dec 2006, 7-9 Feb 2010, April 03-04, 2010, 6 Sept 2011, 23-24 July 2012**

Spectral properties of large gradual solar energetic particle events – II -Systematic Q/M-dependence of heavy ion spectral breaks

M. I. **Desai**, G. M. Mason, M. A. Dayeh, R. W. Ebert, D. J. McComas, G. Li, C. M. S. Cohen, R. A. Mewaldt, N. A. Schwadron, C. W. Smith

ApJ **828** 106 **2016**

http://arxiv.org/pdf/1605.03922v1.pdf

We fit the ~0.1-500 MeV/nucleon H-Fe spectra in 46 large SEP events surveyed by Desai et al. (2016) with the double power-law Band function to obtain a normalization constant, low- and high-energy parameters γa and γb; and break energy EB. We also calculate the low-energy power-law spectral slope $\gamma 1$. We find that: 1) γa, $\gamma 1$, and γb are species-independent within a given SEP event, and the spectra steepen with increasing energy; 2) EB's are well ordered by Q/M ratio, and decrease systematically with decreasing Q/M, scaling as $(Q/M)\alpha$ with α varying between ~0.2-3; 3) α is well correlated with Fe/O at ~0.16-0.23 MeV/nucleon and CME speed; 4) In most events: $\alpha<1.4$, the spectra steepen significantly at higher energy with γb-$\gamma a>3$; and 5) Seven out of 9 extreme SEP events (associated with faster CMEs and GLEs) are Fe-rich, have $\alpha>1.4$, have flatter spectra at low and high energies with γb-$\gamma a<3$. The species-independence of γa, $\gamma 1$, and γb and the systematic Q/M dependence of EB within an event, as well as the range of values for α suggest that the formation of double power-laws in SEP events occurs primarily due to diffusive acceleration at near-Sun CME shocks and not due to scattering in the interplanetary turbulence. In most events, the Q/M-dependence of EB is consistent with the equal diffusion coefficient condition while the event-to-event variations in α are probably driven by differences in the near-shock wave intensity spectra, which are flatter than the Kolmogorov turbulence spectrum but still weaker compared to that inferred for the extreme events.

Table 2: Sampling intervals, spectral indices γa, γb and break energies *EB* from the Band function fits for H, O & Fe, and power-law exponent, α of the Break energies vs. Q/M for 46 SEP events in this survey.

SPECTRAL PROPERTIES OF LARGE GRADUAL SOLAR ENERGETIC PARTICLE EVENTS. I. FE, O, AND SEED MATERIAL

M. I. **Desai**1,2, G. M. Mason3, M. A. Dayeh1, R. W. Ebert1, D. J. Mccomas1,2, G. Li4, C. M. S. Cohen5,R. A. Mewaldt5, N. A. Schwadron1,6, and C. W. Smith

2016 ApJ 816 68

We have surveyed ~0.1–100 MeV nucleon^{-1} O and Fe fluence spectra during 46 isolated, large gradual SEP events observed at ACE during solar cycles 23 and 24. Most SEP spectra are well represented by the four-parameter Band function with a normalization constant, low-energy spectral slope, high-energy spectral slope, and break energy. The O and Fe spectral slopes are similar and most spectra steepen above the break energy, probably due to common acceleration and transport processes affecting different ion species. SEP spectra above the break energies depend on the origin of the seed population; larger contributions of suprathermal flare material result in higher Fe/O ratios and flatter spectra at higher energies. SEP events with steeper O spectra at low energies and higher break energies are associated with slower coronal mass ejections (CMEs), while those associated with fast (>2000 km s^{-1}) CMEs and ground level enhancements have harder or flatter spectra at low and high energies, and O break energies between ~1 and 10 MeV nucleon^{-1}. The latter events are enriched in 3He and higher-energy Fe, and have Fe spectra that rollover at significantly lower energies compared with O, probably because Fe ions with smaller Q/M ratios can escape from the distant shock more easily than O ions with larger Q/M ratios. We conclude that SEP spectral properties result from many complex and competing effects, namely Q/M-dependent scattering, shock properties, and the origin of the seed populations, all of which must be taken into account to develop a comprehensive picture of CME-driven shock acceleration of large gradual SEP events.

Particle acceleration at coronal mass ejection driven interplanetary shocks and the Earth's bow shock,

Desai, M. I., and D. Burgess,

J. Geophys. Res., 113, A00B06, (**2008**)

http://dx.doi.org/10.1029/2008JA013219

Particle acceleration in space plasmas, particularly at collisionless shocks, remains a fundamental yet poorly understood problem in space physics. The most important questions that need to be addressed include (1) where are the particles accelerated, (2) what source material is available for acceleration, (3) what mechanisms are responsible for injecting and accelerating the particles, and (4) how are the particle properties modified during their propagation from the acceleration sites to the observation point? Answering these questions will enable further development of the theoretical framework and models that will facilitate quantitative predictions of key properties of the accelerated particles. In this paper, **we review recent observations associated with two distinct but widely studied energetic ion populations: (1) solar energetic particles associated with coronal mass ejection–driven interplanetary shocks** and (2) energetic ions observed upstream of the Earth's bow shock. We review the common theoretical concepts and physical processes that are believed to be responsible for accelerating particles at these two types of collisionless shocks, emphasizing the commonalities between these distinct structures and their associated particle populations.

Heavy-Ion Elemental Abundances in Large Solar Energetic Particle Events and Their Implications for the Seed Population

M. I. **Desai**, G. M. Mason, R. E. Gold, S. M. Krimigis, C. M. S. Cohen, R. A. Mewaldt, J. E. Mazur, and J. R. Dwyer

The Astrophysical Journal, 649:470-489, 2006

THE SEED POPULATION FOR ENERGETIC PARTICLES ACCELERATED BY CME-DRIVEN SHOCKS

M. I. **DESAI**[1,*], G. M. MASON[2], J. E. MAZUR[3] and J. R. DWYER[4]

Space Science Reviews (2006) 124: 261–275

Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events

M. **Dierckxsens**, K. Tziotziou, S. Dalla, I. Patsou, M. S. Marsh, N. B. Crosby, O. Malandraki, G. Tsiropoula

Solar Phys. March **2015**, Volume 290, Issue 3, pp 841–874

https://arxiv.org/pdf/1410.6070v2.pdf **File**

https://link.springer.com/content/pdf/10.1007%2Fs11207-014-0641-4.pdf

A statistical analysis of the relationship between solar energetic particles (SEPs) and properties of solar flares and coronal mass ejections (CMEs) is presented. SEP events during solar cycle 23 are selected which are associated with solar flares originating on the visible hemisphere of the Sun and at least of magnitude M1. Taking into account all flares and CMEs that occurred during this period, the probability for the occurrence of an SEP event near Earth is determined. A strong rise of this probability is observed for increasing flare intensities, more western locations, larger CME speeds and halo CMEs. The correlations between the proton peak flux and these solar parameters are derived for a low (>10 MeV) and high (>60 MeV) energy range excluding any flux enhancement due to the passage of fast interplanetary shocks. The obtained correlation coefficients are: 0.55+-0.07 (0.63+-0.06) with flare intensity and 0.56+-0.08 (0.40+-0.09) with the CME speed for E>10 MeV (E>60 MeV). For both energy ranges, the correlations with flare longitude and CME width are very small or non-existent. Furthermore, the occurrence probabilities, correlation coefficients and mean peak fluxes are derived in multi-dimensional bins combining the aforementioned solar parameters. The correlation coefficients are also determined in different proton energy channels ranging from 5 to 200 MeV. The results show that the correlation between the proton peak flux and the CME speed decreases with energy, while the correlation with the flare intensity shows the opposite behavior. Furthermore**, the correlation with the CME speed is stronger than the correlation with the flare intensity**

below 15 MeV and becomes weaker above 20 MeV. Excluding the flux enhancements due to interplanetary shocks, only a small but not very significant change is observed in the correlation between the peak flux below 7 MeV and the CME speed. **Tables**

Energy-dependent Charge States and Their Connection with Ion Abundances in Impulsive Solar Energetic Particle Events

R. **DiFabio**, Z. Guo, E. Mobius, B. Klecker, H. Kucharek, G. M. Mason, and M. Popecki
The Astrophysical Journal, Vol. 687, No. 1: 623-634, **2008**.
http://www.journals.uchicago.edu/doi/abs/10.1086/591833

Modelling two Energetic Storm Particle Events Observed by Solar Orbiter Using the Combined EUHFORIA and iPATH Models

Zheyi **Ding**, Gang Li, Glenn Mason, Stefaan Poedts, Athanasios Kouloumvakos, George Ho, Nicolas Wijsen, Robert F. Wimmer-Schweingruber, Javier Rodríguez-Pacheco
A&A 681, A92 **2024**
https://arxiv.org/pdf/2311.08346.pdf
https://www.aanda.org/articles/aa/pdf/2024/01/aa47506-23.pdf
By coupling the EUropean Heliospheric FORcasting Information Asset (EUHFORIA) and the improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, two energetic storm particle (ESP) events, originating from the same active region (AR 13088) and observed by Solar Orbiter (SolO) on **August 31 2022 and September 05 2022**, are modelled. While both events originated from the same active region, they exhibited notable differences, including: 1) the August ESP event lasted for 7 hours, while the September event persisted for 16 hours; 2) The time intensity profiles for the September event showed a clear cross-over upstream of the shock where the intensity of higher energy protons exceeds those of lower energy protons, leading to positive (``reverse'') spectral indices prior to the shock passage. For both events, our simulations replicate the observed duration of the shock sheath, depending on the deceleration history of the CME. Imposing different choices of escaping length scale, which is related to the decay of upstream turbulence, the modelled time intensity profiles prior to the shock arrival also agree with observations. In particular, the cross-over of this time profile in the September event is well reproduced. We show that a ``reverse'' upstream spectrum is the result of the interplay between two length scales. One characterizes the decay of upstream shock accelerated particles, which are controlled by the energy-dependent diffusion coefficient, and the other characterizes the decay of upstream turbulence power, which is related to the process of how streaming protons upstream of the shock excite Alfvén waves. Simulations taking into account real-time background solar wind, the dynamics of the CME propagation, and upstream turbulence at the shock front are necessary to thoroughly understand the ESP phase of large SEP events.

Solar Orbiter Science Nuggets #25 Jan **2024** https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-modelling-two-consecutive-energetic-storm-particle-events-observed-by-solar-orbiter

The East-West Asymmetry of Particle Intensity in Energetic Storm Particle Events

Zheyi **Ding**, Gang Li, Adolfo Santa Fe Dueñas, Robert W. Ebert, Nicolas Wijsen, Stefaan Poedts
JGR **2023**
https://arxiv.org/pdf/2307.02458.pdf
We examine the East-West asymmetry of the peak intensity in energetic storm particle (ESP) events using the improved Particle Acceleration and Transport in the Heliosphere (iPATH) model. We find that injection efficiency peaks east of the nose of coronal mass ejection shock where the shock exhibits a quasi-parallel geometry. We show that the peak intensity at the eastern flank is generally larger than that at the western flank and it positively correlates with the injection efficiency. We also examine this asymmetry for heavy ions, which depends sensitively on the ion energy. Comparison between the modelling results with the measurements of ESP events at 1 au shows a reasonable agreement. We suggest that the injection efficiency can be a primary factor leading to the East-West asymmetry of the peak intensity in ESP events. Additionally, the charge-to-mass (Q/A) dependence of the maximum particle energy affects this asymmetry for heavy ions.

Modelling the 2020 November 29 solar energetic particle event using the EUHFORIA and the iPATH model

Zheyi **Ding**, Nicolas Wijsen, Gang Li, Stefaan Poedts
A&A 668, A71 **2022**
https://arxiv.org/pdf/2210.16967.pdf
https://doi.org/10.1051/0004-6361/202244732
https://www.aanda.org/articles/aa/pdf/2022/12/aa44732-22.pdf

We present the implementation of coupling the EUropean Heliospheric FORcasting Information Asset (EUHFORIA) and the improved Particle Acceleration and Transport in the Heliosphere (iPATH) model and simulate the widespread solar energetic particle (SEP) event of **2020 November 29**. We compare the simulated time intensity profiles with measurements at Parker Solar Probe (PSP), the Solar Terrestrial Relations Observatory (STEREO)-A, SOlar and Heliospheric Observatory (SOHO) and Solar Orbiter (SolO). We focus on the influence of the history of shock acceleration on the varying SEP time intensity profiles and investigate the underlying causes in the origin of this widespread SEP event. The temporal evolution of shock parameters and particle fluxes during this event are examined. We find that adopting a realistic solar wind background can significantly impact the expansion of the shock and consequently the shock parameters. Time intensity profiles with an energetic storm particle event at PSP are well reproduced from the simulation. In addition, the simulated and observed time intensity profiles of protons show a similar two-phase enhancement at STA. These results illustrate that modelling a shock using a realistic solar wind is crucial in determining the characteristics of SEP events. The decay phase of the modelled time intensity profiles at Earth agrees well with observations, indicating the importance of perpendicular diffusion in widespread SEP events. Taking into account the possible large curved magnetic field line connecting to SolO, the modelled time intensity profiles show good agreement with the observation. We suggest that the largely distorted magnetic field lines due to a stream interaction region may be a key factor in understanding the observed SEPs at SolO in this event.

Modeling the East-West Asymmetry of Energetic Particle Fluence in Large Solar Energetic Particle Events Using the iPATH Model

Zheyi **Ding**,Gang Li,Robert W. Ebert,Maher A. Dayeh,Adolfo Santa Fe-Dueñas,Mihir Desai,Hong Xie,N. Gopalswamy,A. Bruno

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It has been noted that in large solar energetic particle (SEP) events, the peak intensities show an East-West asymmetry with respect to the source flare locations. Using the 2D improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, we investigate the origin of this longitudinal trend. We consider multiple cases with different solar wind speeds and eruption speeds of the coronal mass ejections (CMEs) and fit the longitudinal distributions of time-averaged fluence by symmetric/asymmetric Gaussian functions with three time intervals of 8, 24 and 48 hr after the flare onset time respectively. The simulation results are compared with a statistical study of three-spacecraft events. We suggest that the East-West asymmetry of SEP fluence and peak intensity can be primarily caused the combined effect of an extended shock acceleration process and the evolution of magnetic field connection to the shock front. Our simulations show that the solar wind speed and the CME speed are important factors determining the East-West fluence asymmetry.

Modeling the 10 September 2017 solar energetic particle event using the iPATH model

Zhe-Yi **Ding**, Gang Li, Jun-Xiang Hu, Shuai Fu

Research in Astronomy and Astrophysics **2020**

https://arxiv.org/pdf/2005.02326.pdf **File**

On **September 10 2017**, a fast coronal mass ejection (CME) erupted from the active region (AR) 12673, leading to a ground level enhancement (GLE) event at Earth. Using the 2D improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, we model the large solar energetic particle (SEP) event of 10 September 2017 observed at Earth, Mars and STEREO-A. Based on observational evidence,we assume that the CME-driven shock experienced a large lateral expansion shortly after the eruption, which is modelled by a double Gaussian velocity profile in this simulation. We use the in-situ shock arrival times and the observed CME speeds at multiple spacecraft near Earth and Mars as constraints to adjust the input model parameters. The modelled time intensity profiles and fluence for energetic protons are then compared with observations. Reasonable agreements with observations at Mars and STEREO-A are found. The simulated results at Earth differ from observations of GOES-15. Instead, the simulated results at a heliocentric longitude 20 degree west to Earth fit reasonably well with the GOES observation. This can be explained if the pre-event solar wind magnetic field at Earth is not described by a nominal Parker field. Our results suggest that a large lateral expansion of the CME-driven shock and a distorted interplanetary magnetic field due to previous events can be important in understanding this GLE event.

Is the enhancement of type II radio bursts during CME interactions related to the associated solar energetic particle event?

Liu-Guan **Ding**, Zhi-Wei Wang, Li Feng, Gang Li, Yong Jiang

Research in Astronomy and Astrophysics **2018**

https://arxiv.org/pdf/1808.04720.pdf

We investigated 64 pairs of interacting-CME events identified by the simultaneous observations of SOHO and STEREO spacecraft from 2010 January to 2014 August, to examine the relationship between the large SEP events in

the energy of 25-60MeV and the properties of the interacting CMEs. We found that during CME interactions the large SEP events in this study were all generated by CMEs with the presence of enhanced type II radio bursts, which also have wider longitudinal distributions comparing to events with the absence of type II radio burst or its enhancement (almost associated with small SEP events). It seems that the signature of type II radio bursts enhancement is a good discriminator between large SEP and small or none SEP event producers during CME interactions. The type II radio burst enhancement is more likely to be generated by CME interactions, with the main CME having larger speed (v), angular width (WD), mass (m) and kinetic energy (E_k), that taking over the preceding CMEs which also have higher v, WD, m and E_k, than those preceding CMEs in CME pairs missing the type II radio bursts or enhancements. Our analysis also revealed that the intensities of associated SEP events correlate negatively with the intersection height of the two CMEs. Most of type-II-enhanced events and SEP events are coincidentally and almost always made by the fast and wide main CMEs that sweeping fully over a relatively slower and narrower preceding CMEs. We suggest that a fast CME with enough energy completely overtaking a relatively narrower preceding CME, especially in low height, can drive more energetic shock signified by the enhanced type II radio bursts. The shock may accelerate ambient particles and lead to large SEP event more easily.
2014.08.25, 2014.08.28

Table 1 The properties of two interacting CMEs (2010-2014)

Large solar energetic particle event that occurred on 2012 March 7 and its VDA analysis

Liu-Guan **Ding**, Xin-Xin Cao, Zhi-Wei Wang, Gui-Ming Le

Research in Astron. Astrophys. **2016**

http://arxiv.org/pdf/1604.05303v1.pdf

On **2012 March 7**, the STEREO Ahead and Behind spacecraft, along with the near-earth spacecraft (e.g. SOHO, Wind) situated between the two STEREO spacecraft, observed an extremely large global solar energetic particle (SEP) event in Solar Cycle 24. Two successive coronal mass ejections (CMEs) have been detected close in time. From the multi-point in-situ observations, it can be found that this SEP event was caused by the first CME, and the second one was not involved. Using the velocity dispersion analysis (VDA), we find that for well magnetically connected point, the energetic protons and electrons are released nearly at the same time. The path lengths to STEREO-B (STB) of protons and electrons have distinct difference and deviate remarkably from the nominal Parker spiral path length, which is likely due to the presence of interplanetary magnetic structures situated between the source and the STB. Also the VDA method seems only to obtain reasonable results at well-connected locations and the inferred energetic particles release times in different energy channels are similar. We suggest that good-connection is crucial for obtaining both accurate release time and path length simultaneously, agreeing with the modeling result of Wang & Qin (2015).

ARE THERE TWO DISTINCT SOLAR ENERGETIC PARTICLE RELEASES IN THE 2012 MAY 17 GROUND LEVEL ENHANCEMENT EVENT?

Liu-Guan **Ding**1, Yong Jiang2, and Gang Li

2016 ApJ 818 169

We examine ion release times in the solar vicinity for the **2012 May 17** Ground Level Enhancement event using the velocity dispersion analysis method. In situ energetic proton data from Solar and Heliospheric Observatory (SOHO)/Energetic and Relativistic Nuclei and Electron and Geostationary Operational Environmental Satellite are used. We find two distinct releases of Solar Energetic Particles (SEPs) near the Sun, separated by ~40 minutes. From soft X-ray observations, we find that the first release coincides with the solar flare eruption: the release starts from the flare onset and ends near the peak of the soft X-ray; type-III radio bursts also occur when the release starts. A type II radio burst may also start at the begining of the release. However, the associated Coronal Mass Ejection (CME) only has a height of 0.08Rs from extrapolation of SOHO/LASCO data. At the start of the second release, the CME propagates to more than 8.4Rs in height, and there are signatures of an enhanced type II radio burst. The time-integrated spectra for the two releases differ. The spectrum for the second release shows the common double-power-law feature of gradual SEP events. The spectrum for the first release does not resemble power laws because there is considerable modulation at lower energies. Based on our analysis, *we suggest that SEPs of the first release were dominated by particles accelerated at the flare, and those of the second release were dominated by particles accelerated at the associated CME-driven shock.* Our study may be important to understand certain extreme SEP events.

SEED POPULATION IN LARGE SOLAR ENERGETIC PARTICLE EVENTS AND THE TWIN-CME SCENARIO

Liu-Guan **Ding**1, Gang Li2, Gui-Ming Le3, Bin Gu1, and Xin-Xin Cao

2015 ApJ 812 171

http://arxiv.org/pdf/1604.05784v1.pdf

It has recently been suggested that large solar energetic particle (SEP) events are often caused by twin coronal mass ejections (CMEs). In the twin-CME scenario, the preceding CME provides both an enhanced turbulence level and enhanced seed population at the main CME-driven shock. In this work, we study the effect of the preceding CMEs on the seed population. We examine event-integrated abundance of iron to oxygen ratio (Fe/O) at energies above 25 MeV/nuc for large SEP events in solar cycle 23. We find that the Fe/O ratio (normalized to the reference coronal value of 0.134) ≤2.0 for almost all single-CME events and these events tend to have smaller peak intensities. In comparison, the Fe/O ratio of twin-CME events scatters in a larger range, reaching as high as 8, suggesting the presence of flare material from perhaps preceding flares. For extremely large SEP events with peak intensities above 1000 pfu, the Fe/O ratios drop below 2, indicating that the seed particles are dominated by coronal material rather than flare material in these extreme events. The Fe/O ratios of ground level enhancement (GLE) events, which are all twin-CME events, scatter in a broad range. For a given Fe/O ratio, GLE events tend to have larger peak intensities than non-GLE events. Using velocity dispersion analysis, we find that GLE events have lower solar particle release heights than non-GLE events, agreeing with earlier results by Reames.

Table 1: The properties of the large SEP events (solar cycle 23)

Interaction between Two Coronal Mass Ejections in the 2013 May 22 Large Solar Energetic Particle Event

Liu-Guan **Ding**1,2, Gang Li2, Yong Jiang3, Gui-Ming Le4, Cheng-Long Shen5, Yu-Ming Wang5, Yao Chen6, Fei Xu1, Bin Gu1, and Ya-Nan Zhang

2014 ApJ 793 L35.

We investigate the eruption and interaction of two coronal mass ejections (CMEs) during the large **2013 May 22** solar energetic particle event using multiple spacecraft observations. Two CMEs, having similar propagation directions, were found to erupt from two nearby active regions (ARs), AR11748 and AR11745, at ~08:48 UT and ~13:25 UT, respectively. The second CME was faster than the first CME. Using the graduated cylindrical shell model, we reconstructed the propagation of these two CMEs and found that the leading edge of the second CME caught up with the trailing edge of the first CME at a height of ~6 solar radii. After about two hours, the leading edges of the two CMEs merged at a height of ~20 solar radii. Type II solar radio bursts showed strong enhancement during this two hour period. Using the velocity dispersion method, we obtained the solar particle release (SPR) time and the path length for energetic electrons. Further assuming that energetic protons propagated along the same interplanetary magnetic field, we also obtained the SPR time for energetic protons, which were close to that of electrons. These release times agreed with the time when the second CME caught up with the trailing edge of the first CME, indicating that the CME-CME interaction (and shock-CME interaction) plays an important role in the process of particle acceleration in this event.

On the identification of time interval threshold in the twin-CME scenario†

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JGR, Volume 119, Issue 3, pages 1463–1475, March **2014**

http://arxiv.org/pdf/1604.05786v1.pdf

Recently it has been suggested that the "twin-CME" scenario [Li et al., 2012] may be a very effective mechanism in causing extreme Solar Energetic Particle (SEP) events and in particular Ground Level Enhancement (GLE) events. Ding et al. (2013) performed a statistical examination of the twin-CME scenario with a total of 126 fast and wide western Coronal Mass Ejections (CMEs). They found that CMEs having a preceding CME with a speed > 300 km/s within 9 hours from the same active region have larger probability of leading to large SEP events than CMEs that do not have preceding CMEs. The choice of 9 hours being the time lag τ between the preceding CME and the main CME was based on some crude estimates of the decay time of the turbulence downstream of the shock driven by the preceding CME. In this work, we examine this choice. For the 126 fast wide CMEs examined in [Ding et al., 2013], we vary the time lag τ from 1 hour to 24 hours with an increment of 1 hour. By considering three quantities whose values depend on the choice of this time lag τ, we show that the choice of 13 hours for τ is more appropriate. Our study confirms our earlier result that twin CMEs are more likely to lead to large SEP events than single fast CMEs. The results shown here are of great relevance to space weather studies.

Table 1. The onset times of the corresponding preceding CMEs within 24 hours of main CMEs.

THE "TWIN-CME" SCENARIO AND LARGE SOLAR ENERGETIC PARTICLE EVENTS IN SOLAR CYCLE 23

Liuguan **Ding**1,2, Yong Jiang1, Lulu Zhao2, and Gang Li

2013 ApJ 763 30, **File**

Energetic particles in large solar energetic particle (SEP) events are a major concern for space weather. Recently, Li et al. proposed a "twin-CME" scenario for ground-level events. Here we extend that study to large SEP events in solar cycle 23. Depending on whether preceding coronal mass ejections (CMEs) within 9 hr exist and whether ions >10 MeV nucleon–1 exceed 10 pfu, we categorize fast CMEs with speed >900 km s–1 and width >60° from the western hemisphere source regions into four groups: groups I and II are "twin" and single CMEs that lead to large SEPs; groups III and IV are "twin" and single CMEs that do not lead to large SEPs. The major findings of this paper are: first, large SEP events tend to be "twin-CME" events. Of 59 western large SEP events in solar cycle 23, 43 are "twin-CME" (group I) events and 16 are single-CME (group II) events. Second, not all "twin CMEs" produced large SEPs: 28 twin CMEs did not produce large SEPs (group III events). Some of them produced excesses of particles up to a few MeV nucleon–1. Third, there were 39 single fast CMEs that did not produce SEPs (group IV events). Some of these also showed an excess of particles up to a few MeV nucleon–1. For all four groups of events, we perform statistical analyses on properties such as the angular width, the speed, the existence of accompanying metric type II radio bursts, and the associated flare class for the main CMEs and the preceding CMEs.

Tables

Temporal Evolution of Heavy-Ion Spectra in Solar Energetic Particle Events

Donald J. **Doran**, Silvia Dalla, Peter Zelina

Solar Physics May **2019**, 294:55

https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1431-9.pdf

Solar energetic particles (SEPs) are released into the heliosphere by solar flares and coronal mass ejections (CMEs). They are mostly protons, with smaller amounts of heavy ions from helium to iron, and lesser amounts of species heavier than iron. The spectra of heavy ions have been previously studied mostly by using the fluence of the particles in an event-integrated spectrum in a small number of spectral snapshots. In this article, we analyze the temporal evolution of the heavy-ion spectra using two large SEP events (**27 January 2012** and **7 January 2014**) from the Solar TErrestrial Relations Observatory (STEREO) era using Advanced Composition Explorer (ACE) Solar Isotope Spectrometer (SIS) and Ultra Low Energy Isotope Spectrometer (ULEIS), Energetic Particles: Acceleration, Composition and Transport(EPACT) onboard Wind, and the STEREO-A (Ahead) and -B (Behind) Low-Energy Telescope(LET) and Suprathermal Ion Telescope (SIT) instruments, taking a large number of snapshots covering the temporal evolution of the event. We find large differences in the spectra of the ions after the main flux enhancement in terms of the grouping of similar species, but also in terms of the location of the instruments. Although it is somewhat less noticeable than in the case of the temporal evolution of protons (Doran and Dalla, Solar Phys.291, 2071, 2016), we observe a wave-like pattern travelling through the heavy ion spectra from the highest energies to the lowest, creating an “arch” structure that later straightens into a power law after 18 to 24 hours.

Temporal Evolution of Solar Energetic Particle Spectra

Donald J. **Doran**, Silvia Dalla

Solar Phys.   Volume 291, Issue 7, pp 2071–2097   **2016**   **File**

During solar flares and coronal mass ejections, Solar Energetic Particles (SEPs) may be released into the interplanetary medium and near-Earth locations. The energy spectra of SEP events at 1 AU are typically averaged over the entire event or studied in a few snapshots. In this article we analyze the time evolution of the energy spectra of four large selected SEP events using a large number of snapshots. We use a multi-spacecraft and multi-instrument approach for the observations, obtained over a wide SEP energy range. We find large differences in the spectra at the beginning of the events as measured by different instruments. We show that over time, a wave-like structure is observed traveling through the spectra from the highest energies to the lowest energies, creating an “arch” shape that then straightens into a power law later in the event, after times on the order of 10 hours. We discuss the processes that determine SEP intensities and their role in shaping the spectral time evolution. **1977-11-22, 2000-07-14, 2001-04-15, 2012-03-07**

Monitoring and forecasting of great solar proton events using the neutron monitor network in real-time,

Dorman, L., L.A. Pustil'nik; A. Sternlieb; I.G. Zukerman; A.V. Belov; E.A. Eroshenko; V.G. Yanke; et al.

(**2004**),IEEE Trans. Plasma Sci., 32, 1478−1488,

http://sci-hub.st/10.1109/TPS.2004.831738

Obtaining online information on the onset of great solar energetic particle (SEP) events from real-time data of the neutron monitor network (NMN) is considered and the corresponding algorithm and program are proposed. Determination of the particle energy spectrum outside the atmosphere at different moments of the flare is considered on the basis of coupling functions method. The spectra defined in diffusion and kinetic approaches are compared.

Using this information, the time of the SEP ejection into solar wind, the energy spectrum of a SEP event in the source inside the solar corona, and the SEP diffusion coefficient in the interplanetary space during the flare can be estimated. In this work, the significant possibility of the expected SEP fluxes and the energy spectrum forecasting on the early part of the increasing SEP intensity (about 20–30 min after the onset) is considered. Available satellite data in real-time scale combined with real time-data from neutron monitors (NM) are used for extrapolation of this forecast to the region of very small energy particles. The method is checked on the SEP event of September 1989. It is important to note that the accuracy of the developed method sufficiently increases with the increasing dangerous level of the SEP event. The method is not CPU damaging and can run in real time, providing inexpensive means of SEP prediction.

Initial concept for forecasting the flux and energy spectrum of energetic particles using ground level cosmic ray observatories,

Dorman, L., and I. Zuckerman

(**2003**),Adv. Space Res., 31, 925−932,

http://sci-hub.cc/10.1016/S0273-1177(02)00799-8

We describe the principles and operation of automated programs "FEP-Research- 1 st Alert", "FEP-Research-2nd Alert", and "FEP-Research-3rd Alert". The program "FEP-Research- 1 st Alert" gives preliminary determinations of the energy spectrum and flux at the beginning of an event on the basis of l-minute data of total neutron intensity and intensities of different multiplicities in the neutron monitor (NM) at the Emilio Segre' Observatory (2025m above sea level, *R*, =10.8 GV) as well as available l-minute on-line data in the near future of Cosmic Ray Observatories which collaborate with the Israel Cosmic Ray Center (Rome, Haleakala, Climax, Oulu, Moscow, Apatity, Mexico, Aragaz and others). Using well-known coupling functions for neutron monitors we have derived functions that relate the spectral index of flare energetic particles (FEP) to observations of multiplicities. We also derived important functions using ratios of FEP observations from the different cosmic ray monitors mentioned above. All these functions are approximated analytically with good accuracy and can be used for automatic realtime determination of the energy spectrum and fluxes of FEP. Using approximate values of the diffision coefficient for the current level of solar activity as a function of particle energy, the program "FEP-Research-1st Alert" determines very roughly the expected level of radiation in space after l/2, 1,3/2 and 2 hours. If this level is expected to be dangerous for satellites and spacecrafts, the program "FEP.Research-1st Alert" sends preliminary 1st Alert. More accurate forecasts are given after 5-10 minutes by the program "FEP-Research-2nd Alert", and after lo-20 minutes program by the "FEP-Research-3rd Alert" using information on the diffusion coefficient obtained from on-line FEP ground data.

Evolution of several space weather events connected with Forbush decreases

I. **Dorotoviˇc**1, K. Kudela2, M. Lorenc1, T. Pintrer1 and M. Rybanskry2

Universal Heliophysical Processes, Proceedings IAU Symposium No. 257, 2008, N. Gopalswamy & D.F. Webb, eds., ***2009***

http://journals.cambridge.org/action/displayIssue?iid=4866212

In our recent paper (Dorotovič et al. 2008a) we focused on a study of the Forbush decrease (FD) of January 17–18 and 21–22, 2005. It was shown that the corresponding recovery time can depend on the density of high-energy protons in the CME matter. In this paper we identified several additional events in the period between 1995 and 2007. We found that the majority of FDs studied is accompanied by an abrupt count increase in the proton channel P1 and by a simultaneous decrease in the channel P7 (GOES). However, the analysis of temporal evolution of all FDs did not confirm the hypothesis on different recovery time after FD as a function of the energy distribution of the particles penetrating into radiation belts of the Earth.

I. **Dorotoviˇc** · K. Kudela · M. Lorenc · M. Rybanský

Solar Phys (**2008**) 250: 339–346

We focused on a study of Forbush decrease (FD) of **17 – 18 and 21 – 22 January 2005**,

The solar cycle 25 multi-spacecraft solar energetic particle event catalog of the SERPENTINE project

N. **Dresing**, A. Yli-Laurila, S. Valkila, J. Gieseler, D. E. Morosan, G. U. Farwa, +++

A&A 687, A72 **2024**

https://arxiv.org/pdf/2403.00658.pdf

https://data.serpentine-h2020.eu/catalogs/sep-sc25/ **catalog**

https://www.aanda.org/articles/aa/pdf/2024/07/aa49831-24.pdf

Context. The Solar energetic particle analysis platform for the inner heliosphere (SERPENTINE) project, funded through the H2020- SPACE-2020 call of the European Union's Horizon 2020 framework programme, employs measurements of the new inner heliospheric spacecraft fleet to address several outstanding questions of the origin of

solar energetic particle (SEP) events. The data products of SERPENTINE include event catalogs, which are provided to the scientific community.
Aims. In this paper, we present SERPENTINE's new multi-spacecraft SEP event catalog for events observed in solar cycle 25. Observations from five different viewpoints are utilized, provided by Solar Orbiter, Parker Solar Probe, STEREO A, BepiColombo, and the near-Earth spacecraft Wind and SOHO. The catalog contains key SEP parameters for 25 − 40 MeV protons, ∼ 1 MeV electrons, and ∼ 100 keV electrons. Furthermore, basic parameters of the associated flare and type-II radio burst are listed, as well as the coordinates of the observer and solar source locations.
Methods. An event is included in the catalog if at least two spacecraft detect a significant proton event with energies of 25 − 40 MeV. SEP onset times are determined using the Poisson-CUSUM method. SEP peak times and intensities refer to the global intensity maximum. If different viewing directions are available, we use the one with the earliest onset for the onset determination and the one with the highest peak intensity for the peak identification. We furthermore aim at using a high time resolution to provide most accurate event times. Therefore, time averaging of the SEP intensity data is only applied if necessary to determine clean event onsets and peaks. Associated flares are identified using observations from near Earth and Solar Orbiter. Associated type II radio bursts are determined from ground-based observations in the metric frequency range and from spacecraft observations in the decametric range.
Results. The current version of the catalog contains 45 multi-spacecraft events observed in the period from Nov 2020 until May 2023, of which 13 were widespread events and four were classified as narrow-spread events. Using X-ray observations by GOES/XRS and Solar Orbiter/STIX, we were able to identify the associated flare in all but four events. Using ground-based and space-borne radio observations, we found an associated type-II radio burst for 40 events. In total, the catalog contains 142 single event observations, of which 20 (45) have been observed at radial distances below 0.6 AU (0.8 AU). It is anticipated to extend the catalog in the future. **28 Mar 2022, 24-25 Feb 2023**

The 17 April 2021 widespread solar energetic particle event

N. **Dresing**, L. Rodríguez-García, I. C. Jebaraj, A. Warmuth, S. Wallace, et al.
A&A 674, A105 **2023**
https://arxiv.org/pdf/2303.10969.pdf
https://www.aanda.org/articles/aa/pdf/2023/06/aa45938-23.pdf
Context. A complex and long-lasting solar eruption on **17 April 2021** produced a widespread solar energetic particle (SEP) event that was observed by five longitudinally well-separated observers in the inner heliosphere that covered distances to the Sun from 0.42 to 1 au: BepiColombo, Parker Solar Probe, Solar Orbiter, STEREO A, and near-Earth spacecraft. The event was the second widespread SEP event detected in solar cycle 25, and it produced relativistic electrons and protons. It was associated with a long-lasting solar hard X-ray flare that showed multiple hard X-ray peaks over a duration of one hour. The event was further accompanied by a medium-fast coronal mass ejection (CME) with a speed of 880 km s−1 that drove a shock, an extreme ultraviolet wave, and long-lasting and complex radio burst activity that showed four distinct type III burst groups over a period of 40 min.
Aims. We aim to understand the reason for the wide spread of elevated SEP intensities in the inner heliosphere as well as identify the underlying source regions of the observed energetic electrons and protons.
Methods. We applied a comprehensive multi-spacecraft analysis of remote-sensing observations and in situ measurements of the energetic particles and interplanetary context to attribute the SEP observations at the different locations to the various potential source regions at the Sun. We used an ENLIL simulation to characterize the complex interplanetary state and its role in the energetic particle transport. The magnetic connection between each spacecraft and the Sun was determined using ballistic backmapping in combination with potential field source surface extrapolations in the lower corona. Using also a reconstruction of the coronal shock front, we then determined the times when the shock establishes magnetic connections with the different observers. Radio observations were used to characterize the directivity of the four main injection episodes, which were then employed in a 2D SEP transport simulation to test the importance of these different injection episodes.
Results. A comprehensive timing analysis of the inferred solar injection times of the SEPs observed at each spacecraft suggests different source processes being important for the electron and proton events. Comparison among the characteristics and timing of the potential particle sources, such as the CME-driven shock or the flare, suggests a stronger shock contribution for the proton event and a more likely flare-related source for the electron event.
Conclusions. In contrast to earlier studies on widespread SEP events, we find that in this event an important ingredient for the wide SEP spread was the wide longitudinal range of about 110◦ covered by distinct SEP injections, which is also supported by our SEP transport modeling.
CESRA #3619 **2023** https://www.astro.gla.ac.uk/users/eduard/cesra/?p=3619

On the Role of Coronal Shocks for Accelerating Solar Energetic Electrons

Nina **Dresing**1,2, Athanasios Kouloumvakos3, Rami Vainio4, and Alexis Rouillard3
2022 ApJL 925 L21

https://iopscience.iop.org/article/10.3847/2041-8213/ac4ca7/pdf
We study the role of coronal mass ejection (CME) driven shocks in the acceleration of solar energetic electrons. Using observations by the two STEREO spacecraft, we correlate electron peak intensities of solar energetic particle events measured in situ with various parameters of the associated coronal shocks. These shock parameters were derived by combining 3D shock reconstructions with global modeling of the corona. This modeling technique provides also shock properties in the specific shock regions that are magnetically connected to the two STEREO spacecraft. We find significant correlations between the peak intensities and the Mach number of the shock with correlation coefficients of about 0.7, which are similar for electrons at ∼1 MeV and protons at >60 MeV. Lower-energy electrons with <100 keV show a smaller correlation coefficient of 0.47. The causal relationship between electron intensities and the shock properties is supported by the vanishing correlations when peak intensities at STEREO A are related with the Alfvénic Mach number at the magnetic footpoint of STEREO B and vice versa, which yields correlation coefficients of 0.03 and −0.13 for ∼1 MeV and <100 keV electron peak intensities, respectively. We conclude that the high-energy electrons are accelerated mainly by the shock, while the low-energy electrons are likely produced by a mixture of flare and shock-related acceleration processes.
Table 1 Events and Corresponding Peak Intensities (in cm^{-2} sr^{-1} s^{-1} MeV^{-1}) of 55–85 keV Electrons, 0.7–1.4 MeV Electrons, and 60–100 MeV Protons for Events 2011-2017

Connecting solar flare hard X-ray spectra to in situ electron spectra. A comparison of RHESSI and STEREO/SEPT observations

Nina **Dresing**, A. Warmuth, F. Effenberger, K.-L. Klein, S. Musset, L. Glesener, M. Brüdern
A&A **2021**
https://arxiv.org/pdf/2108.09045.pdf
We compare the characteristics of flare-accelerated energetic electrons at the Sun with those injected into interplanetary space. We have identified 17 energetic electron events well-observed with the SEPT instrument aboard STEREO which show a clear association with a hard X-ray (HXR) flare observed with the RHESSI spacecraft. We compare the spectral indices of the RHESSI HXR spectra with those of the interplanetary electrons. Because of the frequent double-power-law shape of the in situ electron spectra, we paid special attention to the choice of the spectral index used for comparison. The time difference between the electron onsets and the associated type III and microwave bursts suggests that the electron events are detected at 1 AU with apparent delays ranging from 9 to 41 minutes. While the parent solar activity is clearly impulsive, also showing a high correlation with extreme ultraviolet jets, most of the studied events occur in temporal coincidence with coronal mass ejections (CMEs). In spite of the observed onset delays and presence of CMEs in the low corona, we find a significant correlation of about 0.8 between the spectral indices of the HXR flare and the in situ electrons. The correlations increase if only events with significant anisotropy are considered. This suggests that transport effects can alter the injected spectra leading to a strongly reduced imprint of the flare acceleration. We conclude that interplanetary transport effects must be taken into account when inferring the initial acceleration of solar energetic electron events. Although our results suggest a clear imprint of flare acceleration for the analyzed event sample, a secondary acceleration might be present which could account for the observed delays. However, the limited and variable pitch-angle coverage of SEPT could also be the reason for the observed delays. **2011 Mar 24**
Table 1. Event list including the basic parameters of the correlated flare and SEE events (2007-2014)

Statistical results for solar energetic electron spectra observed over 12 years with STEREO/SEPT

Nina **Dresing**, Frederic Effenberger, Raul Gomez-Herrero, Bernd Heber, Andreas Klassen, Alexander Kollhoff, Ian Richardson, Solveig Theesen
ApJ **889** 143 **2020**
https://arxiv.org/pdf/1912.10279.pdf
sci-hub.si/10.3847/1538-4357/ab64e5
We present a statistical analysis of near-relativistic (NR) solar energetic electron event spectra near 1au. We use measurements of the STEREO Solar Electron and Proton Telescope (SEPT) in the energyrange of 45-425 keV and utilize the SEPT electron event list containing all electron events observed bySTEREO A and STEREO B from 2007 through 2018. We select 781 events with significant signal tonoise ratios for our analysis and fit the spectra with single or broken power law functions of energy.We find 437 (344) events showing broken (single) power laws in the energy range of SEPT. The eventswith broken power laws show a mean break energy of about 120 keV. We analyze the dependence ofthe spectral index on the rise times and peak intensities of the events as well as on the presence ofrelativistic electrons. The results show a relation between the power law spectral index and the risetimes of the events with softer spectra belonging to rather impulsive events. Long rise-time events areassociated with hard spectra as well as with the presence of higher energy (>0.7 MeV) electrons. Thisgroup of events cannot be explained by a pure flare scenario but suggests an additional accelerationmechanism, involving a prolonged acceleration and/or injection of the particles. A dependence of thespectral index on the longitudinal separation from the parent

solar source region was not found. A statistical analysis of the spectral indices during impulsively rising events (rise times<20 minutes) isalso shown. **2010-02-07; 2017-09-04**

Long-lasting injection of solar energetic electrons into the heliosphere

N. **Dresing**1, R. Gómez-Herrero2, B. Heber1, A. Klassen1, M. Temmer3 and A. Veronig3
A&A 613, A21 (**2018**)
https://www.aanda.org/articles/aa/pdf/2018/05/aa31573-17.pdf
http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2018/05/aa31573-17/aa31573-17.html

Context. The main sources of solar energetic particle (SEP) events are solar flares and shocks driven by coronal mass ejections (CMEs). While it is generally accepted that energetic protons can be accelerated by shocks, whether or not these shocks can also efficiently accelerate solar energetic electrons is still debated. In this study we present observations of the extremely widespread SEP event of **26 Dec 2013** To the knowledge of the authors, this is the widest longitudinal SEP distribution ever observed together with unusually long-lasting energetic electron anisotropies at all observer positions. Further striking features of the event are long-lasting SEP intensity increases, two distinct SEP components with the second component mainly consisting of high-energy particles, a complex associated coronal activity including a pronounced signature of a shock in radio type-II observations, and the interaction of two CMEs early in the event.
Aims. The observations require a prolonged injection scenario not only for protons but also for electrons. We therefore analyze the data comprehensively to characterize the possible role of the shock for the electron event.
Methods. Remote-sensing observations of the complex solar activity are combined with in situ measurements of the particle event. We also apply a graduated cylindrical shell (GCS) model to the coronagraph observations of the two associated CMEs to analyze their interaction.
Results. We find that the shock alone is likely not responsible for this extremely wide SEP event. Therefore we propose a scenario of trapped energetic particles inside the CME–CME interaction region which undergo further acceleration due to the shock propagating through this region, stochastic acceleration, or ongoing reconnection processes inside the interaction region. The origin of the second component of the SEP event is likely caused by a sudden opening of the particle trap.

CESRA nugget #1916 July **2018** http://www.astro.gla.ac.uk/users/eduard/cesra/?p=1916

Efficiency of particle acceleration at interplanetary shocks: Statistical study of STEREO observations

N. **Dresing**, S. Theesen, A. Klassen and B. Heber
A&A 588, A17 (**2016**)
https://www.aanda.org/articles/aa/pdf/2016/04/aa27853-15.pdf
doi:10.1051/0004-6361/201527853

Context. Among others, shocks are known to be accelerators of energetic charged particles. However, many questions regarding the acceleration efficiency and the required conditions are not fully understood. In particular, the acceleration of electrons by shocks is often questioned.
Aims. In this study we determine the efficiency of interplanetary shocks for <100 keV electrons, and for ions at ~0.1 and ~2 MeV energies, as measured by the Solar Electron and Proton Telescope (SEPT) instruments aboard the twin Solar Terrestrial Relations Observatory (STEREO) spacecraft.
Methods. We employ an online STEREO in situ shock catalog that lists all shocks observed between 2007 and mid 2014 (observed by STEREO A) and until end of 2013 (observed by STEREO B). In total 475 shocks are listed. To determine the particle acceleration efficiency of these shocks, we analyze the associated intensity increases (shock spikes) during the shock crossings. For the near-relativistic electrons, we take into account the issue of possible ion contamination in the SEPT instrument.
Results. The highest acceleration efficiency is found for low energy ions (0.1 MeV), which show a shock-associated increase at 27% of all shocks. The 2 MeV ions show an associated increase only during 5% of the shock crossings. In the case of the electrons, the shocks are nearly ineffective. Only five shock-associated electron increases were found, which correspond to only 1% of all shock crossings.

Injection of solar energetic particles into both loop legs of a magnetic cloud

Nina **Dresing**, Ra?l Gómez-Herrero, Bernd Heber, Miguel Angel Hidalgo, Andreas Klassen, Manuela Temmer, Astrid Veronig
A&A 586, A55 **2016**
http://arxiv.org/pdf/1601.00491v1.pdf

Context. Each of the two Solar TErrestrial RElations Observatory (STEREO) spacecraft carries a Solar Electron and Proton Telescope (SEPT) which measures electrons and protons. Anisotropy observations are provided in four

viewing directions: along the nominal magnetic field Parker spiral in the ecliptic towards the Sun (SUN) and away from the Sun (Anti-Sun / ASUN), and towards the north (NORTH) and south (SOUTH). The solar energetic particle (SEP) event on **7 November 2013** was observed by both STEREO spacecraft, which were longitudinally separated by 68? at that time. While STEREO A observed the expected characteristics of an SEP event at a well-connected position, STEREO B detected a very anisotropic bi-directional distribution of near-relativistic electrons and was situated inside a magnetic-cloud-like structure during the early phase of the event.
Aims. We examine the source of the bi-directional SEP distribution at STEREO B. On the one hand this distribution could be caused by a double injection into both loop legs of the magnetic cloud (MC). On the other hand, a mirroring scenario where the incident beam is reflected in the opposite loop leg could be the reason. Furthermore, the energetic electron observations are used to probe the magnetic structure inside the magnetic cloud.
Methods. We investigate in situ plasma and magnetic field observations and show that STEREO B was embedded in an MC-like structure ejected three days earlier on **4 November** from the same active region. We apply a Graduated Cylindrical Shell (GCS) model to the coronagraph observations from three viewpoints as well as the Global Magnetic Cloud (GMC) model to the in situ measurements at STEREO B to determine the orientation and topology of the MC close to the Sun and at 1 AU. We also estimate the path lengths of the electrons propagating through the MC to estimate the amount of magnetic field line winding inside the structure.
Results. The relative intensity and timing of the energetic electron increases in the different SEPT telescopes at STEREO B strongly suggest that the bi-directional electron distribution is formed by SEP injections in both loop legs of the MC separately instead of by mirroring farther away beyond the STEREO orbit. Observations by the Nancay Hadioheliograph (NRH) of two distinct radio sources during the SEP injection further support the above scenario. The determined electron path lengths are around 50% longer than the estimated lengths of the loop legs of the MC itself (based on the GCS model) suggesting that the amount of field line winding is moderate.

Statistical survey of widely spread out solar electron events observed with STEREO and ACE with special attention to anisotropies

N. **Dresing**, R. G?mez-Herrero, B. Heber, A. Klassen, O. Malandraki , W. Dr?ge , and Y. Kartavykh
E-print, July 2014; A&A, Volume 567, A27, July **2014; File**
http://www.aanda.org.sci-hub.cc/articles/aa/abs/2014/07/aa23789-14/aa23789-14.html
Context. In February 2011, the two STEREO spacecrafts reached a separation of 180 degrees in longitude, offering a complete view of the Sun for the first time ever. When the full Sun surface is visible, source active regions of solar energetic particle (SEP) events can be identified unambiguously. STEREO, in combination with near-Earth observatories such as ACE or SOHO, provides three well separated viewpoints, which build an unprecedented platform from which to investigate the longitudinal variations of SEP events.
Aims. We show an ensemble of SEP events that were observed between 2009 and mid-2013 by at least two spacecrafts and show a remarkably wide particle spread in longitude (wide-spread events). The main selection criterion for these events was a longitudinal separation of at least 80 degrees between active region and spacecraft magnetic footpoint for the widest separated spacecraft. We investigate the events statistically in terms of peak intensities, onset delays, and rise times, and determine the spread of the longitudinal events, which is the range filled by SEPs during the events. Energetic electron anisotropies are investigated to distinguish the source and transport mechanisms that lead to the observed wide particle spreads.
Methods. According to the anisotropy distributions, we divided the events into three classes depending on different source and transport scenarios. One potential mechanism for wide-spread events is efficient perpendicular transport in the interplanetary medium that competes with another scenario, which is a wide particle spread that occurs close to the Sun. In the latter case, the observations at 1 AU during the early phase of the events are expected to show significant anisotropies because of the wide injection range at the Sun and particle-focusing during the outward propagation, while in the first case only low anisotropies are anticipated.
Results. We find events for both of these scenarios in our sample that match the expected observations and even different events that do not agree with the scenarios. We conclude that probably both an extended source region at the Sun and perpendicular transport in the interplanetary medium are involved for most of these wide-spread events.
Table 1. Event number, date, type III radio burst onset time, Carrington longitude (CL) of the flare, longitudinal separating angles between the s/c ootpoint and the flaring AR.
Table 2. Event number, date, type III radio burst onset times, onset and maximum times of 55–105 keV electrons at the three spacecrafts.
Table 3. Event number, date, peak intensities of 55–105 keV electrons at the three spacecrafts, and anisotropy class of the event (see Sect. 4.3).
2009-11-03, 2010-01-17, 2010-02-07, 2010-02-12, 2010-08-07, 2010-08-14, 2010-08-18, 2010-08-31, 2010-09-09, 2011-02-24, 2011-11-03, 2011-11-26, 2012-01-23, 2012-03-07, 2012-04-15, 2012-04-16, 2012-05-17, 2012-08-31, 2013-03-05, 2013-04-11, 2013-06-21

The large longitudinal spread of solar energetic particles during the January 17, 2010 solar event

N. **Dresing**, R.G?mez-Herrero, A. Klassen, B. Heber, Y. Kartavykh, W. Droge
E-print, 8 June **2012,** Solar Physics, November **2012**, Volume 281, Issue 1, pp 281-300
https://link.springer.com/content/pdf/10.1007/s11207-012-0049-y.pdf

We investigate multi-spacecraft observations of the **January 17, 2010** solar energetic particle event. Energetic electrons and protons have been observed over a remarkable large longitudinal range at the two STEREO spacecraft and SOHO suggesting a longitudinal spread of nearly 360 degrees at 1,AU. The flaring active region, which was on the **backside of the Sun as seen from Earth**, was separated by more than 100 degrees in longitude from the magnetic footpoints of each of the three spacecraft. The event is characterized by strongly delayed energetic particle onsets with respect to the flare and only small or no anisotropies in the intensity measurements at all three locations. The presence of a coronal shock is evidenced by the observation of a type II radio burst from the Earth and STEREO~B. In order to describe the observations in terms of particle transport in the interplanetary medium, including perpendicular diffusion, a 1D model describing the propagation along a magnetic field line (model 1) (Dr?ge, 2003) and the 3D propagation model (model 2) by (Dr?ge et al., 2010) including perpendicular diffusion in the interplanetary medium have been applied, respectively. While both models are capable of reproducing the observations, model 1 requires injection functions at the Sun of several hours. Model 2, which includes lateral transport in the solar wind, reveals high values for the ratio of perpendicular to parallel diffusion. Because we do not find evidence for unusual long injection functions at the Sun we favor a scenario with strong perpendicular transport in the interplanetary medium as explanation for the observations.

MULTI-SPACECRAFT OBSERVATIONS AND TRANSPORT MODELING OF ENERGETIC ELECTRONS FOR A SERIES OF SOLAR PARTICLE EVENTS IN AUGUST 2010

W. **Dröge**1, Y. Y. Kartavykh1,2, N. Dresing3, and A. Klassen
2016 ApJ 826 134

During **2010 August** a series of solar particle events was observed by the two STEREO spacecraft as well as near-Earth spacecraft. The events, occurring on **August 7, 14, and 18**, originated from active regions 11093 and 11099. We combine in situ and remote-sensing observations with predictions from our model of three-dimensional anisotropic particle propagation in order to investigate the physical processes that caused the large angular spreads of energetic electrons during these events. In particular, we address the effects of the lateral transport of the electrons in the solar corona that is due to diffusion perpendicular to the average magnetic field in the interplanetary medium. We also study the influence of two coronal mass ejections and associated shock waves on the electron propagation, and a possible time variation of the transport conditions during the above period. For the August 18 event we also utilize electron observations from the MESSENGER spacecraft at a distance of 0.31 au from the Sun for an attempt to separate between radial and longitudinal dependencies in the transport process. Our modelings show that the parallel and perpendicular diffusion mean free paths of electrons can vary significantly not only as a function of the radial distance, but also of the heliospheric longitude. Normalized to a distance of 1 au, we derive values of $\lambda_{\parallel}$ in the range of 0.15–0.6 au, and values of $\lambda_{\perp}$ in the range of 0.005–0.01 au. We discuss how our results relate to various theoretical models for perpendicular diffusion, and whether there might be a functional relationship between the perpendicular and the parallel mean free path.

Wide longitudinal distribution of interplanetary electrons following the 7 February 2010 solar event: Observations and transport modeling

W. **Dröge**1,*, Y. Y. Kartavykh1,2, N. Dresing3, B. Heber3 and A. Klassen
JGR Volume 119, Issue 8, pages 6074–6094, August **2014**

We analyze 65–105 keV electrons in the **7 February 2010** solar electron event observed simultaneously by STEREO-A, STEREO-B, and ACE. A method to reconstruct the full-electron pitch angle distributions from the four Solar Electron and Proton Telescope sensors on STEREO-A/B and the Solar Electron and Proton Telescope instrument on ACE in the energy range of approximately 60–300 keV for periods of incomplete angular coverage is presented. A transport modeling based on numerical solutions of a three-dimensional particle propagation model which includes pitch angle scattering and focused transport is applied to the intensity and anisotropy profiles measured on all three spacecraft. Based on an analysis of intensity gradients observed between the three spacecraft, we find that the lateral transport of the electrons occurs partially close to the Sun, due to effects of nonradial divergence of magnetic field lines or particle diffusion, and partially in the interplanetary medium. For the mean free paths characterizing the electron diffusion parallel and perpendicular to the interplanetary magnetic field, we derive values of $\lambda_{\parallel} \sim 0.1$ AU and $\lambda_{\perp} \sim 0.01$ AU. In comparison with results from other particle events which we had previously analyzed in a similar manner we discuss whether the diffusion mean free paths parallel and perpendicular to the average magnetic field might be related with each other, and whether the particle transport perpendicular to the average magnetic field is more likely due to particles following meandering magnetic field lines, or due to particles being scattered off individual field lines.

Nitrate ions spikes in ice cores are not suitable proxies for solar proton events

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Journal of Geophysical Research: Atmospheres **201**5

http://arxiv.org/pdf/1511.03358v1.pdf

Nitrate ion spikes in polar ice cores are contentiously used to estimate the intensity, frequency, and probability of historical solar proton events, quantities that are needed to prepare for potentially society-crippling space weather events. We use the Whole Atmosphere Community Climate Model to calculate how large an event would have to be to produce enough odd nitrogen throughout the atmosphere to be discernible as nitrate peaks at the Earth's surface. These hypothetically large events are compared with probability of occurrence estimates derived from measured events, sunspot records, and cosmogenic radionuclides archives. We conclude that the fluence and spectrum of solar proton events necessary to produce odd nitrogen enhancements equivalent to the spikes of nitrate ions in Greenland ice cores are unlikely to have occurred throughout the Holocene, confirming that nitrate ions in ice cores are not suitable proxies for historical individual solar proton events.

Comparing Energetic Storm Particle Heavy-ion Properties in Solar Cycles 23 and 24

A. Santa Fe **Dueñas**1,2, R. W. Ebert1,2, M. A. Dayeh1,2, M. I. Desai1,2, L. K. Jian3, and G. Li4

2023 ApJ 953 176

https://iopscience.iop.org/article/10.3847/1538-4357/acdede/pdf

We examine variations in energetic storm particle (ESP) heavy-ion average intensities and energy spectra between ∼0.1 and 75 MeV nucleon−1 at coronal mass ejection (CME)–driven interplanetary shocks for events observed at the ACE spacecraft. We compare ESP events observed during the weaker solar cycle (SC) 24 and the relatively stronger SC 23 to investigate any effects on the strength of an SC, including the associated transient events, on ESP properties at 1 au. We find that the number of clearly defined heavy-ion ESP events at ACE during SC 23 is about twice that observed during SC 24 (76 versus 41). The average transit speed of the driving interplanetary CMEs (ICMEs) at 1 au is 20% higher during SC 23 than during SC 24 (859.4 km s−1 versus 729.1 km s−1). The correlation of ESP average intensities with ICME speeds shows that lower-speed ICMEs in SC 24 can be as efficient as the higher-speed events in SC 23 at producing ESPs below 2 MeV nucleon−1. The distribution and magnitude of the average intensities for energies below ∼1 MeV nucleon−1 are consistent between both SCs. However, events with intensity enhancements at higher energies (>∼10 MeV nucleon−1) are more frequent and their intensity distributions are harder for SC 23, resulting in an increase in the rollover energy (E0) for their spectra profiles. This suggests more efficient ESP acceleration at >10 MeV nucleon−1 during SC 23. **2005 September 15**

Table 1. List of ESP Events Used in This Study, Including the Shock Arrival Time, the Average Intensity at 0.1365 MeV n−1, the Spectral Index (γ), and the e-folding Energy (E0) for He, O, and Fe 1998-2017

Dependence of Energetic Storm Particle Heavy Ion Peak Intensities and Spectra on Source CME Longitude and Speed

A. Santa Fe **Dueñas**1,2, R. W. Ebert1,2, M. A. Dayeh1,2, M. I. Desai1,2, L. K. Jian3, G. Li4, and C. W. Smith5

2022 ApJ 935 32

https://iopscience.iop.org/article/10.3847/1538-4357/ac73f5/pdf

We examine variations in energetic storm particle (ESP) heavy ion peak intensities and energy spectra at CME-driven interplanetary shocks. We focus on their dependence with heliolongitude relative to the source region of their associated CMEs, and with CME speed, for events observed in Solar Cycle 24 at the STEREO-A, STEREO-B, and/or ACE spacecraft. We find that observations of ESP events at 1 au are organized by longitude relative to their CME solar source. The ESP event longitude distribution also showed organization with CME speed. The near-Sun CME speeds (Vi) for these events ranged from ∼560 to 2650 km s−1 while the average CME transit speeds to 1 au were significantly slower. The angular width of the events had a clear threshold at Vi of ∼1300 km s−1, above which events showed significantly larger angular extension compared to events with speeds below. High-speed events also showed larger heavy ion peak intensities near the nose of the shock compared to the flanks while their spectral index was smaller near the nose and larger near the flanks. This organization for events with Vi < 1300 km s−1 was not as clear. These ESP events were observed over a narrower range of longitudes though the heavy ion peak intensities still appeared largest near the nose of the shock. Their heavy ion spectra showed no clear organization with longitude. These observations highlight the impact of spacecraft position relative to the CME source longitude and Vi on the properties of ESP events at 1 au. **28 Nov 2011**

Table 1 List of ESP Events Used in This Study, Including the Shock Arrival Time, Observing Spacecraft (SC), Source Flare Location and the Near-Sun and Average Transit CME Speeds 2011-2018

The Class of Type III-L Solar Radio Bursts and Their Associations with Solar Energetic Proton Events

Duffin R.T.

Thesis, **2011**

The source protons of Solar Energetic particle Proton events (defined as "SEP" events for this research) not associated with the Coronal Mass Ejection (CME) shock front are thought to come from either the flare site or the reconnection region beneath the CME. The Type III-L, a new class of solar radio burst has been defined by Cane et al. (2002) and MacDowall et al. (2003) as a sub-set of the Type III burst, beginning after the onset of the soft X-ray (SXR) flare, is long lasting and extends down to at least 1 MHz. The emission source region of Type III-Ls is believed to be at the reconnection region beneath the CME or on the flanks of the CME. Past association studies between SEP events and Type III-Ls began with a biased SEP-selected sample set to see if there can be found support for the emission source region of Type III-Ls and SEPs to come from the same accelerator site at the reconnection region beneath the CME. Unlike previous studies using an SEP-selected sample, I find that when using a radio-selected sample for well-connected SEP events with a solar source in the western hemisphere, the majority of the Type III-L events are associated with SEP events, but not all, and that Type III-L events associated with M- and X- class SXR flares, do not appear to be better predictors of SEP events than do Type II bursts which are associated with the CME shock. Also, I find that the occurrence of Type II events in the radio spectra of SEPs is just as common as the occurrence of Type III-Ls. This indicates that Type III-Ls should not be used as a predictor for SEP events, that the emission source region of Type III-Ls might not be at the reconnection region beneath the CME and reduces the strength of the support found by previous SEP-Type III-L association studies, that the source protons for SEP events necessarily come from the reconnection region beneath the CME. I found that Type III-L events have no strong longitude preference, but SEP events do have a 60% preference between W30 and W90 solar longitude. New data from new long wavelength arrays will help with position mapping the emission source regions of Type III-L bursts. An investigation was done on the internal structure of Type III-Ls. An implication of the result that the separation between components of the Type III-L burst was found to be longer than the separation between the components of Impulsive-Phase Type IIIs (defined as "Imp-Type IIIs"), is that the duration of the Type III-L components appears to be longer than those of Imp-Type IIIs. The result that the components of the Imp-Type IIIs have a faster frequency-time drift-rate than those of the Type III-Ls, shows that the source electrons for the Imp-Type IIIs appear to have a faster source emission velocity than do Type III-Ls. This is understandable as the source electrons for the Imp-Type IIIs are thought to come directly from the active region flare site, whereas the source electrons for Type III-Ls have a longer path along the neutral current sheet to either the reconnection region beneath the CME or up to the flanks of the CME. This gives us a reason as to why the Type III-L emission is delayed in respect to the Imp-Type IIIs. With their energy decreased, these Type III-L source electrons would form emission with a source velocity and frequency-time drift-rate slower than that of the Imp-Type IIIs. Data with better time and frequency resolution should help determine if there are additional weaker Type III-L components. Timing studies between SXR flares, the expansion of CMEs and the evolution of Type III-L components, should determine if electron accelerator sites for the Type III-L components are at a reconnection region beneath the CME or on the flanks of the CME.

PINPOINTING THE PHYSICS OF ENERGETIC STORM PARTICLES OBSERVED IN NEAR EARTH ORBIT

R.W.**Ebert**

Scientia Issue #130 P. 64-67 **2020** **File**

https://www.scientia.global/wp-content/uploads/130.pdf#page=58

When the Sun’s surrounding corona erupts, colossal streams of charged particles are ejected out into interplanetary space, and go on to interact with the material that resides there. Dr Robert Ebert at the Southwest Research Institute and his colleagues combine observations from spacecraft with the latest computer models to uncover the mysteries of these interactions. Their research focuses on advancing astronomers’ understanding of the highly energetic processes that play out in the void that comprises over 99% of the Solar System’s volume.

MULTI-SPACECRAFT ANALYSIS OF ENERGETIC HEAVY ION AND INTERPLANETARY SHOCK PROPERTIES IN ENERGETIC STORM PARTICLE EVENTS NEAR 1 au

R. W. **Ebert**[1], M. A. Dayeh[1], M. I. Desai[1,2], L. K. Jian[3,4], G. Li[5], and G. M. Mason

2016 *ApJ* **831** 153

We examine the longitude distribution of and relationship between interplanetary (IP) shock properties and ~0.1–20 MeV nucleon^{-1} O and Fe ions during **seven multi-spacecraft energetic storm particle (ESP)** events at 1 au. These ESP events were observed at two spacecraft and were primarily associated with low Mach number, quasi-perpendicular shocks. Key observations include the following: (i) the Alfvén Mach number increased from east to west of the coronal mass ejection source longitude, while the shock speed, compression ratios, and obliquity showed no clear dependence; (ii) the O and Fe time intensity profiles and peak intensities varied significantly between longitudinally separated spacecraft observing the same event, the peak intensities being larger near the nose and smaller along the flank of the IP shock; (iii) the O and Fe peak intensities had weak to no correlations with the shock parameters; (iv) the Fe/O time profiles showed intra-event variations upstream of the shock that disappeared downstream of the shock, where values plateaued to those comparable to the mean Fe/O of solar cycle 23; (v) the O and Fe spectral index ranged from ~1.0 to 3.4, the Fe spectra being softer in most events; and (vi) the observed spectral index was softer than the value predicted from the shock compression ratio in most events. We conclude that while the variations in IP shock properties may account for some variations in O and Fe properties within these multi-spacecraft events, detailed examination of the upstream seed population and IP turbulence, along with modeling, are required to fully characterize these observations.

The Relation between Escape and Scattering Times of Energetic Particles in a Turbulent Magnetized Plasma: Application to Solar Flares

Frederic **Effenberger**[1,2] and Vahé Petrosian[3]

2018 ApJL 868 L28

sci-hub.tw/10.3847/2041-8213/aaedb3

A knowledge of the particle escape time from the acceleration regions of many space and astrophysical sources is of critical importance in the analysis of emission signatures produced by these particles and in the determination of the acceleration and transport mechanisms at work. This Letter addresses this general problem, in particular in solar flares, where in addition to scattering by turbulence, the magnetic field convergence from the acceleration region toward its boundaries also influences the particle escape. We test an (approximate) analytic relation between escape and scattering times, and the field convergence rate, based on the work of Malyshkin & Kulsrud, valid for both strong and weak diffusion limits and isotropic pitch-angle distributions of the injected particles, with a numerical model of particle transport. To this end, a kinetic Fokker–Planck transport model of particles is solved with a stochastic differential equation scheme, assuming different initial pitch-angle distributions. This approach enables further insights into the phase-space dynamics of the transport process, which would otherwise not be accessible. We find that in general the numerical results agree well with the analytic equation for the isotropic case; however, there are significant differences in the weak diffusion regime for non-isotopic cases, especially for distributions beamed along the magnetic field lines. The results are important in the interpretation of observations of energetic particles in solar flares and other similar space and astrophysical acceleration sites, and for the determination of acceleration-transport coefficients, commonly used in Fokker–Planck–type kinetic equations.

The Diffusion Approximation versus the Telegraph Equation for Modeling Solar Energetic Particle Transport with Adiabatic Focusing. I. Isotropic Pitch-angle Scattering

Frederic **Effenberger** and Yuri E. Litvinenko

2014 ApJ 783 15

http://arxiv.org/pdf/1410.1225v1.pdf

The diffusion approximation to the Fokker-Planck equation is commonly used to model the transport of solar energetic particles in interplanetary space. In this study, we present exact analytical predictions of a higher order telegraph approximation for particle transport and compare them with the corresponding predictions of the diffusion approximation and numerical solutions of the full Fokker-Planck equation. We specifically investigate the role of the adiabatic focusing effect of a spatially varying magnetic field on an evolving particle distribution. Comparison of the analytical and numerical results shows that the telegraph approximation reproduces the particle intensity profiles much more accurately than does the diffusion approximation, especially when the focusing is strong. However, the telegraph approximation appears to offer no significant advantage over the diffusion approximation for calculating the particle anisotropy. The telegraph approximation can be a useful tool for describing both diffusive and wave-like aspects of the cosmic-ray transport.

Ultraheavy Element Enrichment in Impulsive Solar Flares

David **Eichler**

2014 ApJ 794 6

Particle acceleration by cascading Alfvén wave turbulence was suggested as being responsible for energetic particle populations in 3He-rich solar flares. In particular, it was noted that the damping of the turbulence by the tail of the particle distribution in rigidity naturally leads to the dramatic enhancement of a pre-accelerated species—as 3He is posited to be—and superheavy elements. The subsequent detection of large enrichment of ultraheavies, relative to iron, has apparently confirmed this prediction, lending support to the original idea. It is shown here that this picture could be somewhat sharpened by progress in understanding the three-dimensional geometrical details of cascading Alfvén turbulence. The mechanism may be relevant in other astrophysical environments where the source of turbulence is nonmagnetic, such as clusters of galaxies.

Major solar-energetic particle fluxes: II. Comparison of the interplanetary parameters between the three largest high-energy peak flux events 19-20/10/1989, 14/7/2000 and 9/11/2000
El-Borie, M. A.
(**2003**),Astroparticles Phys., 19, 667-677.
The study of the largest solar-energetic particle (SEP) events gives important information about the physical process in the solar corona and in the heliosphere. The hourly SEPs and interplanetary (IP) and geomagnetic measurements of the three largest SEP events have been compared. The most relevant physical factors which determine the largest SEP properties have been examined. The results indicate that there is a quite different in IP and geomagnetic disturbances and in turn, the mechanism of particle accelerations among the three events. We found that the time profile of 14 July 2000 fluxes was not similar to that observed in 19-20 October 1989. The acceleration of fluxes was not a function of the IP shock's efficiency. The velocity of IP shock has been decelerated in its path in the inner heliosphere. The acceleration of the particles seems probably to happened in the lower part of the solar corona. The rate of geomagnetic disturbances during the 14-19 July 2000 was stronger than the other events and included highly changes. In contrast, the third event of 9 November 2000 was not shed a ground level enhancement. Fast rise and long decay in particle intensities which may be originated from different sources on the Sun. The IP shock was hardly deteriorated in its path to the Earth. Mere reduction in the interplanetary magnetic field connection has been obtained. The geomagnetic disturbances during the considered events have been examined and discussed.

Major solar‐energetic particle fluxes: I. Comparison with the associated ground level enhancement of cosmic rays,
El-Borie, M. A.
(**2003**),Astroparticles Phys., 19, 549**–**558.
We have identified 58 of extremely high solar energetic particle (SEP) events (with flux of over 10 protons (cm2secster)-1 with energy >=60 MeV) that recorded at the Earth between January 1973 and May 2001. Each event had the potential of producing perturbations to the geophysical environment. Nearly 40% of these events shed ground level enhancements (GLEs) of cosmic rays. The March 1989-July 1991 period (29 months) of solar cycle 22 had the larger proton events (in magnitude and fluence) than those recorded in cycle 21. The 19 October 1989 event was the largest well-recorded particle event so far. The time-intensity profile of SEP fluxes showed that multiple particle injection or varying particles acceleration either at the solar source or in propagation to the Earth. Furthermore, high GLE was not a necessarily comes as a sequence of major SEP event and it was not a condition for creating major SEP fluxes. Some proposal factors are presented for production SEP and GLE together.

Ellison, D.C., Ramaty, R.: 1985, Shock acceleration of electrons and ions in solar flares. *Astrophys. J.* **298**, 400. DOI. ADS.

Global Energetics of Thirty-eight Large Solar Eruptive Events
Emslie, A. G.; Dennis, B. R.; Shih, A. Y.; Chamberlin, P. C.; Mewaldt, R. A.; Moore, C. S.; Share, G. H.; Vourlidas, A.; Welsch, B. T.
Astrophysical Journal, Volume 759, Issue 1, article id. 71, 18 pp. (**2012**); **File**
http://arxiv.org/abs/1209.2654
We have evaluated the energetics of 38 solar eruptive events observed by a variety of spacecraft instruments between 2002 February and 2006 December, as accurately as the observations allow. The measured energetic components include: (1) the radiated energy in the Geostationary Operational Environmental Satellite 1-8 Å band, (2) the total energy radiated from the soft X-ray (SXR) emitting plasma, (3) the peak energy in the SXR-emitting plasma, (4) the bolometric radiated energy over the full duration of the event, (5) the energy in flare-accelerated electrons above 20 keV and in flare-accelerated ions above 1 MeV, (6) the kinetic and potential energies of the coronal mass ejection (CME), (7) the energy in solar energetic particles (SEPs) observed in interplanetary space, and (8) the amount of free (non-potential) magnetic energy estimated to be available in the pertinent active region. Major conclusions include: (1) the energy radiated by the SXR-emitting plasma exceeds, by about half an order of magnitude, the peak energy content of the thermal plasma that produces this radiation; (2) the energy content in flare-accelerated electrons and ions is sufficient to supply the bolometric energy radiated across all wavelengths throughout the event; (3) the energy contents of flare-accelerated electrons and ions are comparable; (4) the energy in SEPs is typically a few percent of the CME kinetic energy (measured in the rest frame of the solar wind); and (5) the available magnetic energy is sufficient to power the CME, the flare-accelerated particles, and the hot thermal plasma. **2002 February 20, 2002 May 22, 2002 November 9, 2003 May 27, 2003 October 28, 2004 July 15, 2004 July 25, 2005 January 20,**

Table 1. Event List with Component Energies (× 1030 ergs)

An Improved Treatment of Neutral Sheet Drift in the Inner Heliosphere

N. Eugene **Engelbrecht**1,2, S. T. Mohlolo1, and S. E. S. Ferreira1
2019 ApJL 884 L54
https://doi.org/10.3847/2041-8213/ab4ad6
Drifts due to the curvature and gradients in the heliospheric magnetic field, as well as along the heliospheric current sheet, have long been known to play a significant role in the transport of galactic cosmic rays. Recently, there has been greater interest in the role these drifts play in the transport of solar energetic particles. This study proposes an approach to modeling particle drift velocities in particle transport codes that, while being relatively simple to implement and computationally inexpensive, also models drift effects accurately across a broader range of energies than previous approaches.

On the Pitch-angle-dependent Perpendicular Diffusion Coefficients of Solar Energetic Protons in the Inner Heliosphere

N. Eugene **Engelbrecht**
2019 ApJ 880 60
sci-hub.se/10.3847/1538-4357/ab2871
Various numerical solar energetic particle (SEP) transport studies have shown that perpendicular diffusion plays a significant role in the propagation of these particles in the heliosphere. In particular, computed SEP intensities and anisotropies have been shown to be sensitive to the pitch-angle dependence of the perpendicular diffusion coefficient as well as its magnitude. This study proposes a novel approach to the calculation of this quantity and compares this to the results of previous theoretical approaches. These various perpendicular diffusion coefficient expressions are demonstrated for turbulence conditions prevalent at Earth and closer to the Sun.

Solar Event Simulations using the HAWC Scaler System

O. **Enriquez-Rivera**, A. Lara, R. Caballero-Lopez, for the HAWC Collaboration
the 34th International Cosmic Ray Conference (ICRC**2015**), The Hague, The Netherlands.
http://arxiv.org/pdf/1508.07285v1.pdf
The High Altitude Water Cherenkov (HAWC) Observatory is an air shower array located near the volcano Sierra Negra in Mexico. The observatory has a scaler system sensitive to low energy cosmic rays (the geomagnetic cutoff for the site is 8 GV) suitable for conducting studies of solar or heliospheric transients such as Ground Level Enhancements (GLEs) and Forbush decreases. In this work we present the simulation of the HAWC response to these phenomena. We computed HAWC effective areas for different array configurations (different selection of photomultiplier tubes per detector) relevant for Forbush decreases and GLEs. **2014 September 14**

Anomalous Forbush effects from sources far from Sun center

E. **Eroshenkoa**1, A. Belova1, H. Mavromichalakia2, V. Olenevaa1, A. Papaioannoua2 and V. Yanke
Proceedings of the International Astronomical Union / Volume 4 / Symposium S257, pp 451 – 456, Published online: 16 Март **2009**
http://journals.cambridge.org/action/displayIssue?iid=4866212
The Forbush effects associated with far western and eastern powerful sources on the Sun that occurred on the background of unsettled and moderate interplanetary and geomagnetic disturbances have been studied by data from neutron monitor networks and relevant measurements of the solar wind parameters. These Forbush effects may be referred to a special sub-class of events, with the characteristics like the event in July 2005, and incorporated by the common conditions: absence of a significant disturbance in the Earth vicinity; absence of a strong geomagnetic storm; slow decrease of cosmic ray intensity during the main phase of the Forbush effect. General features and separate properties in behavior of density and anisotropy of 10 GV cosmic rays for this subclass are investigated.

Onset of a CME-Related Shock Within the Large-Angle Spectrometric Coronagraph (LASCO) Field of View

V.G.**Fainshtein**, Ya.I.Egorov
Solar Physics September **2019**, 294:126
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1519-2.pdf
https://doi.org/10.1007/s11207-019-1519-2
We investigated the onset of a CME-related shock within the Large-Angle Spectrometric Coronagraph (LASCO) field of view (FOV). To detect the first moment of the shock onset, we found a CME on **17 July 2012** that formed at a relatively high altitude and moved with slow acceleration. We examined the possible mechanisms of shock

generation. It was shown that bow-shock and piston-shock mechanisms can participate in shock generation, either at different stages of CME movement, or simultaneously. This event has been found to be accompanied by generation of solar energetic particles (SEP). We concluded that, at their initial stage, the source of SEP fluxes may be a solar flare, while the later dramatic increase in the flux of fast protons may be due to their generation in a CME-driven shock.

Multipoint observations of coronal mass ejection and solar energetic particle events on Mars and Earth during November 2001

Falkenberg, T. V.; Vennerstrom, S.; Brain, D. A.; Delory, G.; Taktakishvili, A.
J. Geophys. Res., Vol. 116, No. A6, A06104, **2011**

Multipoint spacecraft observations provide unique opportunities to constrain the propagation and evolution of interplanetary coronal mass ejections (ICMEs) throughout the heliosphere. Using Mars Global Surveyor (MGS) data to study both ICME and solar energetic particle (SEP) events at Mars and OMNI and Geostationary Operational Environmental Satellite (GOES) data to study ICMEs and SEPs at Earth, we present a detailed study of three CMEs and flares in late November 2001. In this period, Mars trailed Earth by 56° solar longitude so that the two planets occupied interplanetary magnetic field lines separated by only ∼25°. We model the interplanetary propagation of CME events using the ENLIL version 2.6 3-D MHD code coupled with the Wang-Sheeley-Arge version 1.6 potential source surface model, using Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) images to determine CME input parameters. We find that multipoint observations are essential to constrain the simulations of ICME propagation, as two very different ICMEs may look very similar in only one observational location. The direction and width of the CME as parameters essential to a correct estimation of arrival time and amplitude of the ICME signal. We find that these are problematic to extract from the analysis of SOHO/LASCO images commonly used for input to ICME propagation models. We further confirm that MGS magnetometer and electron reflectometer data can be used to study not only ICME events but also SEP events at Mars, with good results providing a consistent picture of the events when combined with near-Earth data.

Long-duration neutron production by nonflaring transients in the solar corona

William C. **Feldman**, David J. Lawrence, W. Thomas Vestrand, Daniel N. Baker, Patrick N. Peplowski and Douglas J. Rodgers
JGR Volume 120, Issue 10 October **2015** Pages 8247–8266

The purpose of this work is to study neutron enhancements observed using the Neutron Spectrometer aboard MESSENGER in order to identify events that may have been generated at/or near the Sun by solar transients. To securely establish an origin of the observed neutrons that is nonlocal to the MESSENGER spacecraft, a measurement of the energetic ion environment local to MESSENGER is needed. For this purpose, we use energetic ion spectrometers on several spacecraft at 1 AU when they were magnetically connected to MESSENGER during an event. We report strong evidence that for six neutron events studied in detail, the detected neutrons do not likely have a local spacecraft origin. By implication, most of the detected neutrons for these six events may have originated near the Sun, generated by many moderate-level solar eruptive events that produce an extended solar exosphere of moderate-energy neutrons, protons, and electrons.

Evidence for extended acceleration of solar flare ions from 1-8 MeV solar neutrons detected with the MESSENGER Neutron Spectrometer

Feldman, William C.; Lawrence, David J.; Goldsten, John O.; Gold, Robert E.; Baker, Daniel N.; Haggerty, Dennis K.; Ho, George C.; Krucker, SДm; Lin, Robert P.; Mewaldt, Richard A.; Murphy, Ronald J.; Nittler, Larry R.; Rhodes, Edgar A.; Slavin, James A.; Solomon, Sean C.; Starr, Richard D.; Vilas, Faith; Vourlidas, Angelos
J. Geophys. Res., Vol. 115, No. A1, A01102, **2010**
http://dx.doi.org/10.1029/2009JA014535

Neutrons produced on the Sun during the M2 flare on **31 December 2007** were observed at 0.48 AU by the MESSENGER Neutron Spectrometer. These observations are the first detection of solar neutrons inside 1 AU. This flare contained multiple acceleration episodes as seen in type III radio bursts. After these bursts ended, both the energetic particle and neutron fluxes decayed smoothly to background with an *e*-folding decay time of 2.84 h, spanning a 9 h time period. This time is considerably longer than the mean lifetime of a neutron, which indicates that either the observed neutrons were generated in the spacecraft by solar energetic particle protons, or they originated on the Sun. If most of the neutrons came from the Sun, as our simulations of neutron production on the spacecraft show, they must have been continuously produced. A likely explanation of their long duration is that energetic ions were accelerated over an extended time period onto closed magnetic arcades above the corona and then slowly pitch angle–scattered by coronal turbulence into their chromospheric loss cones. Because of their relatively low energy loss in the Neutron Spectrometer (0.5–7.5 MeV), most of these neutrons beta decay to energetic protons and electrons close to the Sun, thereby forming an extended seed population available for further acceleration by subsequent shocks driven by coronal mass ejections in interplanetary space.

Solar particle event detected by ALTEA on board the International Space Station The March 7th, 2012 X5.4 flare

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J. Space Weather Space Clim. 4 (**2014**) A19

http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130060.pdf

Context. Solar activity poses substantial risk for astronauts of the International Space Station (ISS) both on board and during extravehicular activity. An accurate assessment of the charged radiation flux in space habitats is necessary to determine the risk and the specific type of radiation exposure of ISS crew members, and to develop ways to protect future crews for planetary missions, even in case of high solar activity.
Aims. To reduce the present-day uncertainties about the nature and magnitude of the particle fluxes in space habitats during a solar event, it is fundamental to measure those fluxes in situ.
Methods. The ALTEA (Anomalous Long Term Effects on Astronauts) experiment on board the ISS is an active detector composed of six silicon telescopes and is able to follow the dynamics of the radiation flux. During its operation in 2012 a number of flux peaks were detected in correspondence with solar events.
Results. We present in this work an analysis of the ALTEA data measured during the March 7th, 2012 solar event, produced by NOAA AR11429.
Conclusions. During this event, the flux was enhanced tenfold with respect to ‘‘quiet Sun’’ conditions, producing strong dose increases at high geomagnetic latitudes.

Examination of the relationship between riometer-derived absorption and the integral proton flux in the context of modeling polar cap absorption

R. A. D. **Fiori**, D. W. Danskin

Space Weather Volume 14, Issue 11, Version of Record online: 15 NOV **2016**

Energetic protons can penetrate into the ionosphere increasing ionization in the D region causing polar cap absorption that may potentially block high-frequency radio communications for transpolar flights. The protons are guided by the geomagnetic field into the high-latitude polar cap region. Riometers monitor variations in ionospheric absorption by observing the level of background cosmic radio noise. Current polar cap absorption modeling techniques are based on the linear relationship between absorption and the square root of the integral proton flux, which has previously only been demonstrated using data from a single high-latitude polar station. The proportionality constant describing this relationship is evaluated for two different polar cap absorption events occurring **7–11 March 2012 and 23 January 2012 to 1 February 2012**. Examination of the proportionality constant using data from riometers distributed between 60° and 90° magnetic latitude reveals a previously unreported latitudinal dependence for data at magnetic latitudes of ≤66.8° on the dayside and ≤70.8° on the nightside. Incorporating the latitudinal dependence into the current D Region Absorption Prediction absorption model improves the agreement between measurement-derived and modeled parameters by increasing the correlation coefficient between data sets, reducing the root-mean-square error, and reducing the bias.

On the Possible Mechanisms of the SEP Event and Electron Enhancement over the SEP Decay Phase on 2023 August 5

Kazi A. **Firoz**, Y. P. Li, and W. Q. Gan

2024 ApJ 977 248

https://iopscience.iop.org/article/10.3847/1538-4357/ad90b1/pdf

We carry out this study on the solar energetic particle (SEP) event that occurred on **2023 August 5** over the ascending phase of the current solar cycle 25. It is found that the SEP event might have been initiated by the M1.6 flare, while the SEP peak was caused by the coronal shock manifested in DH-type II radio burst over the propagation phase of a halo coronal mass ejection (CME; ∼1000 km s−1), thus creating a mixed SEP event. There were two enhancements of the electron fluxes lying over the SEP rise and decay phase. It is surprising that, despite a stronger flare (X1.6) and a faster halo CME (∼1647 km s−1), there was no SEP enhancement during the second enhancement of the electron fluxes. In order to investigate this, we make an additional effort to analyze the X1.6 flare based on the availability of the temporal, spectral, and spatial evolution of the electromagnetic radiation components. It is observed that the CME shock was aligned with the flare eruption direction and was close to the western limb (W77°), and thus the radially moving CME shock missed the Earth. In another development, it is observed that the electron impulsive phase lies over the type III radio bursts, indicating that the electrons might have escaped directly during the eruption. The radio flux and radio dynamic spectra of a higher frequency lie over the rise phase of the soft X-ray derivative, indicating that a large number of electrons travelled through magnetic fields.

Duration and Fluence of Major Solar Energetic Particle (SEP) Events

Kazi A. **Firoz**, W. Q. Gan, Y. P. Li, J. Rodríguez-Pacheco & L. I. Dorman
Solar Physics volume 297, Article number: 71 (**2022**)
https://doi.org/10.1007/s11207-022-01994-7

To understand solar energetic particle (SEP) events and their acceleration processes, it is important to study the SEP properties, e.g. duration and fluence. In this work, we analyzed the temporal evolution of fluxes [cm−2 sr−1 s−1] of >10, >30, and >60 MeV protons and the temporal and spectral evolution of electromagnetic-radiation components for 34 major SEP events that include 13 ground-level enhancement (GLE)-SEP and 21 non-GLE-SEP events, and then determined their possible onset and end times [UT], their duration [hours], and fluence [cm−2 sr−1]. It is observed that the temporal fluxes of >30 MeV protons can sometimes be utilized for those of the fluxes of >10 MeV protons. Correspondence between SEP duration and fluence demonstrates the dependence of fluence on duration that helps distinguish the typical and atypical SEP events. For instance, for the >10 MeV protons, correspondence between the duration and fluence exhibited a weaker correlation (r≈r≈ 0.78; pp<0.002) during the 13 GLE-SEPs than that (r≈r≈ 0.83; pp<0.0001) during the 21 non-GLE-SEPs, revealing a few GLE-SEPs with disproportionate comparability. During the 13 GLE-SEPs, correspondence between the SEP duration and fluence for >30 MeV protons exhibited a stronger correlation (r≈r≈ 0.82; pp<0.0006) than that (r≈r≈ 0.78; pp<0.002) for the >10 MeV protons, indicating that the temporal window of >30 MeV protons is sometimes more appropriate for obtaining a reasonable duration of SEPs. Accordingly, when the temporal window of flux of >30 MeV protons is utilized for that of the >10 MeV protons, the correlation increased significantly (r≈r≈ 0.86; pp<0.0002) during the 13 GLE-SEPs.

On the Relation between Flare and CME during GLE-SEP and Non-GLE-SEP Events

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https://iopscience.iop.org/article/10.3847/1538-4357/ab3c4e/pdf

Association of solar flares and coronal mass ejections (CMEs) with ground-level enhancement (GLE) is a recognized fact, but questions arise when a similar association is observed for non-GLEs. In this respect, we carry out a detailed study of the relation between flare fluences (ϕ J m−2) and CME speeds (V cme km s−1) during some selected GLEs and non-GLEs. As we found, most of the data points of ϕ (J m−2) and V cme (km s−1) of GLEs follow a near-linear trend, with the ϕ (J m−2) increasing as the V cme (km s−1) increases, resulting in a strong positive correlation (r ≥ 0.82), while the correlation (r ≤ 0.47) remains weak for non-GLEs. For any exceptional GLE, the ϕ (J m−2) and V cme (km s−1) that do not maintain a near-linear trend over the whole flare phase do maintain at least a minimum rational proportionality over the flare rise phase, whereas this characteristic was not generally observed for non-GLEs. Although the ϕ (J m−2) and V cme (km s−1) of some non-GLEs show a trend similar to those of GLEs, they indeed originated over the flare impulsive phases concomitant with coronal shock manifested in m type II bursts, while GLEs originated over the flare initial phase before the m type II. Flare peak fluences (ϕ pk J m−2) and V cme (km s−1) maintain weak correlation for both GLEs and non-GLEs, likely because the CME main acceleration ceases around the flare peak. However, though the ϕ pk (J m−2) governs the flare total fluence, it does not blur the correlation between the fluence over the flare rise phase (ϕ r J m−2) and V cme (km s−1), indicating that the flare peak/strength does not control the GLE occurrence. **13 Mar 2012, 17 May 2012**
Table 1 Over 14 GLE-SEP Events Associated with Flares >M4.7 (~M5) (1997-2013)
Table 2 Over 23 Non-GLE-SEP Events Associated with Flares of □M4.7 (~M5) (1997-2013)

On the Possible Mechanism of GLE Initiation

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2019 ApJ 872 178
https://doi.org/10.3847/1538-4357/ab0381
sci-hub.ru/10.3847/1538-4357/ab0381

With the goal of understanding the initiations of solar energetic particle (SEP) (MeV) and ground-level enhancement (GLE) (GeV) particles, we have studied relative timings at approximately the Sun between temporal evolutions of the particles and some electromagnetic radiation components representing flares and shocks. Results show that GLE onsets appear after flare prompt onsets and m-type II onsets, while the GLE-associated SEP onsets appear before the flare prompt onsets and m-type II onsets, thus specifying that the GLE-associated SEPs originate over the flare initial phases and get accelerated intensively over the flare prompt phases associated with coronal

shocks. The flare initial phase is found always earlier than the coronal mass ejection (CME) initial phase, further justifying that the MeV particles are initiated particularly by the flare initial phases and are accelerated to GeV energetic by flare prompt phases associated with the coronal shocks. On the contrary, most of the non-GLE-SEP onsets appear well after the flare prompt onsets and m-type II onsets, demonstrating that the non-GLE-SEPs mostly generate over the most intense part of the flare rise phases associated with the coronal shocks. In another development, the relative timings of flare prompt onset and peak times to the m- and DH-type II onsets show that usually the m-type II bursts commence before the flare peaks and DH-type II bursts commence after the flare peaks, signifying that the coronal shocks manifested in m-type II bursts operate over the flare main acceleration phases, while the coronal shocks manifested in DH-type II bursts operate over the flare decay and/or CME propagation phases, thereby suggesting that the evolution of the particles accelerated at the flare main acceleration phases can be prolonged by the shocks associated with the CME propagation phases. **97 Nov 4, 03 Nov 4**
Table 1 Over 13 GLE-SEP Events: Relative Timings between GLE-SEP Events and Some Electromagnetic Radiation Components Representing Flares and Shocks

An Interpretation of a Possible Mechanism for the First Ground-Level Enhancement of Solar Cycle 24

K. A. **Firoz**, W. Q. Gan, Y. P. Li, J. Rodríguez-Pacheco

Solar Phys. February **2015**, Volume 290, Issue 2, pp 613-626

It is well known that solar flares and shocks driven by coronal mass ejections (CMEs) are high-energy particle acceleration processes that might cause a high-energy particle event known as a ground-level enhancement (GLE). In this context, we have attempted to understand the processes responsible for the first GLE event (GLE71 **17 May 2012** 01:50 UT) of Solar Cycle 24. We studied the spatial and spectral data from the Solar Dynamics Observatory (SDO) the Culgoora radio-heliograph, and Wind/WAVES instrument, and analyzed the temporal data of the solar-flare components, the solar radio-flux density, and the electron fluxes from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), the Geostationary Operational Environmental Satellite (GOES), the Radio Solar Telescope Network (RSTN), and Wind spacecraft. The flare had two ribbons separated by the neutral line between negative and positive magnetic polarity. Their structure was also almost consistent with the contours of some flare components, which were almost saturated during the flare-peak time. As indicated by the metric–kilometric Type-II burst, and because it extended over a wide heliolongitude ($>\approx 41\circ$) range, the CME-driven shock was fast enough to cause high-energy particle acceleration at a high altitude in the solar corona. Moreover, the CME and flare-flash phases were aligned along the same direction, which implies that if the CME-driven shock played the leading role in causing the GLE, preceding flare components may have contributed to the shock.

An Interpretation of GLE71 Concurrent CME-driven Shock Wave

Firoz, Kazi A.; Zhang, Q. M.; Gan, W. Q.; Li, Y. P.; Rodríguez-Pacheco, J.; Moon, Y.-J.; Kudela, K.; Park, Y.-D.; Dorman, Lev I.

Astrophysical Journal Supplement, Volume 213, Issue 2, article id. 24, 14 pp. (**2014**)

Particle accelerations in solar flares and CME-driven shocks can sometimes result in very high-energy particle events (>=1 GeV) that are known as ground level enhancements (GLEs). Recent studies on the first GLE event (GLE71 **2012 May 17** 01:50 UT) of solar cycle 24 suggested that CME-driven shock played a leading role in causing the event. To verify this claim, we have made an effort to interpret the GLE71 concurrent shock wave. For this, we have deduced the possible speed and height of the shock wave in terms of the frequency (MHz) of the solar radio type II burst and its drift rate (MHz min-1), and studied the temporal evolution of the particle intensity profiles at different heights of the solar corona. For a better perception of the particle acceleration in the shock, we have studied the solar radio type II burst with concurrent solar radio and electron fluxes. When the particle intensity profiles are necessarily shifted in time at ~1 AU, it is found that the growth phases of the electron and cosmic ray intensity fluxes are strongly correlated (>0.91 >=0.87) with the frequency drift rate of the type II burst, which is also consistent with the intensive particle accelerations at upper coronal heights (~>=0.80 R S < 1.10 R S). Thus, we conclude that the CME-driven shock was possibly capable of producing the high-energy particle event. However, since the peaks of some flare components are found to be strongly associated with the fundamental phase of the type II burst, the preceding flare is supposed to contribute to the shock acceleration process.

On the possible mechanism of the first ground level enhancement in cosmic ray intensity of solar cycle 24

Firoz, Kazi A.; Gan, W. Q.; Li, Y. P.; Rodriguez-Pacheco, J.

Astrophysics and Space Science, Volume 350, Issue 1, pp.21-32, **2014**

We have carried out this work to comprehend the possible mechanisms of the first ground level enhancement (GLE71 **17 May 2012** 01:50 UT) in cosmic ray intensity of the solar cycle 24. For this, the cosmic ray intensities registered by neutron monitors at several sites have been analyzed and studied with concurrent solar flares of different energy channels. To assess empirically whether the GLE might have been caused by the energy released from solar flare or CME-driven shock, we identify the possible time line in terms of the lowest spectral index determined from proton fluxes. If the GLE is caused by the energy released from particle acceleration in solar flare, the intensive phase of the flare representing the extreme emission should exist within/around the possible time line. In this respect, it is observed that the possible time line lies within the prominent phase of CME-driven shock. For better understanding, we have checked the possible relativistic energy with respect to solar flare as well as CME-driven shock. As witnessed, if the extreme emission phase of the flare is considered as the reason for the causation of GLE peak, the flare components procured insufficient amount of energy (≤˜0.085 GeV) to produce a GLE. If the extreme emission phase of the flare is also considered as the dominator along GLE onset, the possible energy procurement (≤˜0.414 GeV) is still not adequate to produce a GLE. In contrast, the CME-driven shock is capable of procuring enough possible relativistic energy (≥˜1.21 GeV) that is sufficient amount of the energy for a GLE production. Any amount of the energy (<0.414 GeV) released from preceding flare components is supposed to have been contributed to the shock process. Thus, it is assumed that the GLE71 was possibly caused by the energy released from the shock acceleration, which might have been boosted by the energy emanated from preceding flare.

AN INTERPRETATION OF THE POSSIBLE MECHANISMS OF TWO GROUND-LEVEL ENHANCEMENT EVENTS

Kazi A. **Firoz**1, W. Q. Gan1, Y.-J. Moon2, and C. LI

2012 ApJ 758 119, **File**

We have carried out this work to clarify the possible mechanisms of two important high-energy particle events (**GLE69 2005 January 20, 06:46 UT and GLE70 2006 December 13, 02:45 UT**). For this purpose, the cosmic-ray intensities registered by neutron monitors at several sites have been analyzed and studied with concurrent solar flares of different energy bands. To determine whether the ground-level enhancement (GLE) might be caused by the energy released from a solar flare or a CME-driven shock, we identify the particle injection time in terms of the lowest value of the spectral indices deduced from proton fluxes. If the GLE is caused by the energy released from particle acceleration in a solar flare, the intensive phase of the flare representing extreme emission should lie within the injection time. While fulfilling this criterion, it is further necessary to understand the possible relativistic energy computed in terms of the possible travel time deduced by employing the observational time lag between the GLE and the concurrent solar flare. Accordingly, we have found that GLE69 is procured with sufficient possible relativistic energy (~1.619 GeV) by the energy released from particle accelerations in the intensive phases of a solar flare components that have been corroborated by the injection time. The intensive phases of the flare components have also been justified with the prominent phases of a solar radio type III burst. For event GLE70, the particle injection time lies within the CME-driven shock justified by a solar radio type II burst which seems to be capable of procuring sufficient possible relativistic energies (~1.231 to ~2.017 GeV). It is also noted that any fractional amount of energy (~0.226 to ~0.694 GeV) from preceding flare components might be considered as a contribution to the shock acceleration process. Thus, GLE70 is presumably caused by the sum of the energy released mostly from a CME-driven shock and partially from preceding flare components.

ON THE POSSIBLE MECHANISMS OF TWO GROUND-LEVEL ENHANCEMENT EVENTS

Kazi A. **Firoz**1, Y.-J. Moon2,3, S.-H. Park4, K. Kudela5, Jamal N. Islam1 and Lev I. Dorman

2011 ApJ 743 190, **File**

We have carried out a case study on the possible mechanism of ground-level enhancement (GLE) occurrence. For this, we have considered two GLE events (**GLE69 and GLE70**) and scrutinized their relationships with simultaneous soft/hard X-rays as well as solar energetic particle (SEP) fluxes of different energy bands. Although most of the energy bands of the flares maintain strong correlations ($r \geq 0.8$) with the GLEs, depending only on this evidence we could not precisely imply that GLEs can be caused by solar flares. So, we have attempted to understand possible relativistic energies of the GLEs, which have been determined by availing the relativistic traversing time and velocities of the particles along the nominal path of Archimedean spiral magnetic field lines. Results suggest that the energy released from accelerated particles in high-energy (γ-ray) solar flares might sometimes cause the GLE. We found that during hard X-ray flares ≤7 MeV, the relativistic energy (≤0.23 GeV) of GLE69 was much less than 1 GeV whereas during SEP flares >30 MeV the possible relativistic energy of GLE69 amounts to ~2.78 GeV, and this makes us believe that GLE69 might be caused by the energy released from particle accelerations in high-energy solar flares. On the contrary, during hard X-ray (≤7 MeV) as well as γ-ray solar flares (>30 MeV) the relativistic energy of GLE70 amounts to ≤~0.35 GeV, indicating that the GLE70 was presumably not caused by the released energy from accelerated particles in the solar flare. Alternatively, the released energy from particle accelerations in solar radio emission type II burst concomitant coronal-mass-ejection-driven shocks seems to have been responsible for causing the GLE70.

20.01.2005, 13.12.2006

On the relationship between ground level enhancement and solar flare

Firoz, K. A.; Moon, Y.-J.; Cho, K.-S.; Hwang, J.; Park, Y. D.; Kudela, K.; Dorman, L. I.
Journal of Geophysical Research, Volume 116, Issue A4, CiteID A04101, **2011**
We made an effort to understand the associations and relationships between ground level enhancement (GLE) events and solar flares for the time period of 1986-2006. Our results show that, on average, the GLE event-associated solar flare (˜0.2 × 10-4 W/m2) is much stronger than the non-GLE-associated solar flare (˜0.3 × 10-5 W/m2). The findings have also been supported by the solar flare indices that, on average, the GLE event-associated solar flare index (˜35.01) is much higher than the non-GLE-associated solar flare index (˜4.88). However, this association does not seem to precisely imply that GLEs can occur because of a solar flare, so we examined cross correlations between GLE events and simultaneous solar flares. We found that most (˜78%) of the highest correlations (r > 0.8) took place during an X class flare. There is no clear indication that the more the time lag, the less or more is the correlation or vice versa. Overall, 50% of the high correlations took place at higher time lag (≥65 min), and ˜36% of the high correlations took place at lower time lag (≤40 min), while the rest (˜14%) of the correlations were abruptly high and low at medium time lag (>40 and <65 min). On the basis of the results of cross correlations, we suggest that the intensive portions of solar flares should be responsible for causing GLEs and that the direct proportionality of the time-integrated intensive portion of a flare with the impulsive phase of a GLE event seems to be the main property for comprehending the mechanism.

Relationship of ground level enhancements with solar, interplanetary and geophysical parameters

Firoz, K. A.; Hwang, J.; Dorotovič, I.; Pintér, T.; Kaushik, Subhash C.
Astrophysics and Space Science, Volume 331, Issue 2, pp.469-484, **2011**
Cosmic rays registered by Neutron Monitor on the surface of the Earth are believed to originate from outer space, and sometimes also from the exotic objects of the Sun. Whilst the intensities of the cosmic rays are observed to be enhanced with sudden, sharp and short-lived increases, they are termed as ground level enhancements (GLEs). They are the occurrences in solar cosmic ray intensity variations on short-term basis, so different solar factors erupted from the Sun can be responsible for causing them. In this context, an attempt has been made to determine quantitative relationships of the GLEs having peak increase >5% with simultaneous solar, interplanetary and geophysical factors from 1997 through 2006, thereby searching the responsible factors which seem to cause the enhancements. Results suggest that GLE peaks might be caused by solar energetic particle fluxes and solar flares. The proton fluxes which seemed to cause GLE peaks were also supported by their corresponding fluences. For most of the flares, the time integrated rising portion of the flare emission refers to the strong portion of X-ray fluxes which might be the concern to GLE peak. On an average, GLE peak associated X-ray flux (0.71×10-4 w/m2) is much stronger than GLE background associated X-ray flux (0.11×10-6 w/m2). It gives a general consent that the GLE peak is presumably caused by the solar flare. Coronal mass ejection alone does not seem to cause GLE. Coronal mass ejection presumably causes geomagnetic disturbances characterized by geomagnetic indices and polarities of interplanetary magnetic fields.

Erratum to: Relationship of ground level enhancements with solar, interplanetary and geophysical parameters

Astrophysics and Space Science, Volume 332, Issue 1, pp.219-219, **2011**

Characteristics of ground-level enhancement–associated solar flares, coronal mass ejections, and solar energetic particles,

Firoz, K. A., K.-S. Cho, J. Hwang, D. V. Phani Kumar, J. J. Lee, S. Y. Oh, S. C. Kaushik, K. Kudela, M. Rybanský, and L. I. Dorman,
J. Geophys. Res., 115, A09105, doi:10.1029/2009JA015023, (**2010**).
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2009JA015023
Ground-level enhancements (GLEs) are sudden, sharp, and short-lived increases in cosmic ray intensities registered by neutron monitors. These enhancements are known to take place during powerful solar eruptions. In the present investigation, the cosmic ray intensities registered by the Oulu neutron monitor have been studied for the period between January 1979 and July 2009. Over this span of time, increase rates of 32 GLEs have been deduced. In addition, we have studied characteristics of the 32 event-associated solar flares, coronal mass ejections (CMEs), and solar energetic particle (SEP) fluxes. We found that all of the 32 GLEs were associated with solar flares, CMEs, and SEP fluxes. Approximately 82% of the events were associated with X-class flares. Most of the flares that were associated with GLEs of increase rates >10% originated from the active regions located on the southwest hemisphere of the Sun. The average speed (1726.17 km/s) of GLE-associated CMEs was much faster than the average speed (423.39 km/s) of non-GLE-associated CMEs. It also became evident that ~67% GLEs were associated with very fast (>1500 km/s) CMEs. Although a GLE event is often associated with a fast CME, this alone does not necessarily cause the enhancement. Solar flares with strong optical signatures may sometimes cause GLE. High SEP fluxes often seem to be responsible for causing GLEs as the correlation with SEP fluxes implies.

The case for a common spectrum of particles accelerated in the heliosphere: Observations and theory

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JGR Volume 119, Issue 11, pages 8733–8749, November **2014**

In the last decade a significant discovery has been made in the heliosphere: the spectrum of particles accelerated in both the inner heliosphere and in the heliosheath is the same: a power law in particle speed with a spectral index of −5, when the spectrum is expressed as a distribution function; or equivalently, a differential intensity spectrum that is a power law in energy with a spectral index of −1.5. In the inner heliosphere this common spectrum occurs at quite low energies and is most evident in instruments designed to measure suprathermal particles. In the heliosheath, the common spectrum is observed over the full energy range of the Voyager energetic particle instruments, up to energies of ~100 MeV. The remarkable discovery of a common spectrum is compounded by the realization that no traditional acceleration mechanism, i.e., diffusive shock acceleration or stochastic acceleration, can account for the common spectrum. There is thus an opportunity to once again demonstrate the relevance of heliospheric physics by developing a new acceleration mechanism that yields the common spectrum, with the expectation that such a new acceleration mechanism will find broader applications in astrophysics. In this paper, the observations of the common spectrum in the heliosphere are summarized, with emphasis on those that best reveal the conditions in which the acceleration must operate. Then, building on earlier work, a complete derivation is presented of an acceleration mechanism, a pump acceleration mechanism, that yields the common spectrum, and the various subtleties associated with this derivation are discussed.

Wave Generation by Flare-accelerated Ions and Implications for 3He Acceleration

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2024 ApJ 964 97

https://iopscience.iop.org/article/10.3847/1538-4357/ad217f/pdf

https://arxiv.org/pdf/2311.12149.pdf

The waves generated by high-energy proton and alpha particles streaming from solar flares into regions of colder plasma are explored using particle-in-cell simulations. Initial distribution functions for the protons and alphas consist of two populations: an energetic, streaming population represented by an anisotropic ($T_\parallel > T_\perp$), one-sided kappa function and a cold, Maxwellian background population. The anisotropies and nonzero heat fluxes of these distributions destabilize oblique waves with a range of frequencies below the proton cyclotron frequency. These waves scatter particles out of the tails of the initial distributions along constant-energy surfaces in the wave frame. Overlap of the nonlinear resonance widths allows particles to scatter into near-isotropic distributions by the end of the simulations. The dynamics of 3He are explored using test particles. Their temperatures can increase by a factor of nearly 20. Propagation of such waves into regions above and below the flare site can lead to heating and transport of 3He into the flare acceleration region. The amount of heated 3He that will be driven into the flare site is proportional to the wave energy. Using values from our simulations, we show that the abundance of 3He driven into the acceleration region should approach that of 4He in the corona. Therefore, waves driven by energetic ions produced in flares are a strong candidate to drive the enhancements of 3He observed in impulsive flares.

Anisotropies of solar energetic electrons in the MeV range measured with Solar Orbiter/EPD/HET

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A&A 676, A58 (**2023**)

https://www.aanda.org/articles/aa/pdf/2023/08/aa45909-23.pdf

Aims. This study analyses relativistic electron measurements obtained by the High Energy Telescope (HET) aboard Solar Orbiter in the energy range from 200 keV to above 10 MeV. Caveats of these measurements are discussed. The purpose of this study is to analyse anisotropies of relativistic solar energetic electrons utilising the different viewing directions of HET.

Methods. We identified time periods of interest, that is, those with enhanced electron flux due to a significant solar component, and composed a list of these time periods, including additional observations such as maximum energy and flux as well as the first-order anistropy.

Results. This study provides an overview of HET measurements of MeV electrons and a list of time periods of enhanced flux of relativistic solar electrons, 21 in total. For the first time with Solar Orbiter/EPD/HET, the anisotropies of high-energy electrons have been measured. Specifically, we find three time periods with significant anisotropy above 1 MeV within 0.5 au. **April 15, 2022**

Table 2. Time periods with enhanced electron flux in the E200 channel. 2021-2022

Effect of acceleration and escape of energetic particles on spectral steepening at shocks

Federico **Fraschetti**
ApJ **2020**
https://arxiv.org/pdf/2012.12073.pdf
Energetic particles spectra at interplanetary shocks often exhibit a power law within a narrow momentum range softening at higher energy. We introduce a transport equation accounting for particle acceleration and escape with diffusion contributed by self-generated turbulence close to the shock and by pre-existing turbulence far upstream. The upstream particle intensity steepens within one diffusion length from the shock as compared with diffusive shock acceleration rollover. The momentum spectrum, controlled by macroscopic parameters such as shock compression, speed, far upstream diffusion coefficient and escape time at the shock, can be reduced to a log-parabola and also to a broken power law. In the case of upstream uniform diffusion coefficient, the largely used power law/exponential cut off solution is retrieved.

Bi-directional streaming of particles accelerated at the STEREO-A shock on 2008 March 9

F **Fraschetti**, J Giacalone
Monthly Notices of the Royal Astronomical Society, Volume 499, Issue 2, December **2020**, 2087–2093,
https://doi.org/10.1093/mnras/staa3021
We present an interpretation of anisotropy and intensity of supra-thermal ions near a fast quasi-perpendicular reverse shock measured by Solar Terrestrial Relations Observatory Ahead (ST-A) on **2008 March 9**. The measured intensity profiles of the supra-thermal particles exhibit an enhancement, or 'spike', at the time of the shock arrival and pitch-angle anisotropies before the shock arrival are bi-modal, jointly suggesting trapping of near-scatter-free ions along magnetic field lines that intersect the shock at two locations. We run test-particle simulations with pre-existing upstream magnetostatic fluctuations advected across the shock. The measured bi-modal upstream anisotropy, the nearly field-aligned anisotropies up to ∼15 min upstream of the shock, as well as the 'pancake-like' anisotropies up to ∼10 min downstream of the shock are well reproduced by the simulations. These results, in agreement with earlier works, suggest a dominant role of the large-scale structure (100s of supra-thermal proton gyroradii) of the magnetic field in forging the early-on particle acceleration at shocks.

Cross-field transport and pitch-angle anisotropy of solar energetic particles in MHD turbulence

F. **Fraschetti**
Proceedings of the workshop "Cosmic Ray Anisotropies", 26-30 January 2015, Bad Honnef, Germany, **2016**
http://arxiv.org/pdf/1512.08973v1.pdf
Recent modelling of solar energetic particles (SEPs) propagation through the heliospheric turbulence, also discussed in this workshop, has investigated the role of the pitch-angle scattering and the perpendicular transport in spreading particles in heliolongitude, as shown by multi-spacecraft measurements (STEREO A/B, ACE, SOHO, etc.) at 1 AU in various energy ranges. In some events the first-order pitch-angle anisotropy of the particles distribution is not-negligible. We calculate the average perpendicular displacement due to the gradient/curvature drift in an inhomogeneous turbulence accounting for pitch-angle dependence for two MHD turbulence models: (a) 3-D isotropic, (b) anisotropic as conjectured by Goldreich-Sridhar. We find in both cases that the drift scales as (1−μ2)2 with the cosine of pitch-angle μ, in contrast with previous models for transport of SEPs. This result can impact the models of propagation of SEPs through the heliosphere.

Acceleration of Solar Energetic Particles through CME-driven Shock and Streamer Interaction

Federica **Frassati**1, Monica Laurenza2, Alessandro Bemporad1, Matthew J. West3, Salvatore Mancuso1, Roberto Susino1, Tommaso Alberti2, and Paolo Romano4
2022 ApJ 926 227
https://iopscience.iop.org/article/10.3847/1538-4357/ac460e/pdf
On **2013 June 21**, a solar prominence eruption was observed, accompanied by an M2.9 class flare, a fast coronal mass ejection, and a type II radio burst. The concomitant emission of solar energetic particles (SEPs) produced a significant proton flux increase, in the energy range 4–100 MeV, measured by the Low and High Energy Telescopes on board the Solar TErrestrial RElations Observatory (STEREO)-B spacecraft. Only small enhancements, at lower energies, were observed at the STEREO-A and Geostationary Operational Environmental Satellite (GOES) spacecraft. This work investigates the relationship between the expanding front, coronal streamers, and the SEP fluxes observed at different locations. Extreme-ultraviolet data, acquired by the Atmospheric Imaging Assembly (AIA) instrument on board the Solar Dynamics Observatory (SDO), were used to study the expanding front and its interaction with streamer structures in the low corona. The 3D shape of the expanding front was reconstructed and extrapolated at different times by using SDO/AIA, STEREO/Sun Earth Connection Coronal and Heliospheric Investigation, and Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph observations

with a spheroidal model. By adopting a potential field source surface approximation and estimating the magnetic connection of the Parker spiral, below and above 2.5 R⨀, we found that during the early expansion of the eruption, the front had a strong magnetic connection with STEREO-B (between the nose and flank of the eruption front) while having a weak connection with STEREO-A and GOES. The obtained results provide evidence, for the first time, that the interaction between an expanding front and streamer structures can be responsible for the acceleration of high-energy SEPs up to at least 100 MeV, as it favors particle trapping and hence increases the shock acceleration efficiency.

First report of a solar energetic particle event observed by China's Tianwen-1 mission in transit to Mars

Shuai **Fu**, Zheyi Ding, Yongjie Zhang, Xiaoping Zhang, Cunhui Li, Gang Li, Shuwen Tang, Haiyan Zhang, Yi Xu, Yuming Wang, Jingnan Guo, Lingling Zhao, Yi Wang, Xiangyu Hu, Pengwei Luo, Zhiyu Sun, Yuhong Yu, Lianghai Xie

ApJL **934** L15 **2022**

https://arxiv.org/pdf/2207.06740.pdf

https://iopscience.iop.org/article/10.3847/2041-8213/ac80f5/pdf

Solar energetic particles (SEPs) associated with flares and/or coronal mass ejection (CME)-driven shocks can impose acute radiation hazards to space explorations. To measure energetic particles in near-Mars space, the Mars Energetic Particle Analyzer (MEPA) instrument onboard China's Tianwen-1 (TW-1) mission was designed. Here, we report the first MEPA measurements of the widespread SEP event occurring on **29 November 2020** when TW-1 was in transit to Mars. This event occurred when TW-1 and Earth were magnetically well connected, known as the Hohmann-Parker effect, thus offering a rare opportunity to understand the underlying particle acceleration and transport process. Measurements from TW-1 and near-Earth spacecraft show similar double-power-law spectra and a radial dependence of the SEP peak intensities. Moreover, the decay phases of the time-intensity profiles at different locations clearly show the reservoir effect. We conclude that the double-power-law spectrum is likely generated at the acceleration site, and that a small but finite cross-field diffusion is crucial to understand the formation of the SEP reservoir phenomenon. These results provide insight into particle acceleration and transport associated with CME-driven shocks, which may contribute to the improvement of relevant physical models.

Heating of Heavy Ions in Low-beta Compressible Turbulence

Xiangrong **Fu**, Fan Guo, Hui Li, Xiaocan Li

ApJ **2019**

https://arxiv.org/pdf/1909.12404.pdf

Enhancement of minor ions such as 3He and heavy ions in flare-associated solar energetic particle (SEP) events remains one of the major puzzles in heliophysics. In this work, we use 3D hybrid simulations (kinetic protons and fluid electrons) to investigate particle energization in a turbulent low-beta environment similar to solar flares. It is shown that in this regime the injected large-amplitude Alfvén waves develop into compressible and anisotropic turbulence, which efficiently heats thermal ions of different species. We find that temperature increase of heavy ions is inversely proportional to the charge to mass ratio, which is consistent with observations of impulsive SEP events. Further analysis reveals that ions are energized by interacting with nearly perpendicular magnetosonic waves near proton inertial scale.

Effect of Star Rotation Rates on the Characteristics of Energetic Particle Events

Shuai **Fu**, Yong Jiang, Vladimir Airapetian, Junxiang Hu, Gang Li, Gary Zank

ApJL **2019**

https://arxiv.org/pdf/1906.05167.pdf

Recent detection of superflares on solar-type stars by Kepler mission raised a possibility that they can be associated with energetic coronal mass ejections (CMEs) and energetic particle events (SEPs). These space weather events can impact habitability of exoplanets around these stars. Here we use the improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, to model the time intensity profile and spectrum of SEPs accelerated at CME-driven shocks from stars of different ages traced by their rotation rates. We consider a solar-like (G-type) star with 6 different rotation rates varying from 0.5 to 3.0 times rotation speed of the sun. In all 6 cases, a fast CME is launched with the same speed of 1500 km/sec and the resulting time intensity profiles at 3 locations and and energy spectra at 5 locations at 1 AU are obtained. The maximum particle energy at the shock front as a function of r is also shown. Our results suggest that within 0.8 AU the maximum particle energy at the shock front increases with the rotation rate of the star. However, event integrated spectra for the five selected locations along the CME path show complicated patterns. This is because the Parker magnetic field for rapidly rotating stars is more tightly winded. Our results can be used in estimating the radiation environments of terrestrial-type exoplanets around solar-type stars.

SEP events and multi-spacecraft observations: Constraints on theory

Angela **Gardini**a, b, , , Monica Laurenzaa, and Marisa Storini
Advances in Space Research, Volume 47, Issue 12, 15 June **2011**, Pages 2127-2139
Fifteen solar energetic particle (SEP) events have been analyzed using proton flux data recorded by the Helios 1, Helios 2, and IMP 8 spacecraft in the energy range 4–40 MeV during 1974–1982. For each of the events at least two of the spacecraft have their nominal magnetic footpoint within 20° in heliocentric longitude from each other. The SEP events are sub-grouped as a function of their heliocentric longitudinal separation and heliocentric radial distance from the SEP associated solar flare and several case studies are presented in this paper. Main results concerning their usage in estimating the SEP radial dependence are given. Moreover, we investigate the behavior of the third not connected spacecraft in order to study the dependence of the proton flux as a function of flare location. It is found that the contribution of the longitudinal gradient in determining variations in the SEP proton flux is particularly relevant for spacecraft having their magnetic connection footpoint separated from the flare between 30° and 50°.

SEP acceleration in CME driven shocks using a hybrid code
L. **Gargate**, R. A. Fonseca, L. O. Silva, R.A. Bamford, R.Bingham
ApJ, 792 9, **2014**
http://arxiv.org/pdf/1406.5543v1.pdf
We preform hybrid simulations of super Alfvenic quasi-parallel shock, driven by a Coronal Mass Ejection (CME), propagating in the Outer Coronal or Solar Wind at distances of between 3 to 6 solar radii. The hybrid treatment of the problem enable the study of the shock propagation on the ion time scale, preserving ion kinetics and allowing for a self consistent treatment of the shock propagation and particle acceleration. The CME plasma drags the embedded magnetic field lines stretching from the sun, and propagates out into interplanetary space at a greater velocity than the in-situ solar wind, driving the shock, and producing very energetic particles. Our results show electromagnetic Alfven waves are generated at the shock front. The waves propagate upstream of the shock and are produced by the counter streaming ions of the solar wind plasma being reflected at the shock. A significant fraction of the particles are accelerated in two distinct phases: first, particles drift from the shock and are accelerated in the upstream region and, second, particles arriving at the shock get trapped, and are accelerated at the shock front. A fraction of the particles diffused back to the shock, which is consistent with the Fermi acceleration mechanism

Forecasting methods for occurrence and magnitude of proton storms with solar hard X rays
Garcia, Howard A.
Space Weather **Volume2, Issue 6** S06003 February **2004** doi:10.1029/2003SW000035
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2003SW000035
A hard X-ray spectrometer (HXRS) was developed jointly by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center and the Astronomical Institute of the Czech Republic to determine if proton storms could be forecast with greater accuracies than presently available by the existing methods. The HXRS experiment was conceived as a means of proof testing previously discovered empirical relationships between anomalous hard X-ray spectra of hard X-ray flares and solar energetic proton events (SEPs) for space weather forecasting applications. SEPs are showers of highly energetic electrons and ions, mostly protons, that can reach Earth's vicinity within minutes to hours following a moderate to large flare and have the potential of affecting the performance of civilian, military and research satellites as well as certain surface assets. The primary SEP predictor criterion educed during the present study is the requirement that the spectral index, g, must decline (harden) to at least 4 for at least 3 min. Flares meeting this criterion have a high association with SEPs. Flares that fail this criterion do not. Other SEP correlative phenomena such as depressed hard X-ray flux and anomalous low temperatures were studied to determine their utility for forecasting purposes. During the study period, March 2000 through December 2002, 107 hard X-ray flares were spectrally analyzed including 16 SEP-associated flares. Fourteen SEP flares were correctly identified, two SEPs were missed, and three false alarms (untrue predictions) were incurred.

Forecasting methods for occurrence and magnitude of proton storms with solar soft X rays
Garcia, Howard A.
Space Weather, 2, Issue 2, S02002, **2004** doi:10.1029/2003SW000001.
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2003SW000001
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2003SW000001
Solar energetic proton (SEP) events in the vicinity of Earth have the potential of affecting the performance of civilian, military, and research satellites, including such diverse functions as communications, spacecraft operations, surveillance, navigation, and life support systems. The National Oceanic and Atmospheric Administration's (NOAA) Space Environment Center and the U. S. Air Force Weather Agency cooperate to provide advance warnings of SEP events. Their explicit duties include the need to continually upgrade and improve the accuracy,

timeliness, and scope of SEP forecasts. Previous work on this topic established the empirical connection between SEPs and low-temperature X-ray flares. The main focus of the present work is to improve the quality of SEP forecasts by enhancing the size and content of the flare database used to quantify the probability model, tuning the model with imposed operational constraints, and augmenting each SEP prediction with an estimate of the magnitude of the particle event itself.

Low temperature soft X-ray flares, spectrally hardening hard X-ray flares and energetic interplanetary protons,

Garcia, H. A., and A. L. Kiplinger (**1996**),
in *Solar Drivers of Interplanetary and Terrestrial Disturbances*, ASP Conf. Ser., vol. **95**, pp. 91–99, edited by K. Balasubramaniam, S. Keil, and R. Smartt, Astron. Soc. of the Pac., San Fransisco, Calif.
http://articles.adsabs.harvard.edu/pdf/1996ASPC...95...91G

Abstract. Recent studies of soft x-ray emission (Garcia 1994) and hard x-ray spectroscopy (Kiplinger 1995) from samples of flares covering large portions of solar cycles 21 and 22 indicate that most solar energetic proton (SEP) events observed in the vicinity of Earth are highly associated with occurrences of particular types of solar flare characteristics. There are two apparent signatures of flares that are associated with SEP events that distinguish them from the common impulsive solar flare. Garcia's study showed that these flares have anomalously low temperatures in soft x-rays. Kiplinger's study revealed signatures of hard x-ray spectra that progressively harden during periods of decaying fluxes. Progressive hardening in hard x-rays may be the observable consequence of electron acceleration in large, low-density loops that are in close proximity to open field topologies. Low temperatures in soft x-rays are a newly discovered trait that may be interpreted as a thermal energy deficit in comparison with normal impulsive flares of the same soft x-ray intensity. Kiplinger (1995) noted that when an event exhibited a period of impulsive behavior and a period of progressive spectral hardening, the impulsive periods always occur first. Moreover, the relative flux contributions from the two periods varied widely from event to event. Some progressively hardening events showed no evidence of an impulsive component. This study compares soft x-ray flare peak temperatures with hard x-ray flares having differing relative intensities in the impulsive versus progressive hardening phases. This comparison revealed that the lowest temperature flares corresponded to hard x-ray events that had no, or weak, impulsive phases in relation to the hardening phase, and that the more intense soft x-ray flares corresponded to hard x-ray flares with a dominant impulsive phase.

Temperature and Hard X-Ray Signatures for Energetic Proton Events

Garcia, Howard A.
1994 ApJ...420..422G
http://articles.adsabs.harvard.edu/pdf/1994ApJ...420..422G

The temperature distributions of flares associated with solar energetic protons (SEPs) have been found to differ significantly from those of normal (non-SEP-associated) flares. At high temperature (greater than or about = 20 MK) and high X-ray intensity, the two temperature distributions merge. At lower temperature (less than or about = 20 MK) and low X-ray intensity, the distributions separate; the SEP-associated flares tend to exhibit temperatures anomalously lower than those of normal flares. At high X-ray intensity, gradual hard X-ray flares are highly correlated with SEPs; at low-to-moderate X-ray intensities, this correlation is much weaker. These two properties, a low-temperature signature for weak flares and a gradual hard X-ray signature for intense flares, may prove useful in identifying events potentially productive of SEPs for all levels of intensity above soft X-ray class M1.

Prediction and warning system of SEP events and solar flares for risk estimation in space launch operations

Alberto **García-Rigo**1*, Marlon Núñez2, Rami Qahwaji3, Omar Ashamari3, Piers Jiggens4, Gustau Pérez1, Manuel Hernández-Pajares1 and Alain Hilgers
J. Space Weather Space Clim., 6, A28 (**2016**)
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150014.pdf

A web-based prototype system for predicting solar energetic particle (SEP) events and solar flares for use by space launch operators is presented. The system has been developed as a result of the European Space Agency (ESA) project SEPsFLAREs (Solar Events Prediction system For space LAunch Risk Estimation). The system consists of several modules covering the prediction of solar flares and early SEP Warnings (labeled Warning tool), the prediction of SEP event occurrence and onset, and the prediction of SEP event peak and duration. In addition, the system acquires data for solar flare nowcasting from Global Navigation Satellite Systems (GNSS)-based techniques

(GNSS Solar Flare Detector, GSFLAD and the Sunlit Ionosphere Sudden Total Electron Content Enhancement Detector, SISTED) as additional independent products that may also prove useful for space launch operators. **5-8 Dec 2006, 18th April, 2014**

Forecasting methods for occurrence and magnitude of proton storms with solar hard X rays,

Garcia, H. A.

Space Weather, *2*, S06003, **2004**,

http://onlinelibrary.wiley.com/doi/10.1029/2003SW000035/epdf

A hard X-ray spectrometer (HXRS) was developed jointly by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center and the Astronomical Institute of the Czech Republic to determine if proton storms could be forecast with greater accuracies than presently available by the existing methods. The HXRS experiment was conceived as a means of proof testing previously discovered empirical relationships between anomalous hard X-ray spectra of hard X-ray flares and solar energetic proton events (SEPs) for space weather forecasting applications. SEPs are showers of highly energetic electrons and ions, mostly protons, that can reach Earth's vicinity within minutes to hours following a moderate to large flare and have the potential of affecting the performance of civilian, military and research satellites as well as certain surface assets. The primary SEP predictor criterion educed during the present study is the requirement that the spectral index, γ, must decline (harden) to at least ≤ 4 for at least 3 min. Flares meeting this criterion have a high association with SEPs. Flares that fail this criterion do not. Other SEP correlative phenomena such as depressed hard X-ray flux and anomalous low temperatures were studied to determine their utility for forecasting purposes. During the study period, March 2000 through December 2002, 107 hard X-ray flares were spectrally analyzed including 16 SEP-associated flares. Fourteen SEP flares were correctly identified, two SEPs were missed, and three false alarms (untrue predictions) were incurred.

Forecasting methods for occurrence and magnitude of proton storms with solar soft X-rays.

Garcia, H.A.:

2004, Space Weather 2, S02002.

http://onlinelibrary.wiley.com/doi/10.1029/2003SW000001/epdf **File**

Solar energetic proton (SEP) events in the vicinity of Earth have the potential of affecting the performance of civilian, military, and research satellites, including such diverse functions as communications, spacecraft operations, surveillance, navigation, and life support systems. The National Oceanic and Atmospheric Administration's (NOAA) Space Environment Center and the U. S. Air Force Weather Agency cooperate to provide advance warnings of SEP events. Their explicit duties include the need to continually upgrade and improve the accuracy, timeliness, and scope of SEP forecasts. Previous work on this topic established the empirical connection between SEPs and low-temperature X-ray flares. The main focus of the present work is to improve the quality of SEP forecasts by enhancing the size and content of the flare database used to quantify the probability model, tuning the model with imposed operational constraints, and augmenting each SEP prediction with an estimate of the magnitude of the particle event itself.

Hard x-ray spectroscopy for proton flare prediction

Garcia, Howard A. ; Farnik, Frantisek ; Kiplinger, Alan L.

Proc. SPIE Vol. 3442, p. 210-216, **1998**, Missions to the Sun II, Clarence M. Korendyke; Ed.

https://doi.org/10.1117/12.330259

https://sci-hub.ru/10.1117/12.330259

High energy interplanetary proton events can jeopardize vital military and civilian spacecraft by disrupting logical circuits and by actually damaging spacecraft electronic components. Studies of solar hard x-rays indicate that high-energy proton events observed near Earth are highly associated with an uncommon type of solar flare exhibiting temporal progressively hardening hard x-ray spectra. A hard x-ray spectrometer is being developed by the Czech Astronomical Institute to provide a test bed for evaluating this phenomenon as a possible proton-storm prediction method. The instrument is designed to measure hard x-ray spectra in a high fluence, high-energy particle background environment such as that found at geosynchronous altitude. This experiment has been selected for space flight by the DoD Space Test Program and will fly aboard the Department of Energy satellite, Multi-spectral thermal Imager, scheduled for a three year mission, beginning in late 1999. The timing of this mission, fortuitously, coincides with the experiment are: 1) to evaluate the efficacy of this type of solar instrument in predicting interplanetary proton storms; 2) to study the high-energy physics of solar flares in concert with the premier flight of the NOAA soft x-ray imaging telescope, SXI, on the GOES 12 weather satellite and other solar mission. If the first goal is demonstrated by this mission, continuous monitoring of the Sun for proton events could become operational from geo-synchronous orbit during solar cycle 24. **December 7, 1982**

Low-Temperature Soft X-ray Flares, Spectrally Hardening Hard X-ray Flares, and Energetic Interplanetary Protons

Garcia, H. A. ; Kiplinger, A. L.

Solar drivers of the interplanetary and terrestrial disturbances. Astronomical Society of the Pacific Conference Series, Proceedings of the 16th (sixteenth) international workshop National Solar Observatory/Sacramento Peak, Sunspot, New Mexico, USA, 16-20 October 1995, San Francisco: Astronomical Society of the Pacific (ASP), **1996**, edited by K. S. Balasubramaniam, Stephen L. Keil, and Raymond N. Smartt, p.91

https://articles.adsabs.harvard.edu/pdf/1996ASPC...95...91G

Abstract. Recent studies of soft x-ray emission (Garcia 1994) and hard x-ray spectroscopy (Kiplinger 1995) from samples of flares covering large portions of solar cycles 21 and 22 indicate that most solar energetic proton (SEP) events observed in the vicinity of Earth are highly associated with occurrences of particular types of solar flare characteristics. There are two apparent signatures of flares that are associated with SEP events that distinguish them from the common impulsive solar flare. Garcia's study showed that these flares have anomalously low temperatures in soft x-rays. Kiplinger's study revealed signatures of hard x-ray spectra that progressively harden during periods of decaying fluxes. Progressive hardening in hard x-rays may be the observable consequence of electron acceleration in large, low-density loops that are in close proximity to open field topologies. Low temperatures in soft x-rays are a newly discovered trait that may be interpreted as a thermal energy deficit in comparison with normal impulsive flares of the same soft x-ray intensity. Kiplinger (1995) noted that when an event exhibited a period of impulsive behavior and a period of progressive spectral hardening, the impulsive periods always occur first. Moreover, the relative flux contributions from the two periods varied widely from event to event. Some progressively hardening events showed no evidence of an impulsive component. This study compares soft x-ray flare peak temperatures with hard x-ray flares having differing relative intensities in the impulsive versus progressive hardening phases. This comparison revealed that the lowest temperature flares corresponded to hard x-ray events that had no, or weak, impulsive phases in relation to the hardening phase, and that the more intense soft x-ray flares corresponded to hard x-ray flares with a dominant impulsive phase.

Temperature and Hard X-Ray Signatures for Energetic Proton Events

Garcia, Howard A.

Astrophysical Journal v.420, p.422, **1994**

https://articles.adsabs.harvard.edu/pdf/1994ApJ...420..422G **File**

The temperature distributions of flares associated with solar energetic protons (SEPs) have been found to differ significantly from those of normal (non-SEP-associated) flares. At high temperature (greater than or about = 20 MK) and high X-ray intensity, the two temperature distributions merge. At lower temperature (less than or about = 20 MK) and low X-ray intensity, the distributions separate; the SEP-associated flares tend to exhibit temperatures anomalously lower than those of normal flares. At high X-ray intensity, gradual hard X-ray flares are highly correlated with SEPs; at low-to-moderate X-ray intensities, this correlation is much weaker. These two properties, a low-temperature signature for weak flares and a gradual hard X-ray signature for intense flares, may prove useful in identifying events potentially productive of SEPs for all levels of intensity above soft X-ray class M1.

Diffusive shock acceleration and turbulent reconnection

Christian **Garrel** Loukas Vlahos Heinz Isliker Theophilos Pisokas

Monthly Notices of the Royal Astronomical Society, Volume 478, Issue 3, August **2018**, Pages 2976–2986,
sci-hub.se/10.1093/mnras/sty1260
Diffusive shock acceleration (DSA) cannot efficiently accelerate particles without the presence of self-consistently generated or pre-existing strong turbulence (δB/B∼ 1) in the vicinity of the shock. The problem we address in this article is: if large-amplitude magnetic disturbances are present upstream and downstream of a shock then Turbulent Reconnection (TR) will set in and will participate not only in the elastic scattering of particles but also in their heating and acceleration. We demonstrate that large-amplitude magnetic disturbances and Unstable Current Sheets (UCS), spontaneously formed in the strong turbulence in the vicinity of a shock, can accelerate particles as efficiently as DSA in large-scale systems and on long time scales. We start our analysis with 'elastic' scatterers upstream and downstream and estimate the energy distribution of particles escaping from the shock, recovering the well-known results from the DSA theory. Next we analyse the additional interaction of the particles with active scatterers (magnetic disturbances and UCS) upstream and downstream of the shock. We show that the asymptotic energy distribution of the particles accelerated by DSA/TR has very similar characteristics with the one due to DSA alone, but the synergy of DSA with TR is much more efficient: The acceleration time is an order of magnitude shorter and the maximum energy reached two orders of magnitude higher. We claim that DSA is the dominant acceleration mechanism in a short period before TR is established, and then strong turbulence will dominate the heating and acceleration of the particles. In other words, the shock serves as the mechanism to set up a strongly turbulent environment, in which the acceleration mechanism will ultimately be the synergy of DSA and TR.

Analysis and interpretation of inner-heliospheric SEP events with the ESA Standard Radiation Environment Monitor (SREM) onboard the INTEGRAL and Rosetta Missions

Manolis K. **Georgoulis**1*, Athanasios Papaioannou2, Ingmar Sandberg2, Anastasios Anastasiadis2, Ioannis A. Daglis2, Rosa Rodríguez-Gasén4, Angels Aran4, Blai Sanahuja4 and Petteri Nieminen5
J. Space Weather Space Clim. **2018**, 8, A40
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc160041.pdf
Using two heliospheric vantage points, we study 22 solar energetic particle (SEP) events, 14 of which were detected at both locations. SEP proton events were detected during the declining phase of solar cycle 23 (November 2003–December 2006) by means of two nearly identical Standard Radiation Environment Monitor (SREM) units in energies ranging between 12.6 MeV and 166.3 MeV. In this work we combine SREM data with diverse solar and interplanetary measurements, aiming to backtrace solar eruptions from their impact in geospace (i.e., from L1 Lagrangian point to Earth's magnetosphere) to their parent eruptions at the Sun's low atmosphere. Our SREM SEP data support and complement a consistent inner-heliospheric description of solar eruptions (solar flares and coronal mass ejections [CMEs]) and their magnetospheric impact. In addition, they provide useful information on the understanding of the origin, acceleration, and propagation of SEP events at multi-spacecraft settings. All SEP events in our sample originate from major eruptions consisting of major (>M-class) solar flares and fast (>1800 km/s, on average), overwhelmingly (>78%) halo, CMEs. All but one SEP event studied are unambiguously associated with shock-fronted CMEs, suggesting a CME-driven shock acceleration mechanism. Moreover, a significant correlation is found between the SEP event peak and the onset of the storm sudden commencement, that might help improve prediction of magnetospheric disturbances. In general, SEP events correlate better with interplanetary (i.e., in-situ; L1-based) than with solar eruption features. Our findings support (a) the routine use of cost-effective SREM units, or future improvements thereof, for the detection of SEP events and (b) their implementation in multi-spacecraft settings as a means to improve both the physical understanding of SEP events and their forecasting. **2003-Nov-2, 4, 2004-Jul-25, 2004-Sep-13,19, 2004-Nov-1,7,10, 2005 January 15,17,20, 2005 May 13, 2005-Jun-16, 2005-Jul-13,17,26, August 22, 2005, 2005 September 7,13, 2006-Dec-5, 16**
Table 2. Basic properties of detected INTEGRAL/(I1 – I22) and Rosetta/(R1 – R14) SREM SEP events. (November 2003–December 2006)
Table 3. Solar sources of detected SEPs

A study of the first solar proton event of current solar cycle recorded by satellites and ground based detectors

Gerontidou, M.; Mavromichalaki, H.; Plainaki, C.; Belov, A.; Eroshenko, E.; Yanke, V.; Laurenza, M.; Storini, M.
The 11th Hellenic Astronomical Conference, held 8-12 September, 2013 in Athens, Greece. Online at http://www.helas.gr/conf/2013/, pp.17-17, **2013**
On 2012, May 17 the GOES satellites recorded a great and simultaneous increase on proton flux in different energy channels thereby producing a solar proton event (SPE). These protons had enough energy to be recorded by the ground based worldwide network of neutron monitors thereby producing the first ground level enhancement of solar cosmic rays (GLE71) of the current solar cycle. In this work a combined study of the this solar proton event, as it is recorded by GOES satellites as well as by the ground based network of Neutron monitors is presented. On 2012,

May 17 at 02:10 UTC the GOES spacecraft recorded a fast rise in the flux of solar protons, followed by a slower decay, which was still ongoing on 18 May 2012. Several solar proton events stronger than that of 17 May 2012 were detected by GOES in January and March 2012. This event of 17 May extended to much higher energies than those earlier ones, but was weaker at lower energies. Through this research an attempt to understand the reason for these differences is performed. Additionally, a first attempt to derive the characteristics of this recent proton event, by applying an updated version of the NMBANGLE PPOLA model, already used for modeling past GLEs (e.g. GLE70) is presented. The special characteristics of this event with respect to the result of NMBANGLE POLLA model can provide useful information not only about the solar source that triggered this SPE, but also its special impact at interplanetary space.

Solar proton enhancements in different energy channels and coronal mass ejections during the last solar cycle

M. **Gerontidou**, H. Mavromichalaki[a], A. Belov[b] and V. Kurt

Advances in Space Research

Volume 43, Issue 4, 16 February **2009**, Pages 687-693

The main properties of 11622 coronal mass ejections (CMEs) observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO-C2) from January 1996 through December 2006 are considered. Moreover, the extended database of solar proton enhancements (SPEs) with proton flux >0.1 pfu at energy >10 MeV measured at the Earth's orbit is also studied. A comparison of these databases gives new results concerning the sources and acceleration mechanisms of solar energetic particles. Specifically, coronal mass ejections with width >180° (wide) and linear speed >800 km/s (fast) seem they have the best correlation with solar proton enhancements. The study of some specific solar parameters, such as soft X-ray flares, sunspot numbers, solar flare index etc. has showed that the soft X-ray flares with importance >M5 may provide a reasonable proxy index for the SPE production rate. From this work, it is outlined that the good relation of the fast and wide coronal mass ejections to proton enhancements seems to lead to a similar conclusion. In spite of the fact that in the case of CMEs the statistics cover only the last solar cycle, while the measurements of SXR flares are extended over three solar cycles, it is obvious for the studied period that the coronal mass ejections can also provide a good index for the solar proton production.

PSP/IS⊙IS Observation of a Solar Energetic Particle Event Associated With a Streamer Blowout Coronal Mass Ejection During Encounter 6

T. **Getachew**, D. J. McComas, C. J. Joyce, E. Palmerio, E. R. Christian, +++

ApJ **925** 212 **2022**

https://arxiv.org/pdf/2112.04671.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac408f/pdf

In this paper we examine a low-energy SEP event observed by IS⊙IS's Energetic Particle Instrument-Low (EPI-Lo) inside 0.18 AU on **September 30, 2020**. This small SEP event has a very interesting time profile and ion composition. Our results show that the maximum energy and peak in intensity is observed mainly along the open radial magnetic field. The event shows velocity dispersion, and strong particle anisotropies are observed throughout the event showing that more particles are streaming outward from the Sun. We do not see a shock in the in-situ plasma or magnetic field data throughout the event. Heavy ions, such as O and Fe were detected in addition to protons and 4He, but without significant enhancements in 3He or energetic electrons. Our analysis shows that this event is associated with a slow streamer-blowout coronal mass ejection (SBO-CME) and the signatures of this small CME event are consistent with those typical of larger CME events. The time-intensity profile of this event shows that PSP encountered the western flank of the SBO-CME. The anisotropic and dispersive nature of this event in a shockless local plasma give indications that these particles are most likely accelerated remotely near the Sun by a weak shock or compression wave ahead of the SBO-CME. This event may represent direct observations of the source of low-energy SEP seed particle population. **11 Nov 2018, 29-30 Sep 2020**

Neutron monitors and muon detectors for solar modulation studies: 2. φ time series

A. **Ghelfi**, D. Maurin, A. Cheminet, L. Derome, G. Hubert, F. Melot

AdSR **2016**

http://arxiv.org/pdf/1607.01976v1.pdf

The level of solar modulation at different times (related to the solar activity) is a central question of solar and galactic cosmic-ray physics. In the first paper of this series, we have established a correspondence between the uncertainties on ground-based detectors count rates and the parameter ϕ (modulation level in the force-field approximation) reconstructed from these count rates. In this second paper, we detail a procedure to obtain a reference ϕ time series from neutron monitor data. We show that we can have an unbiased and accurate ϕ reconstruction (Δϕ/ϕ≃10%). We also discuss the potential of Bonner spheres spectrometers and muon detectors to provide ϕ time series. Two by-products of this calculation are updated ϕ values for the cosmic-ray database and a web interface to retrieve and plot ϕ from the 50's to today (\url{this http URL}).

Analyses of ∼0.05–2 MeV Ions Associated with the 2022 February 16 Energetic Storm Particle Event Observed by Parker Solar Probe

Joe **Giacalone**1, C. M. S. Cohen2, D. J. McComas3, X. Chen1, M. A. Dayeh

2023 ApJ 958 144

https://iopscience.iop.org/article/10.3847/1538-4357/acfb86/pdf

We present analyses of 0.05–2 MeV ions from the **2022 February 16** energetic storm particle event observed by Parker Solar Probe's (PSP) IS⊙IS/EPI-Lo instrument at 0.35 au from the Sun. This event was characterized by an enhancement in ion fluxes from a quiet background, increasing gradually with time with a nearly flat spectrum, rising sharply near the arrival of the coronal mass ejection (CME)–driven shock, becoming nearly a power-law spectrum, then decaying exponentially afterward, with a rate that was independent of energy. From the observed fluxes, we determine diffusion coefficients, finding that far upstream of the shock the diffusion coefficients are nearly independent of energy, with a value of 1020 cm2 s−1. Near the shock, the diffusion coefficients are more than 1 order of magnitude smaller and increase nearly linearly with energy. We also determine the source of energetic particles, by comparing ratios of the intensities at the shock to estimates of the quiet-time intensity to predictions from diffusive shock acceleration theory. We conclude that the source of energetic ions is mostly the solar wind for this event. We also present potential interpretations of the near-exponential decay of the intensity behind the shock. One possibility we suggest is that the shock was overexpanding when it crossed PSP and the energetic particle intensity decreased behind the shock to fill the expanding volume. Overexpanding CMEs could well be more common closer to the Sun, and this is an example of such a case.

Anomalous Cosmic Rays and Heliospheric Energetic Particles **Review**

J. **Giacalone**, H. Fahr, H. Fichtner, V. Florinski, B. Heber, M. E. Hill, J. Kóta, R. A. Leske, M. S. Potgieter & J. S. Rankin

Space Science Reviews volume 218, Article number: 22 (**2022**)

https://link.springer.com/content/pdf/10.1007/s11214-022-00890-7.pdf

We present a review of Anomalous Cosmic Rays (ACRs), including the history of their discovery and recent insights into their acceleration and transport in the heliosphere. We focus on a few selected topics including a discussion of mechanisms of their acceleration, escape from the heliosphere, their effects on the dynamics of the heliosheath, transport in the inner heliosphere, and their solar cycle dependence. A discussion concerning their name is also presented towards the end of the review. We note that much is known about ACRs and perhaps the term Anomalous Cosmic Ray is not particularly descriptive to a non specialist. We suggest that the more-general term: “Heliospheric Energetic Particles”, which is more descriptive, for which ACRs and other energetic particle species of heliospheric origin are subsets, might be more appropriate.

Solar Energetic Particles Produced by a Slow Coronal Mass Ejection at ~0.25 au

J. **Giacalone**1, D. G. Mitchell2, R. C. Allen2, M. E. Hill2, R. L. McNutt Jr.2, J. R. Szalay3, M. I. Desai4, A. P. Rouillard5, A. Kouloumvakos5, D. J. McComas3Show full author list

2020 ApJS 246 29

https://doi.org/10.3847/1538-4365/ab5221

https://iopscience.iop.org/article/10.3847/1538-4365/ab5221/pdf

We present an analysis of Parker Solar Probe (PSP) IS⊙IS observations of ~30–300 keV n−1 ions on **2018 November 11** when PSP was about 0.25 au from the Sun. Five hours before the onset of a solar energetic particle (SEP) event, a coronal mass ejection (CME) was observed by STEREO-A/COR2, which crossed PSP about a day later. No shock was observed locally at PSP, but the CME may have driven a weak shock earlier. The SEP event was dispersive, with higher energy ions arriving before the lower energy ones. Timing suggests the particles originated at the CME when it was at ~7.4R ⊙. SEP intensities increased gradually from their onset over a few hours, reaching a peak, and then decreased gradually before the CME arrived at PSP. The event was weak, having a very soft energy spectrum (−4 to −5 spectral index). The earliest arriving particles were anisotropic, moving outward from the Sun, but later, the distribution was observed to be more isotropic. We present numerical solutions of the Parker transport equation for the transport of 30–300 keV n−1 ions assuming a source comoving with the CME. Our model agrees well with the observations. The SEP event is consistent with ion acceleration at a weak shock driven briefly by the CME close to the Sun, which later dissipated before arriving at PSP, followed by the transport of ions in the interplanetary magnetic field.

Diffusive Shock Acceleration of High-energy Charged Particles at Fast Interplanetary Shocks: A Parameter Survey
Joe **Giacalone**
2015 ApJ 799 80
We present results from numerical simulations of the acceleration of solar energetic particles (SEPs) associated with strong, fast, and radially propagating interplanetary shocks. We focus on the phase of the SEP event at the time of the shock passage at 1 AU, which is when the peak intensity at energies below a few MeV is the highest. The shocks in our study start between 2 and 10 solar radii and propagate beyond 1 AU. We study the effect of various shock and particle input parameters, such as the spatial diffusion coefficient, shock speed, solar wind speed, initial location of the shock, and shock deceleration rate, on the total integrated differential intensity, I, of SEPs with kinetic energies > 10 MeV. I is the integral over energy of the differential intensity spectrum at the time of the shock passage at 1 AU. We find that relatively small changes in the parameters can lead to significant event-to-event changes in I. For example, a factor of 2 increase in the diffusion coefficient at a given energy and spatial location, can lead to a decrease in I by as much as a factor of 50. This may help explain why there are fewer large SEP events seen during the current solar maximum compared to previous maxima. It is known that the magnitude of the interplanetary magnetic field is noticeably weaker this solar cycle than it was in the previous cycle and this will naturally lead to a somewhat larger diffusion coefficient of SEPs.

The Acceleration Mechanism of Anomalous Cosmic Rays **Review**
J. **Giacalone**, J. F. Drake, J. R. Jokipii
Space Science Reviews, November **2012**, Volume 173, Issue 1-4, pp 283-307
This paper reviews our current understanding of the acceleration mechanism of anomalous cosmic rays (ACRs). ACRs were first discovered in the early 1970s and soon afterwards it was recognized that they were accelerated interstellar pickup ions that obtained most of their energization in the outer heliosphere. Their observed composition and charge state suggest they are accelerated to over 200 MeV total energy in about a year. Diffusive shock acceleration at the solar-wind termination shock, which provided a natural explanation for spacecraft observations prior to the Voyager crossings of the termination shock in 2004 and 2007, was the long-held paradigm for the acceleration mechanism. But when both Voyagers crossed the shock, the ACR energy spectrum remained modulated, suggesting a source more distant than the shock. While shock acceleration remains a popular mechanism, other ideas have emerged recently to explain the observations. This review focuses on three main acceleration mechanisms that have been proposed: (a) acceleration at the termination shock including new effects such as the global blunt-shape of the shock and large-scale turbulence, (b) acceleration by magnetic reconnection in the heliosheath, and (c) acceleration by diffusive compression acceleration in the heliosheath.

THE LONGITUDINAL TRANSPORT OF ENERGETIC IONS FROM IMPULSIVE SOLAR FLARES IN INTERPLANETARY SPACE
J. **Giacalone** and J. R. Jokipii
2012 ApJ 751 L33
https://iopscience.iop.org/article/10.1088/2041-8205/751/2/L33/pdf
We present a study of the longitudinal spread of energetic charged particles from a localized instantaneous compact source on the Sun. Our study utilizes a diffusive-transport model for the propagation of energetic ions in interplanetary space. We show that even for very small values of the ratio of perpendicular to parallel diffusion coefficients—a few percent—the particles spread significantly in longitude. Spatial diffusion and adiabatic energy loss of ions in the interplanetary plasma cause impulsive particle events at Earth's orbit to last a few days. In this time, the combination of transport both along and across the local Parker-spiral magnetic field and the longitudinal motion of the magnetic lines of forces rooted at the Sun as it rotates leads to substantial longitudinal transport of the particles. We show that spacecraft separated by as much as 180° or more may observe events associated with compact solar sources, such as those from impulsive solar flares. Our results are qualitatively consistent with recent multi-spacecraft observations.

Solar-MACH: An open-source tool to analyze solar magnetic connection configurations
Jan **Gieseler**, Nina Dresing, Christian Palmroos, et al.
Front. Astron. Space Sci. 9:1058810. **2023** doi: 10.3389/fspas.2022.1058810
https://www.frontiersin.org/articles/10.3389/fspas.2022.1058810/pdf
https://www.frontiersin.org/articles/10.3389/fspas.2022.1058810/full
The Solar MAgnetic Connection HAUS1 tool (Solar-MACH) is an open-source tool completely written in Python that derives and visualizes the spatial configuration and solar magnetic connection of different observers (i.e.,

spacecraft or planets) in the heliosphere at different times. For doing this, the magnetic connection in the interplanetary space is obtained by the classic Parker Heliospheric Magnetic Field (HMF). In close vicinity of the Sun, a Potential Field Source Surface (PFSS) model can be applied to connect the HMF to the solar photosphere. Solar-MACH is especially aimed at providing publication-ready figures for the analyses of Solar Energetic Particle events (SEPs) or solar transients such as Coronal Mass Ejections (CMEs). It is provided as an installable Python package (listed on PyPI and conda-forge), but also as a web tool at solar-mach.github.io that completely runs in any web browser and requires neither Python knowledge nor installation. The development of Solar-MACH is open to everyone and takes place on GitHub, where the source code is publicly available under the BSD 3-Clause License. Established Python libraries like sunpy and pfsspy are utilized to obtain functionalities when possible. In this article, the Python code of Solar-MACH is explained, and its functionality is demonstrated using real science examples. In addition, we introduce the overarching SERPENTINE project, the umbrella under which the recent development took place. **2021-04-17, 9 October 2021, 28 October 2021**

New Anisotropic Cosmic-Ray Enhancement (ACRE) Event on 5 November 2023 Due to Complex Heliospheric Conditions.

Gil, A., Asvestari, E., Mishev, A. et al.

Sol Phys 299, 97 (**2024**).

https://doi.org/10.1007/s11207-024-02338-3

https://link.springer.com/content/pdf/10.1007/s11207-024-02338-3.pdf

https://link.springer.com/article/10.1007/s11207-024-02338-3

The variability of galactic cosmic rays near Earth is nearly isotropic and driven by large-scale heliospheric modulation but rarely can very local anisotropic events be observed in low-energy cosmic rays. These anisotropic cosmic-ray enhancement (ACRE) events are related to interplanetary transients. Until now, two such events have been known. Here, we report the discovery of the third ACRE event observed as an increase of up to 6.4% in count rates of high- and midlatitude neutron monitors between ca. 09 – 14 UT on **5 November 2023** followed by a moderate Forbush decrease and a strong geomagnetic storm. This is the first known observation of ACRE in the midrigidity range of up to 8 GV. The anisotropy axis of ACRE was in the nearly anti-Sun direction. Modeling of the geomagnetic conditions implies that the observed increase was not caused by a storm-induced weakening of the geomagnetic shielding. As suggested by a detailed analysis and qualitative modeling using the EUHFORIA model, the ACRE event was likely produced by the scattering of cosmic rays on an intense interplanetary flux rope propagating north of the Earth and causing a glancing encounter. The forthcoming Forbush decrease was caused by an interplanetary coronal mass ejection that hit Earth centrally. A comprehensive analysis of the ACRE and complex heliospheric conditions is presented. However, a full quantitative modeling of such a complex event is not possible even with the most advanced models and calls for further developments.

Geomagnetic Storm Effects on the LEO Proton Flux During Solar Energetic Particle Events

Kirolosse M. **Girgis**, Tohru Hada, Akimasa Yoshikawa, Shuichi Matsukiyo, Viviane Pierrard, Susan W. Samwel

Space Weather Volume21, Issue12 December **2023** e2023SW003664

https://doi.org/10.1029/2023SW003664

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003664

During a few solar energetic particle (SEP) events, solar protons were trapped within the geomagnetic field and reached the outer edge of the inner radiation belt. We reproduced this phenomenon by modeling the proton flux distribution at the Low-Earth Orbit (LEO) for different geomagnetic conditions during solar particle events. We developed a three-dimensional relativistic test particle simulation code to compute the 70–180 MeV solar proton Lorentz trajectories in low L-shell range from 1 to 3. The Tsyganenko model (T01) generated the background static magnetic field with the IGRF (v12) model. We have selected three Dst index values: −7, −150, and −210 nT, to define quiet time, strong, and severe geomagnetic storms and to generate the corresponding inner magnetic field configurations. Our results showed that the simulated solar proton flux was more enhanced in the high-latitude regions and more expanded toward the lower latitude range as long as the geomagnetic storm was intensified. Satellite observations and geomagnetic cutoff rigidities confirmed the numerical results. Furthermore, the LEO proton flux distribution was deformed, so the structure of the proton flux inside the South Atlantic Anomaly (SAA) became longitudinally extended as the Dst index decreased. Moreover, we have assessed the corresponding radiation environment of the LEO mission. We realized that, for a higher inclined LEO mission during an intense geomagnetic storm (Dst = −210 nT), the probability of the occurrence of the Single Event Upset (SEU) rates increased by 19% and the estimated accumulated absorbed radiation doses increased by 17% in comparison with quiet conditions. **31 March 2001**

Sunward-propagating Solar Energetic Electrons inside Multiple Interplanetary Flux Ropes

Raúl **Gómez-Herrero**1, Nina Dresing2, Andreas Klassen2, Bernd Heber2, Manuela Temmer3, Astrid Veronig3, Radoslav Bučík4,5, Miguel A. Hidalgo1, Fernando Carcaboso1, Juan J. Blanco
2017 ApJ 840 85
http://sci-hub.cc/10.3847/1538-4357/aa6c5c
On **2013 December 2 and 3**, the SEPT and STE instruments on board STEREO-A observed two solar energetic electron events with unusual sunward-directed fluxes. Both events occurred during a time interval showing typical signatures of interplanetary coronal mass ejections (ICMEs). The electron timing and anisotropies, combined with extreme-ultraviolet solar imaging and radio wave spectral observations, are used to confirm the solar origin and the injection times of the energetic electrons. The solar source of the ICME is investigated using remote-sensing observations and a three-dimensional reconstruction technique. In situ plasma and magnetic field data combined with energetic electron observations and a flux-rope model are used to determine the ICME magnetic topology and the interplanetary electron propagation path from the Sun to 1 au. Two consecutive flux ropes crossed the STEREO-A location and each electron event occurred inside a different flux rope. In both cases, the electrons traveled from the solar source to 1 au along the longest legs of the flux ropes still connected to the Sun. During the December 2 event, energetic electrons propagated along the magnetic field, while during the December 3 event they were propagating against the field. As found by previous studies, the energetic electron propagation times are consistent with a low number of field line rotations N < 5 of the flux rope between the Sun and 1 au. The flux rope model used in this work suggests an even lower number of rotations. **2013 November 29**

The Solar Orbiter Mission: an Energetic Particle Perspective

R. **Gómez-Herrero**, J. Rodríguez-Pacheco, R. F. Wimmer-Schweingruber, G.M. Mason, S. Sánchez-Prieto, C. Martín, M. Prieto, G.C. Ho, F. Espinosa Lara, I. Cernuda, J.J. Blanco, A. Russu, O. Rodríguez Polo, S.R. Kulkarni, C. Terasa, L. Panitzsch, S.I. Böttcher, S. Boden, B. Heber, J. Steinhagen, J. Tammen, J. Köhler, C. Drews, R. Elftmann, A. Ravanbakhsh, L. Seimetz, B. Schuster, M. Yedla, E. Valtonen, R. Vainio
XXV ECRS 2016 Proceedings - eConf C16-09-04.3 **2017**
https://arxiv.org/pdf/1701.04057v1.pdf
Solar Orbiter is a joint ESA-NASA mission planed for launch in October 2018. The science payload includes remote-sensing and in-situ instrumentation designed with the primary goal of understanding how the Sun creates and controls the heliosphere. The spacecraft will follow an elliptical orbit around the Sun, with perihelion as close as 0.28 AU. During the late orbit phase the orbital plane will reach inclinations above 30 degrees, allowing direct observations of the solar polar regions. The Energetic Particle Detector (EPD) is an instrument suite consisting of several sensors measuring electrons, protons and ions over a broad energy interval (2 keV to 15 MeV for electrons, 3 keV to 100 MeV for protons and few tens of keV/nuc to 450 MeV/nuc for ions), providing composition, spectra, timing and anisotropy information. We present an overview of Solar Orbiter from the energetic particle perspective, summarizing the capabilities of EPD and the opportunities that these new observations will provide for understanding how energetic particles are accelerated during solar eruptions and how they propagate through the Heliosphere.

Circumsolar Energetic Particle Distribution on 2011 November 3

R. **Gómez-Herrero**1,2, N. Dresing3, A. Klassen3, B. Heber3, D. Lario4, N. Agueda5, O. E. Malandraki6, J.J. Blanco1,2, J. Rodríguez-Pacheco1,2, and S. Banjac
2015 ApJ 799 55
Late on **2011 November 3**, STEREO-A, STEREO-B, MESSENGER, and near-Earth spacecraft observed an energetic particle flux enhancement. Based on the analysis of in situ plasma and particle observations, their correlation with remote sensing observations, and an interplanetary transport model, we conclude that the particle increases observed at multiple locations had a common single-source active region and the energetic particles filled a very broad region around the Sun. The active region was located at the solar backside (as seen from Earth) and was the source of a large flare, a fast and wide coronal mass ejection, and an EIT wave, accompanied by type II and type III radio emission. In contrast to previous solar energetic particle events showing broad longitudinal spread, this event showed clear particle anisotropies at three widely separated observation points at 1 AU, suggesting direct particle injection close to the magnetic footpoint of each spacecraft, lasting for several hours. We discuss these observations and the possible scenarios explaining the extremely broad particle spread for this event.

Solar Energetic Particle Events and Radio Bursts **Review**

Nat **Gopalswamy**
Proc. UN/Germany workshop on the International Space Weather Initiative: Preparing for the Solar Maximum, 10-14 June, 2024 **2024**
https://arxiv.org/pdf/2410.08690 **File**

Solar Energetic Particles (SEPs) and radio bursts are indicators of particle acceleration on the Sun and in the heliosphere. The accelerated particles have energies significantly higher than thermal particles up to several orders of magnitude. SEPs are detected directly by particle detectors on Earth and in space. Understanding SEPs is important from both science and application points of view because they are poorly understood and present space weather hazard to humans and their technology in space. SEPs accompany energetic flares, coronal mass ejections (CMEs), and intense radio bursts, which help us understand particle properties such as intensity, spectra, and time evolution. This paper summarizes how SEP properties are closely related to solar eruptions and the associated solar radio bursts. **2000.09.12, 2001.04.15, 2002.04.21, 2006.12.14, 2011.03.09**

Type III Radio Bursts from Solar Eruptions and their Connection to GLE and SGRE Events

Nat **Gopalswamy**, Anshu Kumari, Pertti A. Mäkelä

Proceedings of the URSI GASS 2023, Sapporo, Japan, 19 to 26 August 2023 **2023**

https://arxiv.org/ftp/arxiv/papers/2308/2308.11779.pdf **File**

We report on the close similarity of coronal mass ejection (CME) properties in ground level enhancement (GLE) in solar energetic particle (SEP) events and sustained gamma ray emission (SGRE) from the Sun as indicated by low frequency type III radio bursts observed in the interplanetary medium. The complex type III bursts have an average 1 MHz duration of 36 and 34 min in the SGRE and GLE events, respectively. Similarly, the CMEs underlying SGRE and GLE have average space speeds of 1866 and 2084 km/s, respectively. These are larger than the corresponding values (32 min, 1407 km/s) for a control sample of type III bursts associated with frontside halo CMEs with sky plane speed exceeding 800 km/s. These results are consistent with the idea that energetic CME driven shocks accelerate particles to very high energies that are responsible for GLE and SGRE events. **2014 February 24-25**

The Relation between Type III Radio Storms and CIR Energetic Particles

Nat **Gopalswamy**, Pertti Mäkelä, Seiji Yashiro, Sachiko Akiyama, Hong Xie

Proc. of 3rd URSI AT-AP-RASC, Gran Canaria, 29 May to 3 June 2022 **2022**

https://arxiv.org/ftp/arxiv/papers/2205/2205.15852.pdf

We report on a study that compares energetic particle fluxes in corotating interaction regions (CIRs) associated with type III radio storm with those in nonstorm CIRs. In a case study, we compare the CIR particle events on **2010 October 21 and 2005 November 2**. The two events have similar solar and solar wind circumstances, except that the former is associated with a type III radio storm and has a higher CIR particle flux and fluence. We also perform a statistical study, which shows that the proton and electron fluences are higher in the storm associated CIRs by factor of about 6 and 8, respectively than those in the storm-free CIRs.

Can Type III Radio Storms be a Source of Seed Particles to Shock Acceleration?

Nat **Gopalswamy**, Sachiko Akiyama, Pertti Mäkelä, Seiji Yashiro, Hong Xie

Proc. 3rd URSI AT-AP-RASC, Gran Canaria, 29 May to 3 June 2022, **2022**

https://arxiv.org/ftp/arxiv/papers/2205/2205.15233.pdf

An intense type III radio storm has been disrupted by a fast halo coronal mass ejection (CME) on **2000 April 4**. The CME is also associated with a large solar energetic particle (SEP) event. The storm recovers after about10 hrs. We identified another CME that occurs on **2003 November 11** with similar CME properties but there is no type III storm in progress. The 2003 November 11 CME is also not associated with an SEP event above the background (less than 2 pfu), whereas the one with type III storm has an intense SEP event (about 56 pfu). One of the factors affecting the intensity of SEP events is the presence of seed particles that are accelerated by CME-driven shocks. We suggest that the type III storm source, which accelerates electrons to produce the storm, also accelerates ions that serve as seed particles to the CME shock. **15 Jan 2005**

The Common Origin of High-energy Protons in Solar Energetic Particle Events and Sustained Gamma-ray Emission from the Sun

N. **Gopalswamy**, S. Yashiro, P. Makela, H. Xie, S. Akiyama

ApJ **915** 82 **2021**

https://arxiv.org/ftp/arxiv/papers/2105/2105.01206.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac004f/pdf
https://doi.org/10.3847/1538-4357/ac004f

We report that the number of > 500 MeV protons (Ng) inferred from sustained gamma ray emission (SGRE) from the Sun is significantly correlated with that of protons propagating into space (NSEP) as solar energetic particles (SEPs). Under the shock paradigm for SGRE, shocks driven by coronal mass ejections (CMEs) accelerate high-energy protons sending them toward the Sun to produce SGRE by interacting with the atmospheric particles. Particles also escape into the space away from the Sun to be detected as SEP events. Therefore, the significant

NSEP vs. Ng correlation (correlation coefficient 0.77) is consistent with the common shock origin for the two proton populations. Furthermore, the underlying CMEs have properties akin to those involved in ground level enhancement (GLE) events indicating the presence of high-energy (up to GeV) particles required for SGRE. We show that the observed gamma-ray flux is an underestimate in limb events (central meridian distance > 60 degrees) because SGRE sources are partially occulted when the emission is spatially extended. With the assumption that the SEP spectrum at the shock nose is hard and that the 100 MeV particles are accelerated throughout the shock surface (half width in the range 60 to 120 degrees) we find that the latitudinal widths of SEP distributions are energy dependent with the smallest width at the highest energies. Not using the energy-dependent width results in an underestimate of NSEP in SGRE events occurring at relatively higher latitudes. Taking these two effects into account removes the apparent lack of NSEP - Ng correlation reported in previous studies. **2011/03/07, 2011/06/07, 2011/08/04, 2011/08/09, 2011/09/06, 2012/01/23, 2012/01/27, 2012/03/07, 2012/05/17, 2012/07/07, 2013/04/11, 2013/10/28, 2014/02/25, 2014/09/01**
Table 1. CME, Flare, and SEP properties of SGRE events

Source of Energetic Protons in the 2014 September 1 Sustained Gamma-ray Emission Event

N. **Gopalswamy**, P. Mäkelä, S. Yashiro, H. Xie, S. Akiyama, N. Thakur

Solar Phys. **295**, Article number: 18 **2020** **File**

https://arxiv.org/ftp/arxiv/papers/2001/2001.03816.pdf
https://link.springer.com/content/pdf/10.1007/s11207-020-1590-8.pdf

We report on the source of greater than 300 MeV protons during the **SOL2014-09-01** sustained gamma-ray emission (SGRE) event based on multi-wavelength data from a wide array of space- and ground-based instruments. Based on the eruption geometry we provide concrete explanation for the spatially and temporally extended {\gamma}-ray emission from the eruption. We show that the associated flux rope is of low inclination (roughly oriented in the east-west direction), which enables the associated shock to extend to the frontside. We compare the centroid of the SGRE source with the location of the flux rope leg to infer that the high-energy protons must be precipitating between the flux rope leg and the shock front. The durations of the SOL2014-09-01 SGRE event and the type II radio burst agree with the linear relationship between these parameters obtained for other SGRE events with duration exceeding 3 hrs. The fluence spectrum of the SEP event is very hard, indicating the presence of high-energy (GeV) particles in this event. This is further confirmed by the presence of an energetic coronal mass ejection (CME) with a speed more than 2000 km/s, similar to those in ground level enhancement (GLE) events. The type II radio burst had emission components from metric to kilometric wavelengths as in events associated with GLE events. All these factors indicate that the high-energy particles from the shock were in sufficient numbers needed for the production of {\gamma}-rays via neutral pion decay.

A Catalog of Type II Radio Bursts Observed by Wind/WAVES and their Statistical Properties

Nat **Gopalswamy**, Pertti Mäkelä, Seiji Yashiro

Sun and Geosphere **2019**

https://arxiv.org/ftp/arxiv/papers/1912/1912.07370.pdf **File**

Solar type II radio bursts are the signature of particle acceleration by shock waves in the solar corona and interplanetary medium. The shocks originate in solar eruptions involving coronal mass ejections (CMEs) moving at super-Alfvenic speeds. Type II bursts occur at frequencies ranging from hundreds of MHz to tens of kHz, which correspond to plasma frequencies prevailing in the inner heliosphere from the base of the solar corona to the vicinity of Earth. Type II radio bursts occurring at frequencies below the ionospheric cutoff are of particular importance, because they are due to very energetic CMEs that can disturb a large volume of the heliosphere. The underlying shocks accelerate not only electrons that produce the type II bursts, but also protons and heavy ions that have serious implications for space weather. The type II radio burst catalog (this https URL) presented here provides detailed information on the bursts observed by the Radio and Plasma Wave Experiment (WAVES) on board the Wind Spacecraft. The catalog is enhanced by compiling the associated flares, **CMEs**, solar energetic particle (**SEP**) events including their basic properties. We also present the statistical properties of the radio bursts and the associated phenomena, including solar-cycle variation of the occurrence rate of the type II bursts. **2000.11.09, 2005.01.15-16. 2012.07.04**

See https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html

Extreme Kinematics of the 2017 September 10 Solar Eruption and the Spectral Characteristics of the Associated Energetic Particles

N. **Gopalswamy**, S. Yashiro, P. Makela, H. Xie, S. Akiyama, C. Monstein

ApJL 863:L39 **2018**

https://arxiv.org/ftp/arxiv/papers/1807/1807.09906.pdf https://iopscience.iop.org/article/10.3847/2041-8213/aad86c/pdf

We report on the **2017 September 10** ground level enhancement (GLE) event associated with a coronal mass ejection (CME) whose initial acceleration (~9.1km s^-2) and initial speed (~4300 km/s) were among the highest observed in the SOHO era. The GLE event was of low intensity (~4.4% above background) and softer-than-average fluence spectrum. We suggest that poor connectivity (longitudinal and latitudinal) of the source to Earth compounded by the weaker ambient magnetic field contributed to these GLE properties. Events with similar high initial speed either lacked GLE association or had softer fluence spectra. The shock-formation height inferred from the metric type II burst was ~1.4 Rs, consistent with other GLE events. The shock height at solar particle release (SPR) was ~4.4+/-0.38 Rs, consistent with the parabolic relationship between the shock height at SPR and source longitude. **2012 July 7, 2014 January 7**

Extreme Solar Eruptions and their Space Weather Consequences **Review**

Nat **Gopalswamy**

2017, be published by Elsevier as a chapter in the book, "Extreme Events in the Geospace: Origins, Predictability and Consequences", Ed. Natalia Buzulukova

In: Buzulukova N (ed) Extreme events in geospace, Elsevier, p 37.

https://arxiv.org/ftp/arxiv/papers/1709/1709.03165.pdf **File**

https://doi.org/10.1016/B978-0-12-812700-1.00002-9

Solar eruptions generally refer to coronal mass ejections (CMEs) and flares. Both are important sources of space weather. Solar flares cause sudden change in the ionization level in the ionosphere. CMEs cause solar energetic particle (SEP) events and geomagnetic storms. A flare with unusually high intensity and/or a CME with extremely high energy can be thought of examples of extreme events on the Sun. These events can also lead to extreme SEP events and/or geomagnetic storms. Ultimately, the energy that powers CMEs and flares are stored in magnetic regions on the Sun, known as active regions. Active regions with extraordinary size and magnetic field have the potential to produce extreme events. Based on current data sets, we estimate the sizes of one-in-hundred and one-in-thousand year events as an indicator of the extremeness of the events. We consider both the extremeness in the source of eruptions and in the consequences. We then compare the estimated 100-year and 1000-year sizes with the sizes of historical extreme events measured or inferred.

Carrington flare , 2003 October 28, 2004 November 10, October 2014

Table 1. Integral fluence values for different models in units of 1010 p cm-2

Table 2. Expected 100-year and 1000-year event sizes estimated from the tail of observed distributions fitted to various functions.

See: Extreme solar events **Review**

Edward W. **Cliver**, Carolus J. Schrijver, Kazunari Shibata & Ilya G. Usoskin

Living Reviews in Solar Physics volume 19, Article number: 2 (**2022**)

https://link.springer.com/content/pdf/10.1007/s41116-022-00033-8.pdf **File**

A Hierarchical Relationship between the Fluence Spectra and CME Kinematics in Large Solar Energetic Particle Events: A Radio Perspective

N **Gopalswamy**, P Mäkelä, S Yashiro, N Thakur, S Akiyama, H Xie

Journal of Physics: Conference Series (JPCS), Proceedings of the 16th Annual International Astrophysics Conference held in Santa Fe, NM, **2017** Volume 900, Issue 1, article id. 012009

https://arxiv.org/ftp/arxiv/papers/1707/1707.00209.pdf

http://iopscience.iop.org/article/10.1088/1742-6596/900/1/012009/pdf

We report on further evidence that solar energetic particles are organized by the kinematic properties of coronal mass ejections (CMEs)[1]. In particular, we focus on the starting frequency of type II bursts, which is related to the distance from the Sun where the radio emission starts. We find that the three groups of solar energetic particle (SEP) events known to have distinct values of CME initial acceleration, also have distinct average starting frequencies of the associated type II bursts. SEP events with ground level enhancement (GLE) have the highest starting frequency (107 MHz), while those associated with filament eruption (FE) in quiescent regions have the lowest starting frequency (22 MHz); regular SEP events have intermediate starting frequency (81 MHz). Taking the onset time of type II bursts as the time of shock formation, we determine the shock formation heights measured from the Sun center. We find that the shocks form on average closest to the Sun (1.51 Rs) in GLE events, farthest from the Sun in FE SEP events (5.38 Rs), and at intermediate distances in regular SEP events (1.72 Rs). Finally, we present the results of a case study of a CME with high initial acceleration (~3 km s^-2) and a type II radio burst with high starting frequency (~200 MHz) but associated with a minor SEP event. We find that the relation between the fluence spectral index and CME initial acceleration continues to hold even for this minor SEP event. **2010 June 12, 2011 November 26, 2012 May 17,**

The 2012 July 23 Backside Eruption: An Extreme Energetic Particle Event?

Nat **Gopalswamy**, Seiji Yashiro, Neeharika Thakur, Pertti Mäkelä, Hong Xie, Sachiko Akiyama
ApJ 833 216 **2016**
https://arxiv.org/pdf/1610.05790v1.pdf **File**
https://iopscience.iop.org/article/10.3847/1538-4357/833/2/216/pdf

The backside coronal mass ejection (CME) of **2012 July 23** had a short Sun to Earth shock transit time (18.5 hours). The associated solar energetic particle (SEP) event had a >10 MeV proton flux peaking at ~5000 pfu, and the energetic storm particle (ESP) event was an order of magnitude larger, making it the most intense event in the space era at these energies. By a detailed analysis of the CME, shock, and SEP characteristics, we find that the July 23 event is consistent with a high-energy SEP event (accelerating particles to GeV energies). The time of maximum and fluence spectra in the range 10-100 MeV were very hard, similar to those of ground level enhancement (GLE) events. ***We found a hierarchical relationship between the CME initial speeds and the fluence spectral indices: CMEs with low initial speeds had SEP events with the softest spectra, while those with highest initial speeds had SEP events with the hardest spectra***. CMEs attaining intermediate speeds result in moderately hard spectra. The July 23 event was in the group of hard-spectrum events. During the July 23 event, the shock speed (>2000 km s-1), the initial acceleration (~1.70 km s-2), and the shock formation height (~1.5 solar radii) were all typical of GLE events. The associated type II burst had emission components from metric to kilometric wavelengths suggesting a strong shock. These observation confirm that the 2012 July 23 event is likely to be an extreme event in terms of the energetic particles it accelerated.

Table 1: Intense ESP and GLE events since 1976

Table 2. List of SEP events, the fluence spectral indices, and the CME information (1997-2016)

Short term Variability of the Sun Earth System: An Overview of Progress Made during the CAWSES II Period **Review**

Nat **Gopalswamy**, Bruce Tsurutani, Yihua Yan
Progress in Earth and Planetary Science, v. 2, 13, **2015, File**
http://arxiv.org/pdf/1504.06332v1.pdf

This paper presents an overview of results obtained during the CAWSES II period on the short term variability of the Sun and how it affects the near Earth space environment. CAWSES II was planned to examine the behavior of the solar terrestrial system as the solar activity climbed to its maximum phase in solar cycle 24. After a deep minimum following cycle 23, the Sun climbed to a very weak maximum in terms of the sunspot number in cycle 24 (MiniMax24), so many of the results presented here refer to this weak activity in comparison with cycle 23. The short term variability that has immediate consequence to Earth and geospace manifests as solar eruptions from closed field regions and high speed streams from coronal holes. Both electromagnetic (flares) and mass emissions (coronal mass ejections, CMEs) are involved in solar eruptions, while coronal holes result in high speed streams that collide with slow wind forming the so called corotating interaction regions (CIRs). Fast CMEs affect Earth via leading shocks accelerating energetic particles and creating large geomagnetic storms. CIRs and their trailing high speed streams (HSSs), on the other hand, are responsible for recurrent small geomagnetic storms and extended (days) of auroral zone activity, respectively. The latter lead to the acceleration of relativistic magnetospheric killer electrons. One of the major consequences of the weak solar activity is the altered physical state of the heliosphere that has serious implications for the shock-driving and storm causing properties of CMEs. Finally, a discussion is presented on extreme space weather events prompted by the 2012 July 23 super storm event that occurred on the backside of the Sun. Many of these studies were enabled by the simultaneous availability of remote-sensing and in situ observations from multiple vantage points with respect to the Sun Earth line.

TABLE 2 Major geomagnetic storms of cycle 24 (Dst < -100 nT)

CMEs during the Two Activity Peaks in Cycle 24 and their Space Weather Consequences

N. **Gopalswamy**, P. Mäkelä, S. Akiyama, S. Yashiro, N. Thakur
Sun and Geosphere, vol.10, no.2, p.111-118. **2015**
http://arxiv.org/pdf/1509.04216v1.pdf **File**

We report on a comparison between space weather events that occurred around the two peaks in the sunspot number (SSN) during solar cycle 24. The two SSN peaks occurred in the years 2012 and 2014. Even though SSN was larger during the second peak, we find that there were more space weather events during the first peak. The space weather events we considered are large solar energetic particle (SEP) events and major geomagnetic storms associated with coronal mass ejections (CMEs). We also considered interplanetary type II radio bursts, which are indicative of energetic CMEs driving shocks. When we compared the CME properties between the two SSN peaks, we find that more energetic CMEs occurred during the 2012 peak. In particular, we find that CMEs accompanying IP type II bursts had an average speed of 1543 km/s during the 2012 peak compared to 1201 km/s during the 2014 peak. This result is consistent with the reduction in the average speed of the general population of CMEs during the second peak. All SEP events were associated with the interplanetary type II bursts, which are better than halo CMEs as indicators of space weather. The comparison between the two peaks also revealed the discordant behavior CME rate and SSN is more pronounced during the second peak. None of the 14 disk-center halo CMEs was associated with a major storm in 2014. The lone major storm in 2014 was due to the intensification of the (southward) magnetic field in the associated magnetic cloud by a shock that caught up and propagated into the magnetic cloud. **23-24 Apr 2012; 18-19 Feb 2014**

Table 2. List of DH-km type II bursts in 2012, the associated CMEs and SEP events

Table 3. List of DH-km type II bursts in 2014, the associated CMEs and SEP events

High-energy solar particle events in cycle 24

Nat **Gopalswamy**, Pertti Makela, Seiji Yashiro, Hong Xie, Sachiko Akiyama, Neeharika Thakur

The 14th International Astrophysics Conference held in Tampa, FL during April 24-29, 2015. Accepted for publication in Journal of Physics: Conference Series (JPCS). edited by G. Zank, **2015**

http://arxiv.org/ftp/arxiv/papers/1507/1507.06162.pdf; **File**

The Sun is already in the declining phase of cycle 24, but the paucity of high-energy solar energetic particle (SEP) events continues with only two ground level enhancement (GLE) events as of March 31, 2015. In an attempt to understand this, we considered all the large SEP events of cycle 24 that occurred until the end of 2014. We compared the properties of the associated CMEs with those in cycle 23. We found that the CME speeds in the sky plane were similar, but almost all those cycle-24 CMEs were halos. A significant fraction of (16%) of the frontside SEP events were associated with eruptive prominence events. CMEs associated with filament eruption events accelerate slowly and attain peak speeds beyond the typical GLE release heights. When we considered only western hemispheric events that had good connectivity to the CME nose, there were only 8 events that could be considered as GLE candidates. One turned out to be the first GLE event of cycle 24 (2012 May 17). In two events, the CMEs were very fast (>2000 km/s) but they were launched into a tenuous medium (high Alfven speed). In the remaining five events, the speeds were well below the typical GLE CME speed (~2000 km/s). Furthermore, the CMEs attained their peak speeds beyond the typical heights where GLE particles are released. We conclude that several factors contribute to the low rate of high-energy SEP events in cycle 24: (i) reduced efficiency of shock acceleration (weak heliospheric magnetic field), (ii) poor latitudinal and longitudinal connectivity), and (iii) variation in local ambient conditions (e.g., high Alfven speed).

CME Date UT Imp. Flr Loc. FR Loc B0 Final Loc Vsp Max E Ip 4
2011/06/07 06:16 M2.5 S21W54 S08W51 +0.1 S08W51 1680 330-420 72 5 **S5~910** **J10~50**
2011/08/04 03:41 M9.3 N19W36 N19W30 +6.0 N13W30 2450 165-500 96 6 **S9~2400** **J10~70**
2011/08/09 07:48 X6.9 N17W69 N08W68 +6.3 N02W68 2496 330-420 26 8 **S15~1600** **J10~25**
2011/11/26 06:09 C1.2 N08W49 N10W47 +1.5 N08W47 1187 40-80 80 13 без микроволн **J10~15**
мягкий спектр эрупция волокна
2012/05/17 01:25 M5.1 N11W76 S07W76 -2.4 S05W76 1997 >700 255 23 **GLE S5~750 J10~220**
SEP с жестким спектром от умеренной вспышки; исключение
2012/09/27 23:24 C3.7 N06W34 N16W29 +6.9 N09W29 1479 80-165 28 27 без микроволн **J10~27**
мягкий спектр
2013/05/22 13:08 M5.0 N15W70 N02W59 -1.8 N04W59 1881 330-420 1660 33 **S1.5-3~370, дм** **J10~100**
2014/02/20 07:26 M3.0 S15W73 S14W70 -7.0 S07W70 1281 330-420 22 **S5~500** **J10~20**

Почти все кандидаты на GLE – умеренные микроволны и умеренные протоны

Large Solar Energetic Particle Events Associated with Filament Eruptions Outside of Active Regions

N. **Gopalswamy**, P. Makela, S. Akiyama, S. Yashiro, H. Xie, N. Thakur, S. W. Kahler

ApJ **806** 8 **2015**

http://arxiv.org/ftp/arxiv/papers/1504/1504.00709.pdf

https://iopscience.iop.org/article/10.1088/0004-637X/806/1/8/pdf

We report on four large filament eruptions (FEs) from solar cycles 23 and 24 that were associated with large solar energetic particle (SEP) events and interplanetary type II radio bursts. The post-eruption arcades corresponded to *mostly C-class soft X-ray enhancements, but an M1.0 flare was associated with one event. However, the associated* coronal mass ejections (CMEs) were fast (speeds about 1000 km/s) and appeared as halo CMEs in the coronagraph field of view. The interplanetary type II radio bursts occurred over a wide wavelength range indicating the existence of strong shocks throughout the inner heliosphere. No metric type II bursts were present in three events, indicating that the shocks formed beyond 2 to 3 Rs. In one case, there was a metric type II burst with low starting frequency indicating a shock formation height of about 2 Rs. The FE-associated SEP events did have softer spectra (spectral index greater than 4) in the 10 to 100 MeV range, but there were other low-intensity SEP events with spectral indices >/=4. Some of these events are likely FE-SEP events, but were not classified so in the literature because they occurred close to active regions. Some were definitely associated with large active region flares, but the shock formation height was large. We definitely find a diminished role for flares and complex type III burst durations in these large SEP events. Fast CMEs and shock formation at larger distances from the Sun seem to be the primary characteristics of the FE-associated SEP events. **2000/04/04, 2000/07/22, 2000/09/12, 2000/10/25, 2001/09/15, 2001/10/19, 2002/03/16, 2002/04/17, 2002/05/22, 2002/08/14, 2003/05/31, 2004/04/11, 2010/08/14, 2011/08/09, 2011/11/26, 2012/09/28, 2013/09/29, 2014/02/20**

Major Solar Eruptions and High Energy Particle Events during Solar Cycle 24

N. **Gopalswamy**, H. Xie, S. Akiyama, P. Makela, S. Yashiro

2014, Earth, Planets, and Space, 66:104-118 **File**

http://arxiv.org/pdf/1408.3617v1.pdf

https://earth-planets-space.springeropen.com/track/pdf/10.1186/1880-5981-66-104.pdf

We report on a study of all major solar eruptions that occurred on the front-side of the Sun during the rise to peak phase of cycle 24 (first 62 months) in order to understand the key factors affecting the occurrence of large solar energetic particle events (SEPs) and the ground levels enhancement (GLE) events. The eruptions involve major flares with soft X-ray peak flux >/= 5.0 x10-5 Wm-2 (i.e., flare size >/= M5.0) and accompanying coronal mass ejections (CMEs). The selection criterion was based on the fact that the only front-side GLE in cycle 24 (GLE 71) had a flare size of M5.1. Only ~37% of the major eruptions from the western hemisphere resulted in large SEP events. Almost the same number of large SEP events was produced in weaker eruptions (flare size <M5.0), suggesting that the soft X-ray flare is not a good indicator of SEP or GLE events. On the other hand, the CME speed is a better indicator of SEP and GLE events because it is consistently high supporting the shock acceleration mechanism for SEPs and GLEs. We found the CME speed, magnetic connectivity to Earth, and ambient conditions as the main factors that contribute to the lack of high energy particle events during cycle 24. Several eruptions poorly connected to Earth (eastern-hemisphere or behind-the-west-limb events) resulted in very large SEP events detected by the STEREO spacecraft. Some very fast CMEs, likely to have accelerated particles to GeV energies, did not result in a GLE event because of poor latitudinal connectivity. The stringent latitudinal requirement suggests that the highest energy particles are likely accelerated in the nose part of shocks. There were also well-connected fast CMEs, which did not seem to have accelerated high energy particles due to possible unfavorable ambient conditions (high Alfven speed, overall reduction in acceleration efficiency in cycle 24). **2011-08-04, 2011-09-22, 2012-07-23, 2014-01-06**

Table 2. Major eruptions associated with large SEP events in cycle 24
Table 3. Major Eruptions of cycle 24 poorly connected to Earth
Table 4. List of M5 or larger flares non-SEP west of E15 (23 events)
Table 5: Large SEP events of cycle 24 associated with weaker flares (<M5.0)

Latitudinal Connectivity of Ground Level Enhancement Events

N. **Gopalswamy** and P. Mäkelä

Outstanding Problems in Heliophysics: From Coronal Heating to the Edge of the Heliosphere. Proceedings of a conference held 14-19 April 2013 at Myrtle Beach, South Carolina, USA. Edited by Qiang Hu and Gary P. Zank. ASP Conference Series, Vol. 484, **2014**, p.63**; File**

http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2013IAC.pdf

http://arxiv.org/pdf/1310.8506v1.pdf

We examined the source regions and coronal environment of the historical ground level enhancement (GLE) events in search of evidence for non-radial motion of the associated coronal mass ejection (CME). For the 13 GLE events that had source latitudes >30° we found evidence for possible non-radial CME motion due to deflection by large-scale magnetic structures in nearby coronal holes, streamers, or pseudo streamers. Polar coronal holes are the main source of deflection in the rise and declining phases of solar cycles. In the maximum phase, deflection by large-scale streamers or pseudo streamers overlying high-latitude filaments seems to be important. The B0 angle reduced the ecliptic distance of some GLE source regions and increased in others with the net result that the average latitude of GLE events did not change significantly. The non-radial CME motion is the dominant factor that reduces the ecliptic distance of GLE source regions, thereby improving the latitudinal connectivity to Earth. We further infer that the GLE particles must be accelerated at the nose part of the CME-driven shocks, where the shock is likely to be quasi-parallel. **Table 1. Historical GLE events with flare latitudes >30◦**

Solar Eruptions and Energetic Particles: An Introduction **Review**

N. **Gopalswamy**1 , R. Mewaldt2 , and J. Torsti3

Book Series: Geophysical Monograph Series Volume 165, **2013**

https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/GM165

http://sci-hub.tw/10.1029/165GM02

This introductory article highlights current issues concerning two related phenomena involving mass emission from the Sun: solar eruptions and solar energetic particles. A brief outline of the chapters is provided indicating how the current issues are addressed in the monograph. The sections in this introduction roughly group the chapters dealing with coronal mass ejections (CMEs), solar energetic particles (SEPs), shocks, and space weather. The concluding remarks include a brief summary of outstanding issues that drive current and future research on CMEs and SEPs.

THE FIRST GROUND LEVEL ENHANCEMENT EVENT OF SOLAR CYCLE 24: DIRECT OBSERVATION OF SHOCK FORMATION AND PARTICLE RELEASE HEIGHTS

N. **Gopalswamy**1, H. Xie1,2, S. Akiyama1,2, S. Yashiro1,2, I. G. Usoskin3, and J. M. Davila

2013 ApJ 765 L30, preprint **File**

http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2013ApJL.pdf

http://arxiv.org/pdf/1302.1474v1.pdf

https://iopscience.iop.org/article/10.1088/2041-8205/765/2/L30/pdf

We report on the **2012 May 17** ground level enhancement (GLE) event, which is the first of its kind in solar cycle 24. This is the first GLE event to be fully observed close to the surface by the Solar Terrestrial Relations Observatory (STEREO) mission. We determine the coronal mass ejection (CME) height at the start of the associated metric type II radio burst (i.e., shock formation height) as 1.38 Rs (from the Sun center). The CME height at the time of GLE particle release was directly measured from a STEREO image as 2.32 Rs, which agrees well with the estimation from CME kinematics. These heights are consistent with those obtained for cycle-23 GLEs using back-extrapolation. By contrasting the 2012 May 17 GLE with six other non-GLE eruptions from well-connected regions with similar or larger flare sizes and CME speeds, we find that the latitudinal distance from the ecliptic is rather large for the non-GLE events due to a combination of non-radial CME motion and unfavorable solar B0 angle, making the connectivity to Earth poorer. We also find that the coronal environment may play a role in deciding the shock strength.

A Tell-Tale Sign of a Wimpy Solar Cycle: the First GLE Event of Solar Cycle 24

N. **Gopalswamy**

E-print, Jan **2013**; IAU General assembly, **2012**

http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2012IAU.pdf

The current cycle 24 has produced only one GLE event so far on May 17, 2012, whereas cycle 23 had produced five of the 16 GLEs in the frst 4.5 years. The Sun is already in its solar maximum phase, which means it did not produce any GLE event during its rise phase. The lone GLE event is consistent with a weak cycle 24: the sunspot number peaked at 97 compared to 170 in cycle 23, indicating that cycle 24 is 40% weaker.

17 May 2012

Energetic Particle and Other Space Weather Events of Solar Cycle 24

N. **Gopalswamy**

E-print, Jan **2013**, **File**; In Space Weather: The space Radiation Environment, Ed. Q. Hu, G. Li, G. P. Zank, X. Ao, O. Verkhoglyadova, J. H. Adama, AIP Conf Proc. 1500, pp. 14-19, **2012**

We report on the space weather events of solar cycle 24 in comparison with those during a similar epoch in cycle 23. We find major differences in all space weather events: solar energetic particles, geomagnetic storms, and interplanetary shocks. Dearth of ground level enhancement (GLE) events and major geomagnetic storms during cycle 24 clearly standout. The space weather events seem to reflect the less frequent solar eruptions and the overall weakness of solar cycle 24.

TABLE 1. List of large SEP events from solar cycle 24.

2010/08/14; 2011/03/08; 2011/03/21; 2011/06/07; 2011/08/04; 2011/08/09; 2011/09/23; 2011/11/26; 2012/01/23; 2012/01/27; 2012/03/07; 2012/03/13; 2012/05/17; 2012/05/27; 2012/06/16; 2012/07/07; 2012/07/09; 2012/07/12; 2012/07/17; 2012/07/19; 2012/07/23

TABLE 2. Major geomagnetic storms of cycle 24 (Dst < -100 nT)

2011/09/27; 2011/10/25; 2012/03/09; 2012/04/24; 2012/07/15

Energetic Particle and Other Space Weather Events of Solar Cycle 24

Nat **Gopalswamy**

American Institute of Physics Conference Proceedings, Proc. 11th International Astrophysical Conference, edited by Q. Hu, G. Li, G. P. Zank, G. Fry, X. Ao, and J. Adams, **2012** (in press), **File**

We report on the space weather events of solar cycle 24 in comparison with those during a similar epoch in cycle 23. We find major differences in all space weather events: solar energetic particles, geomagnetic storms, and interplanetary shocks. Dearth of ground level enhancement (GLE) events and major geomagnetic storms during cycle 24 clearly standout. The space weather events seem to reflect the less frequent solar eruptions and the overall weakness of solar cycle 24.

Factors Affecting The Intensity of Solar Energetic Particle Events

Nat **Gopalswamy**

in Proc. Tenth annual Astrophysics Conf., ed. J. Heerikhuisen, G. Li, and G. Zank, American Institute of Physics, in press, **2012, File**.

This paper updates the influence of environmental and source factors of shocks driven by coronal mass ejections (CMEs) that are likely to influence the solar energetic particle (SEP) events. The intensity variation due to CME interaction reported in [1] is confirmed by expanding the investigation to all the large SEP events of solar cycle 23. The large SEP events are separated into two groups, one associated with CMEs running into other CMEs, and the other with CMEs running into the ambient solar wind. SEP events with CME interaction generally have a higher intensity. New possibilities such as the influence of coronal holes on the SEP intensity are also discussed. For example, the presence of a large coronal hole between a well-connected eruption and the solar disk center may render the shock poorly connected because of the interaction between the CME and the coronal hole. This point is illustrated using the **2004 December 3** SEP event delayed by about 12 hours from the onset of the associated CME. There is no other event at the Sun that can be associated with the SEP onset. This event is consistent with the possibility that the coronal hole interaction influences the connectivity of the CMEs that produce SEPs, and hence the intensity of the SEP event.

Properties of Ground level enhancement events and the associated solar eruptions during solar cycle 23.

N. **Gopalswamy**, H. Xie, S. Yashiro, S. Akiyama, P. Mäkelä, I.G. Usoskin,

E-print, May **2012, File**;

Space Sci. Rev., **171**, 23-60 **2012**

https://link.springer.com/content/pdf/10.1007/s11214-012-9890-4.pdf

https://doi.org/10.1007/s11214-012-9890-4

Solar cycle 23 witnessed the most complete set of observations of coronal mass ejections (CMEs) associated with the Ground Level Enhancement (GLE) events. We present an overview of the observed properties of the GLEs and those of the two associated phenomena, viz., flares and CMEs, both being potential sources of particle acceleration. Although we do not find a striking correlation between the GLE intensity and the parameters of flares and CMEs, the solar eruptions are very intense involving X-class flares and extreme CME speeds (average ~2000 km/s). An M7.1 flare and a 1200 km/s CME are the weakest events in the list of 16 GLE events. Most (80%) of the CMEs are full halos with the three non-halos having widths in the range 167 to 212 degrees. The active regions in which the GLE events originate are generally large: 1290 msh (median 1010 msh) compared to 934 msh (median: 790 msh) for SEP-producing active regions. For accurate estimation of the CME height at the time of metric type II onset and GLE particle release, we estimated the initial acceleration of the CMEs using flare and CME observations. The initial acceleration of GLE-associated CMEs is much larger (by a factor of 2) than that of ordinary CMEs (2.3 km/s2 vs.1 km/s2). We confirmed the initial acceleration for two events for which CME measurements are available in the inner corona. The GLE particle release is delayed with respect to the onset of all electromagnetic signatures of the eruptions: type II bursts, low frequency type III bursts, soft X-ray flares and CMEs. The presence of metric type II radio bursts some 17 min (median: 16 min; range: 3 to 48 min) before the GLE onset indicates shock formation well before the particle release. The release of GLE particles occurs when the CMEs reach an average height of ~3.09 Rs (median: 3.18 Rs; range: 1.71 to 4.01 Rs) for well-connected events (source longitude in the range W20 ? W90). For poorly connected events, the average CME height at GLE particle release is ~66% larger (mean: 5.18 Rs; median: 4.61 Rs; range: 2.75 ? 8.49 Rs). The longitudinal dependence is consistent with shock accelerations because the shocks from poorly connected events need to expand more to cross the field lines connecting to an Earth observer. On the other hand, the CME height at metric type II burst onset has no longitudinal dependence because electromagnetic signals do not require magnetic connectivity to the observer. For several events, the GLE particle release is very close to the time of first appearance of the CME in the coronagraphic field of view, so we independently confirmed the CME height at particle release. The CME height at metric type II burst onset is in the narrow range 1.29 to 1.8 Rs, with mean and median values of 1.53 and 1.47 Rs. The CME heights at metric type II burst onset and GLE particle release correspond to the minimum and maximum in the Alfvén speed profile. The increase in CME speed between these two heights suggests an increase in Alfvénic Mach number from 2 to 3. The CME heights at GLE particle release are in good agreement with those obtained from the velocity dispersion analysis (Reames, 2009a,b) including the source longitude dependence. We also discuss the implications of the delay of GLE particle release with respect to complex type III bursts by ~18 min (median: 16 in; range: 2 to 44 min) for the flare acceleration mechanism. A similar analysis is also performed on the delay of particle release relative to the hard X-ray emission. **6 Nov 1997 , 1998 August 24, 02-Nov-03, 17-Jan-05, 14-Jul-05**

Table 1 Summary of observed and derived properties of GLEs, radio bursts, flares, and CMEs

LOW-FREQUENCY TYPE III RADIO BURSTS AND SOLAR ERGEIC PATCLE EVENTS.
Gopalswamy1 andP.Mäkelä2
Cent. Eur. Astrophys. Bul. Vol. 1 (**2011), File**
Complex type III bursts at low-frequencies (>14 MHz) are thought to indicate large solar energetic particle (SEP) events. We analyzed six complex type III bursts from the same active region, one of which was not accompanied by a SEP event. This event was accompanied by a fast and wide coronal mass ejection (CME), but lacked a type II burst and an interplanetary shock. When we examined the evolution and the magnetic configuration of the active region, we did not find anything peculiar. The lowest frequency of type III emission occurred at the local plasma frequency in the vicinity of the Wind spacecraft that observed the type III, which confirms that the magnetic connectivity of the source region was good. We conclude that the lack of SEPs is due to the lack of production rather than due to poor magnetic connectivity. We also show that neither the type III burst duration nor the burst intensity was able to distinguish between SEP and non-SEP events. The lack of SEP event can be readily explained under the shock-acceleration paradigm, but not under the flare-acceleration paradigm.
2004 April

LONG-DURATION LOW-FREQUENCY TYPE III BURSTS AND SOLAR ENERGETIC PARTICLE EVENTS
Nat **Gopalswamy**1 and Pertti M¨akel¨a
Astrophysical Journal Letters, 721:L62–L66, **2010**: **File**
We analyzed the coronal mass ejections (CMEs), flares, and type II radio bursts associated with a set of three complex, long-duration, low-frequency (<14 MHz) type III bursts from active region 10588 in **2004 April**. The durations were measured at 1 and 14 MHz using data from *Wind/*WAVES and were well above the threshold value (>15 minutes) normally used to define these bursts. One of the three type III bursts was not associated with a type II burst, which also lacked a solar energetic particle (SEP) event at energies >25 MeV. The 1 MHz duration of the type III burst (28 minutes) for this event was near the median value of type III durations found for gradual SEP events and ground level enhancement events. Yet, there was no sign of an SEP event. On the other hand, the other two type III bursts from the same active region had similar duration but were accompanied by WAVES type II bursts; these bursts were also accompanied by SEP events detected by *SOHO/*ERNE. The CMEs for the three events had similar speeds, and the flares also had similar size and duration. This study suggests that the occurrence of a complex, long-duration, low-frequency type III burst is not a good indicator of an SEP event.

Ground Level Enhancement Events of Solar Cycle 23
N **Gopalswamy**1, H Xie2, S Yashiro2 & I Usoskin3
Indian Journal of Radio & Space Physics 39, pp. 240-248, **2010, File**
Ground Level Enhancement (GLE) events, typically in the GeV energy range, are the most energetic of solar energetic particle (SEP) events that penetrate Earth's neutral atmosphere. During solar cycle 23, sixteen GLE events were observed with excellent data coverage of the associated solar eruptions. In this paper we examine the question of the source of these GLE particles using white light observations of coronal mass ejections, type II radio bursts, and soft X-ray flares. We show that the GLE events are consistent with shock acceleration in every single case. While we cannot rule out the possibility of the presence of a flare component during GLE events, we can definitely say that a shock component is present in all the GLE events. During the 2001 April 18 GLE event, the source was located ~30 degrees behind the west limb, which is too far away from the magnetic field lines connecting Earth and hence we can rule out the flare component. We also show the presence of interplanetary shocks using radio and in-situ observations.

The SOHO/LASCO CME Catalog
N. **Gopalswamy**, S. Yashiro, G. Michalek, G. Stenborg, A. Vourlidas, S. Freeland & R. Howard
Earth, Moon, and Planets volume 104, pages295–313(**2009**)
https://link.springer.com/content/pdf/10.1007/s11038-008-9282-7.pdf
sci-hub.si/10.1007/s11038-008-9282-7 **File**
Coronal mass ejections (CMEs) are routinely identified in the images of the solar corona obtained by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO) since 1996. The identified CMEs are measured and their basic attributes are cataloged in a data base known as the SOHO/LASCO CME Catalog. The Catalog also contains digital data, movies, and plots for each CME, so detailed scientific investigations can be performed on CMEs and the related phenomena such as flares, radio bursts, solar energetic particle events, and geomagnetic storms. This paper provides a brief description of the Catalog and summarizes the statistical properties of CMEs obtained using the Catalog. Data products relevant to space weather

research and some CME issues that can be addressed using the Catalog are discussed. The URL of the Catalog is: http://cdaw.gsfc.nasa.gov/CME_list.

Type II Radio Emission and Solar Energetic Particle Events

Nat **Gopalswamy**

PARTICLE ACCELERATION AND TRANSPORT IN THE HELIOSPHERE AND BEYOND: 7th Annual International Astrophysics Conference. AIP Conference Proceedings, Volume 1039, pp. 196-202 (**2008**); **File**

Type II radio bursts, solar energetic particle (SEP) events, and interplanetary (IP) shocks all have a common cause, viz., fast and wide (speed > 900 km/s and width > 60 deg) coronal mass ejections (CMEs). Deviations from this general picture are observed as (i) lack of type II bursts during many fast and wide CMEs and IP shocks, (ii) slow CMEs associated with type II bursts and SEP events, and (iii) lack of SEP events during many type II bursts. I examine the reasons for these deviations. I also show that ground level enhancement (GLE) events areconsistent with shock acceleration because a type II burst is present in every event well beforethe release of GLE particles and SEPs at the Sun.

Coronal Mass Ejections, Type II Radio Bursts, and Solar Energetic Particle Events in the SOHO Era

N. **Gopalswamy**1, S. Yashiro2, S. Akiyama2, P. Makela2, H. Xie2, M. L. Kaiser1, R. A. Howard3 and J. L. Bougeret4

E-print, Feb **2008**, **File**; Annales Geophysicae 26, 3033–3047, **2008**.

sci-hub.tw/10.5194/angeo-26-3033-2008

https://www.ann-geophys.net/26/3033/2008/angeo-26-3033-2008.pdf

Using the extensive and uniform data on coronal mass ejections (CMEs), solar energetic particle (SEP) events, and type II radio bursts during the SOHO era, we discuss how the CME properties such as speed, width and solar-source longitude decide whether CMEs are associated with type II radio bursts and SEP events. We discuss why some radio-quiet CMEs are associated with small SEP events while some radio-loud CMEs are not associated with SEP events. We conclude that either some fast and wide CMEs do not drive shocks or they drive weak shocks that do not produce significant levels of particle acceleration. We also infer that the Alfv?n speed in the corona and near-Sun interplanetary medium ranges from <200 km/s to ~1600 km/s. Radio-quiet fast and wide CMEs are also poor SEP producers and the association rate of type II bursts and SEP events steadily increases with CME speed and width (i.e., energy). If we consider western hemispheric CMEs, the SEP association rate increases linearly from ~30% for 800 km/s CMEs to 100% for ≥1800 km/s. Essentially all type II bursts in the decametre-hectometric (DH) wavelength range are associated with SEP events once the source location on the Sun is taken into account. This is a significant result for space weather applications, because if a CME originating from the western hemisphere is accompanied by a DH type II burst, there is a high probability that it will produce an SEP event. **28 Nov 1996, 14 Nov 1997, 23 Sep 1999, 9 Feb 2000, 23 Apr 2000, 12 Jul 2000, 27 Jul 2000, 16 Sep 2000, 17 Mar 2002, 4 Jul 2002, 20 Aug 2002, 17 Sep 2002, 17 Mar 2003, 13 Apr 2003, 27 May 2003, 22 Oct 2003, 24 Oct 2003, 9 Apr 2004, 17 Feb 2005**, **6 May 2005**,

Table 2. Properties of radio-quiet fast and wide CMEs with possible SEP association. (1996-2005)

Table 4. List of RQ CMEs with source locations overlapping with RL disk CMEs (199-2005)

Energetic Phenomena on the Sun

Nat **Gopalswamy**

E-print, Nov. **2007**

AIP Conf. Proc. , Kodai School on Solar Physics, edited by S. S. Hasan and D. Banerjee, V. 919, pp. 275-313, **2007**; File

Solar flares, coronal mass ejections (CMEs), solar energetic particles (SEPs), and fast solar wind represent the energetic phenomena on the Sun.

This paper provides an **over view** of the energetic phenomena on the Sun including their origin interplanetary propagation and space weather consequences.

Energetic particles related with coronal and interplanetary shocks

N. **Gopalswamy**

E-print, Nov. 2007. Lecture Notes in Physics 725, Eds. K.-L. Klein and A. McKinnon, p. 139-160, **2007; File**

Acceleration of electrons and ions at the Sun is discussed in the framework of CME-driven shocks. Based on the properties of coronal mass ejections associated with type II bursts at various wavelengths, the possibility of a unified approach to the type II phenomena is suggested. Two aspects of primary importance to shock accelerations are: (1) Energy of the driving CME and (2) the conditions in the medium that supports shock propagation. The high degree of overlap between CMEs associated with large solar energetic particle events and type II bursts occurring at all wavelengths underscores the importance of CME energy in driving shocks far into the interplanetary medium. Presence of preceding CMEs can alter the conditions in the ambient medium, which is shown to influence the intensity of large solar energetic particle events. Both statistical evidence and case studies are presented that underscore the importance of the ambient medium.

Coronal Mass Ejections and Ground Level Enhancements
N. **Gopalswamy**, H. Xie, S. Yashiro, I. Usoskin.
29th International Cosmic Ray Conference Pune (**2005**), **00**, 101-104 **File**
We study the relation between ground level enhancements (GLEs) and coronal mass ejections (CMEs). The Solar and Heliospheric Observatory (SOHO) spacecraft has observed CMEs during 13 of the 14 GLEs recorded in cycle 23 (as of August 2005). The GLE-associated CMEs represent the fastest known population of CMEs. All the GLEs were also associated with metric type II bursts. Comparison between GLE and metric type II onsets suggests that coronal shocks are formed before GLEs are released at the Sun. These results are consistent with particle acceleration by CME-driven shocks.

Intensity variation of large solar energetic particle events associated with coronal mass ejections.
Gopalswamy, N., Yashiro, S., Krucker, S., Stenborg, G., Howard, R.A.:
2004, J. Geophys. Res. 109, A12105.

Why was there no Solar Energetic Particle Event Associated with the Gamma-ray-line Flare of 2002 July 23?
N. **Gopalswamy**1, S. Krucker2, B. R. Dennis1, R. P. Lin2, M. L. Kaiser1, and A. Vourlidas3
Submitted to ApJL, **2003**?, **File**
We investigated the coronal and interplanetary (IP) events associated with two X-class flares on **2002 July 20 and 23**. Both flares were associated with high-speed (>2000 km s−1) coronal mass ejections (CMEs) and IP shocks. The July 20 flare was partly occulted by the east limb, yet it resulted in a major solar energetic particle event with intensity _ 20 particles per (cm2 s sr MeV) in the >10 MeV channel. The July 23 event was the _rst gamma-ray-line flare detected by RHESSI, but it did not show any enhancement in SEPs above the elevated background from the July 20 event. The coronal and IP environment of the July 20 event was highly disturbed due to preceding CMEs (as compared to the July 23 event). We suggest that the di_erent coronal/IP environments may be responsible for the lack of SEP event associated with the July 23 event.

Large solar energetic particle events of cycle 23: A global view.
Gopalswamy, N., Yashiro, S., Lara, A., Kaiser,M.L., Thompson, B.J., Gallagher, P.T., Howard, R.A.:
2003, Geophys. Res. Lett. 30, 8015.

Solar and geospace connections of energetic particle events.
Gopalswamy, N.
Geophys. Res. Lett., 30, 8013, **2003**. 10.1029/2003GL017277.

Interacting Coronal Mass Ejections and Solar Energetic Particles
N**. Gopalswamy**1, S. Yashiro1,2, G. Michałek1,2, M. L. Kaiser1, R. A. Howard3, D. V. Reames1, R. Leske4, and T. von Rosenvinge1
Astrophysical Journal, 572:L103–L107, **2002**
https://iopscience.iop.org/article/10.1086/341601/pdf

We studied the association between solar energetic particle (SEP) events and coronal mass ejections (CMEs) and found that CME interaction is an important aspect of SEP production. Each SEP event was associated with a primary CME that is faster and wider than average CMEs and originated from west of E45°. For most of the SEP events, the primary CME overtakes one or more slower CMEs within a heliocentric distance of ~20 R☉. In an inverse study, we found that for all the fast (speed greater than 900 km s-1) and wide (width greater than 60°) western hemispheric frontside CMEs during the study period, the SEP-associated CMEs were ~4 times more likely to be preceded by CME interaction than the SEP-poor CMEs; i.e., CME interaction is a good discriminator between SEP-poor and SEP-associated CMEs. **We infer that the efficiency of the CME-driven shocks is enhanced as they propagate through the preceding CMEs** and that they accelerate SEPs from the material of the preceding CMEs rather than from the quiet solar wind. We also found a high degree of association between major SEP events and interplanetary type II radio bursts, suggesting that proton accelerators are also good electron accelerators.

Particle Acceleration and Their Escape into the Heliosphere in Solar Flares with Open Magnetic Field

Mykola **Gordovskyy**1,2, Philippa K. Browning2, Kanya Kusano3, Satoshi Inoue4, and Grigory E. Vekstein2

2023 ApJ 952 75

https://arxiv.org/pdf/2305.19449.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/acdb4d/pdf

Energetic particle populations in the solar corona and in the heliosphere appear to have different characteristics even when produced in the same solar flare. It is not clear what causes this difference: properties of the acceleration region, the large-scale magnetic field configuration in the flare, or particle transport effects, such as scattering. In this study, we use a combination of magnetohydrodynamic and test-particle approaches to investigate magnetic reconnection, particle acceleration, and transport in two solar flares: an M-class flare on **2013 June 19**, and an X-class flare on **2011 September 6**. We show that in both events, the same regions are responsible for the acceleration of particles remaining in the coronal and being ejected toward the heliosphere. However, the magnetic field structure around the acceleration region acts as a filter, resulting in different characteristics (such as energy spectra) acquired by these two populations. We argue that this effect is an intrinsic property of particle acceleration in the current layers created by the interchange reconnection, and therefore, may be ubiquitous, particularly, in noneruptive solar flares with substantial particle emission into the heliosphere.

Characteristics of solar particle events at Mars relative to Earth

Camron **Gorguinpour**

Advances in Space Research 50 (**2012**), 1300-1309

While not specifically designed to detect solar energetic particle radiation, the Electron Reflectometer onboard Mars Global Surveyor (MGS/ER) collected such data from January 1999 through October 2006. Energetic protons (⩾25 MeV) and other ions penetrated the MGS/ER shielding and registered counts within the instrument's electronics. During solar particle events (SPE's), prolonged enhancements in the particle background were observed at Mars with time intensity profiles similar to Earth based SPE observations. Throughout the lifespan of MGS/ER, 85 distinct SPE's were observed. Basic characteristics of Mars based SPE observations and the frequency of SPE occurrences at Mars are compared to corresponding Earth based observations. Approximately 22% of SPE's that occurred during MGS/ER operation were observed at Earth but not Mars. Similarly, 19% of SPE's were observed at Mars but not Earth. Time intensity profiles at Earth and Mars match predictions provided in the literature, based on the physical location of the detector with respect to the motion of the interplanetary shock wave.

A STATISTICAL STUDY OF SPECTRAL HARDENING IN SOLAR FLARES AND RELATED SOLAR ENERGETIC PARTICLE EVENTS

James A. **Grayson**, S¨am Krucker, and R. P. Lin1

Astrophysical Journal, 707:1588–1594, **2009** December; **File**

Using hard X-ray observations from the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*), we investigate the reliability of spectral hardening during solar flares as an indicator of related solar energetic particle (SEP) events at Earth. All *RHESSI* data are analyzed, from 2002 February through the end of Solar Cycle 23, thereby expanding upon recent work on a smaller sample of flares. Previous investigations have found very high success when associating soft–hard–harder (SHH) spectral behavior with energetic proton events, and confirmation of this link would suggest a correlation between electron acceleration in solar flares and SEPs seen in interplanetary space. In agreement with these past findings, we find that of 37 magnetically wellconnected flares (W30−W90), 12 of 18 flares with SHH behavior produced SEP events and none of 19 flares without SHH behavior produced SEPs. ***This demonstrates a statistically significant dependence of SHH and SEP observations, a link that is unexplained in the standard scenario of SEP acceleration at the shock front of coronal mass ejections and encourages further investigation of the mechanisms which could be responsible.***

Mysteries of the 17 May 2012 Solar Event Responsible for GLE71. II. Features of the Flare and its Atypical Microwave Emission

V.V. **Grechnev**, V.I. Kiselev, A.M. Uralov, N.S. Meshalkina, A.L. Lysenko

Solar Phys. **2024**

As known, large near-Earth proton enhancements usually occur after major eruptive solar flares accompanied by strong microwave bursts. Typically, the spectral-maximum frequency of such a burst exceeds 10 GHz and the flux exceeds 104 sfu. Ground-level cosmic-ray enhancements (GLEs) are the most energetic subset of large proton events, and it seems that microwave bursts in GLE-associated flares should follow this pattern. However, only moderate microwave bursts were observed in the individual events that produced GLEs. This was the case in the SOL2012-05-17 event responsible for GLE71, when the spectral-maximum frequency of the microwave burst did not exceed 10 GHz and the flux did not reach 103 sfu. We found that the temporal profile of the microwave burst followed the smoothed magnetic-reconnection rate, lagging behind it by about 50 s; the properties of this burst were determined by the following circumstances: i) the magnetic configuration was asymmetrical, and ii) the sources of the gyrosynchrotron emission were the entire flare arcade and the compact region above the sunspot umbra. The observations directly demonstrate these features, which were previously inferred for the SOL2001-12-26 event responsible for GLE63. A long-known discrepancy was observed between the estimates of the electron spectrum obtained from hard X-rays and microwaves. The hardening of the spectrum of trapped electrons, which is invoked to explain this discrepancy, is not confirmed in this event. Indications of a relationship between flare processes and proton acceleration are discussed.

Mysteries of the 17 May 2012 Solar Event Responsible for GLE71. I. CME Development and the Role of Disturbances Excited by Eruptions.

Grechnev, V.V., Kiselev, V.I., Uralov, A.M. et al.

Sol Phys 299, 129 (**2024**).

https://doi.org/10.1007/s11207-024-02373-0

The SOL**2012-05-17** event is remarkable in that it caused one of two ground-level enhancements (GLE71) in Solar Cycle 24. Despite the efforts spent studying this solar event, some aspects of it remain unclear. This relates to the development of a coronal mass ejection (CME), the history of the shock wave, and the flare. Our measurements reveal the following chain of phenomena. Two successive eruptions occurred within a few minutes. The rate of change of the reconnected magnetic flux shows a series of increases corresponding to the acceleration or deceleration of the erupting structures. The temporal profile of the magnetic-flux change rate is similar to the hard X-ray burst. Each eruption excited a disturbance that, propagating outward, accelerated all structures above it. This led to complex kinematic characteristics of the erupting structures that eventually formed a self-similarly expanding CME. The two disturbances became piston shocks and merged into a single, stronger shock. There are indications of transformation of the piston shock into a bow shock, but this occurs at distances exceeding ten solar radii. Components of the described picture were observed in a number of events and can serve as a guide for studies of eruptive flares.

A Geoeffective CME Caused by the Eruption of a Quiescent Prominence on 29 September 2013

V. V. **Grechnev** & I. V. Kuzmenko

Solar Physics volume 295, Article number: 55 (**2020**) **File**

https://link.springer.com/content/pdf/10.1007/s11207-020-01619-x.pdf

The eruption of a large prominence that occurred away of active regions in the SOL**2013-09-29** event produced a fast coronal mass ejection (CME) and a shock wave. The event caused considerable geospace disturbances, including a proton enhancement that have been addressed in previous studies. Continuing with the analysis of this event, we focus on the development of the CME and shock wave, assess an expected geospace impact using simplest considerations, and compare the expectations with in situ measurements near Earth. The high CME speed in this non-flare-associated event was determined by a considerable reconnected flux that corresponds to a pattern established by different authors. Estimations based on a few approaches showed the reconnection flux in this event to be comparable with a typical value in flare-associated eruptions. The shock wave was most likely impulsively excited by the erupting prominence in the same way as in flare-associated events and changed to the bow-shock regime later. The trajectory calculated for this scenario reproduces the Type II emission observed from 30 MHz to 70 kHz; its interruptions were probably caused by propagation effects. Properties of the near-Earth proton enhancement are discussed considering the results of recent studies

The 26 December 2001 Solar Eruptive Event Responsible for GLE63. III. CME, Shock Waves, and Energetic Particles

V.V. **Grechnev** (1), V.I. Kiselev (1), A.M. Uralov (1), K.-L. Klein (2), A.A. Kochanov (1)
Solar Phys. 292:102 **2017**
https://arxiv.org/pdf/1612.04092v1.pdf **File**
The 26 December 2001 moderate solar eruptive event (GOES importance M7.1, microwaves up to 4000 sfu at 9.4 GHz, CME speed 1446 km/s) produced strong fluxes of solar energetic particles (SEPs) and ground-level enhancement of cosmic-ray intensity (GLE63). To find a possible reason for the atypically high proton outcome of this event, we study its multi-wavelength images and dynamic radio spectra, and quantitatively reconcile the findings with each other. An additional eruption probably occurred in the same active region about half an hour before the main eruption, which produced two blast-wave-like shocks during the impulsive phase. Later on, the two shock waves merged around the frontal direction into a single shock, which is traced up to 25R⊙ as a halo ahead of the expanding CME body, in agreement with an interplanetary type II event recorded by Wind/WAVES. The shape and kinematics of the halo indicate that the shock wave was in an intermediate regime between the blast wave and bow shock at these distances. The results show that i) the shock wave appeared during the flare rise and could accelerate particles earlier than usually assumed; ii) the particle event could be amplified by the preceding eruption, which stretched closed structures above the developing CME, facilitating its lift-off and escape of flare-accelerated particles, enabling a higher CME speed and a stronger shock ahead; iii) escape of flare-accelerated particles could be additionally facilitated by reconnection of the flux rope, where they were trapped, with a large coronal hole; iv) a rich seed population was provided by the first eruption for the acceleration by a trailing shock wave.

The 26 December 2001 Solar Eruptive Event Responsible for GLE63. II. Multi-Loop Structure of Microwave Sources in a Major Long-Duration Flare

V.V. **Grechnev** . A. M. Uralov, V. I. Kiselev, A.A. Kochanov
Solar Phys. January **2017**, 292:3 **File**
https://arxiv.org/pdf/1611.08349v1.pdf
Our analysis of the observations of the SOL**2001-12-26** event, which was related to ground-level enhancement of cosmic-ray intensity GLE63, including microwave spectra and images from the *Nobeyama Radioheliograph* at 17 and 34 GHz, from the *Siberian Solar Radio Telescope* at 5.7 GHz, and from the *Transition Region and Coronal Explorer* in 1600 A, has led to the following results: A flare ribbon overlapped with the sunspot umbra, which is typical of large particle events. Atypical were i) the long duration of the flare, which lasted more than one hour; ii) the moderate intensity of the microwave burst, which was about 104 sfu; iii) the low peak frequency of the gyrosynchrotron spectrum, which was about 6 GHz; and its insensitivity to the flux increase by more than one order of magnitude. This was accompanied by a nearly constant ratio of the flux emitted by the volume in the high-frequency part of the spectrum to its elevated low-frequency part determined by the area of the source. With the self-similarity of the spectrum, a similarity was observed between the moving microwave sources and the brightest parts of the flare ribbons in 1600 A images. We compared the 17 GHz and 1600 A images and confirm that the microwave sources were associated with multiple flare loops, whose footpoints appeared in the ultraviolet as intermittent bright kernels. To understand the properties of the event, we simulated its microwave emission using a system of several homogeneous gyrosynchrotron sources above the ribbons. The scatter between the spectra and the sizes of the individual sources is determined by the inhomogeneity of the magnetic field within the ribbons. The microwave flux is mainly governed by the magnetic flux passing through the ribbons and the sources. The apparent simplicity of the microwave structures is caused by a poorer spatial resolution and dynamic range of the microwave imaging. The results indicate that microwave manifestations of accelerated electrons correspond to the structures observed in thermal emissions, as well-known models predict.

The 26 December 2001 Solar Event Responsible for GLE63. I. Observations of a Major Long-Duration Flare with the Siberian Solar Radio Telescope

V.V. **Grechnev** . A.A. Kochanov
Solar Phys. Volume 291, Issue 12, pp 3705–3723 **2016 File**
http://arxiv.org/pdf/1609.02256v1.pdf
Ground Level Enhancements (GLEs) of cosmic-ray intensity occur, on average, once a year. Due to their rareness, studying the solar sources of GLEs is especially important to approach understanding their origin. The SOL2001-12-26 eruptive-flare event responsible for GLE63 seems to be challenging in some aspects. Deficient observations limited its perception. Analysis of extra observations found for this event provided new results presented in three companion papers. This paper, Paper I, addresses the observations of this flare with the Siberian Solar Radio Telescope (SSRT). Taking advantage of its instrumental particularities, we analyze the detailed SSRT observations of a major long-duration flare at 5.7 GHz without cleaning the images. The analysis confirms that the source of GLE63 was associated with an event in active region 9742 that was manifested in the first flare and the main flare. The first flare (04:30-05:03 UT) reached a GOES level of about M1.6. Two microwave sources have been revealed, whose brightness temperatures at 5.7 GHz exceeded 10 MK. The main flare, up to the M7.1 level, started at 05:04

UT, and occurred in strong magnetic .elds. The observed microwave sources reached about 250 MK. They appeared on the weaker-fi.eld periphery of the active region, approached each other nearly along the magnetic neutral line, coming closer to a stronger-field core of the active region, and then moved away from the neutral line like expanding ribbons. These motions rule out an association of the non-thermal microwave sources with a single flaring loop. These issues and the possible causes of the high proton productivity of this event are addressed in Paper II and Paper III.

Relations Between Microwave Bursts and Near-Earth High-Energy Proton Enhancements and Their Origin

V. V. **Grechnev** , V. I. Kiselev, N. S. Meshalkina, I. M. Chertok

Solar Phys. Volume 290, Issue 10, pp. 2827-2855 **2015**

http://arxiv.org/pdf/1511.05839v1.pdf

We further study the relations between parameters of bursts at 35 GHz recorded with the Nobeyama Radio Polarimeters during 25 years and solar proton events (Grechnev et al. in Publ. Astron. Soc. Japan 65, S4, 2013a). Here we address the relations between the microwave fluences at 35 GHz and near-Earth proton fluences above 100 MeV to find information on their sources and evaluate their diagnostic potential. The correlation between the microwave and proton fluences is pronouncedly higher than between their peak fluxes. This probably reflects a dependence of the total number of protons on the duration of the acceleration process. In events with strong flares, the correlation coefficients of high-energy proton fluences with microwave and soft X-ray fluences are higher than those with the speeds of coronal mass ejections. The results indicate a statistically larger contribution of flare processes to high-energy proton fluxes. Acceleration by shock waves seems to be less important at high energies in events associated with strong flares, although its contribution is probable and possibly prevails in weaker events. The probability of a detectable proton enhancement was found to directly depend on the peak flux, duration, and fluence of the 35 GHz burst, while the role of the Big Flare Syndrome might have been overestimated previously. Empirical diagnostic relations are proposed. **Table 1.** Analyzed events 6, **7 January 2014**

An Updated View of Solar Eruptive Flares and Development of Shocks and CMEs: History of the 2006 December 13 GLE-Productive Extreme Event

V. **Grechnev**, V. Kiselev, A. Uralov, N. Meshalkina, A. Kochanov

E-print, Aug **2013**; Publ. Astron. Soc. Japan 65, No SP1, S9 [18 pages] (2013)), **File**

An extreme **2006 December 13** event marked the onset of the Hinode era being the last major flare in the solar cycle 23 observed with NoRH and NoRP. The event produced a fast CME, strong shock, and big particle event responsible for GLE70. We endeavor to clarify relations between eruptions, shock wave, and the flare, and to shed light on a debate over the origin of energetic protons. One concept relates it with flare processes. Another one associates acceleration of ions with a bow shock driven by a CME at (2-4)R_sun. The latter scenario is favored by a delayed particle release time after the flare. However, our previous studies have established that a shock wave is typically excited by an impulsively erupting magnetic rope (future CME core) during the flare rise, while the outer CME surface evolves from an arcade whose expansion is driven from inside. Observations of the 2006 December 13 event reveal two shocks following each other, whose excitation scenario contradicts the delayed CME-driven bow-shock hypothesis. Actually, the shocks developed much earlier, and could accelerate protons still before the flare peak. Then, the two shocks merged into a single stronger one and only decelerated and dampened long afterwards.

Relations between strong high-frequency microwave bursts and proton events

V. **Grechnev**, N. Meshalkina, I. Chertok, V. Kiselev

E-print, Aug **2013**; PASJ **65**, S4, **2013**

http://arxiv.org/pdf/1308.2275v1.pdf

Proceeding from close association between solar eruptions, flares, shock waves, and CMEs, we analyze relations between bursts at 35 GHz recorded with the Nobeyama Radio Polarimeters during 1990-2012, on the one hand, and solar energetic particle (SEP) events, on the other hand. Most west to moderately east solar events with strong bursts at 35 GHz produced near-Earth proton enhancements of J(E > 100 MeV) > 1 pfu. The strongest and hardest those caused ground level enhancements. There is a general, although scattered, correspondence between proton enhancements and peak fluxes at 35 GHz, especially pronounced if the 35 GHz flux exceeds 10^4 sfu and the microwave peak frequency is high. These properties indicate emission from numerous high-energy electrons in very strong magnetic fields suggesting a high rate of energy release in the flare-CME formation process. Flaring above the sunspot umbra appears to be typical of such events. Irrespective of the origin of SEPs, these circumstances demonstrate significant diagnostic potential of high-frequency microwave bursts and sunspot-associated flares for space weather forecasting. Strong prolonged bursts at 35 GHz promptly alert to hazardous SEP events with hard spectra. A few exceptional events with moderate bursts at 35 GHz and strong proton fluxes look challenging and should be investigated. **Table. 2000 November 8, 2001 August 25, 2001 December 26, 2002 April 21, 2005 January 20, 2006 December 13, 2012 March 07, 2012 May 17**

An Extreme Solar Event of 20 January 2005: Properties of the Flare and the Origin of Energetic Particles

V.V. **Grechnev** · V.G. Kurt · I.M. Chertok · A.M. Uralov · H. Nakajima · A.T. Altyntsev · A.V. Belov · B.Yu. Yushkov · S.N. Kuznetsov · L.K. Kashapova · N.S. Meshalkina · N.P. Prestage

Solar Phys **(2008**) 252: 149–177, 2008, DOI 10.1007/s11207-008-9245-1

http://www.springerlink.com/content/6guv12r430282x2j/fulltext.pdf

The famous extreme solar and particle event of 20 January 2005 is analyzed from two perspectives. Firstly, using multi-spectral data, we study temporal, spectral, and spatial features of the main phase of the flare, when the strongest emissions from microwaves up to 200 MeV gamma-rays were observed. Secondly, we relate our results to a long-standing controversy on the origin of solar energetic particles (SEP) arriving at Earth, *i.e.*, acceleration in flares, or shocks ahead of coronal mass ejections (CMEs). Our analysis shows that all electromagnetic emissions from microwaves up to 2.22MeV line gamma-rays during the main flare phase originated within a compact structure located just above sunspot umbrae. In particular, a huge (≈10^5 sfu) radio burst with a high frequency maximum at 30 GHz was observed, indicating the presence of a large number of energetic electrons in very strong magnetic fields. Thus, protons and electrons responsible for various flare emissions during its main phase were accelerated within the magnetic field of the active region. The leading, impulsive parts of the ground-level enhancement (GLE), and highest-energy gamma-rays identified with π^0-decay emission, are similar and closely correspond in time. The origin of the π^0-decay gamma-rays is argued to be the same as that of lower-energy emissions, although this is not proven. On the other hand, we estimate the sky-plane speed of the CME to be 2 000 – 2 600 km s^{-1}, *i.e.*, high, but of the same order as preceding non-GLE-related CMEs from the same active region. Hence, the flare itself rather than the CME appears to determine the extreme nature of this event. We therefore conclude that the acceleration, at least, to sub-relativistic energies, of electrons and protons, responsible for both the major flare emissions and the leading spike of SEP/GLE by 07 UT, are likely to have occurred nearly simultaneously within the flare region. However, our analysis does not rule out a probable contribution from particles accelerated in the CME-driven shock for the leading GLE spike, which seemed to dominate at later stages of the SEP event.

Observation of solar energetic particles with Metis on board Solar Orbiter on February 25, 2023

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A&A, 686, A74 (**2024**)

https://www.aanda.org/articles/aa/pdf/2024/06/aa49386-24.pdf

Context. The Solar Orbiter Metis coronagraph captures images of the solar corona in both visible (VL) and ultraviolet (UV) light. Tracks ascribable to the passage of galactic and solar particles appear in the Metis images. An algorithm implemented in the Metis processing electronics allows us to separate the pixels fired by VL photons from those crossed by high-energy particles. These spurious pixels are stored in cosmic-ray matrices that can be visually analyzed for particle monitoring deep into the spacecraft's interior. This algorithm has been enabled for the VL instrument only, since the process of separating the particle tracks from pixels fired by photons in the UV images was shown to be quite challenging with respect to a quantitative analysis.

Aims. This work is aimed at studying galactic cosmic rays (GCRs) and solar energetic particles (SEPs) with the Metis cosmic-ray matrices in February 2023.

Methods. We compared a visual analysis of Metis cosmic-ray matrices gathered on February 22, 2023, with GCRs only, and on **February 25, 2023** with both GCRs and SEPs, to Monte Carlo simulations of the VL instrument during the same days.

Results. We estimated the solar modulation parameter associated with the GCR proton energy spectrum in February 2023. We show that Metis plays the role of monitoring galactic and solar protons. The Metis particle observations are used for the diagnostics of the VL instrument performance and to study the spacecraft inner charging from solar minimum towards the next solar maximum. These achievements have been attained with the benefit of the joint observations of Metis, the Energetic Particle Detector/High Energy Telescope, and near-Earth and Earth-based instruments.

Particle monitoring capability of the Solar Orbiter Metis coronagraph through the increasing phase of solar cycle 25

Catia **Grimani**, Vincenzo Andretta, Ester Antonucci, Paolo Chioetto, +++

A&A 677, A45 **2023**

https://arxiv.org/pdf/2307.11598.pdf

https://www.aanda.org/articles/aa/pdf/2023/09/aa46679-23.pdf

Context. Galactic cosmic rays (GCRs) and solar particles with energies greater than tens of MeV penetrate spacecraft and instruments hosted aboard space missions. The Solar Orbiter Metis coronagraph is aimed at observing the solar corona in both visible (VL) and ultraviolet (UV) light. Particle tracks are observed in the Metis

images of the corona. An algorithm has been implemented in the Metis processing electronics to detect the VL image pixels crossed by cosmic rays. This algorithm was initially enabled for the VL instrument only, since the process of separating the particle tracks in the UV images has proven to be very challenging. Aims. We study the impact of the overall bulk of particles of galactic and solar origin on the Metis coronagraph images. We discuss the effects of the increasing solar activity after the Solar Orbiter mission launch on the secondary particle production in the spacecraft. Methods. We compared Monte Carlo simulations of GCRs crossing or interacting in the Metis VL CMOS sensor to observations gathered in 2020 and 2022. We also evaluated the impact of solar energetic particle events of different intensities on the Metis images. Results. The study of the role of abundant and rare cosmic rays in firing pixels in the Metis VL images of the corona allows us to estimate the efficiency of the algorithm applied for cosmic-ray track removal from the images and to demonstrate that the instrument performance had remained unchanged during the first two years of the Solar Orbiter operations. The outcome of this work can be used to estimate the Solar Orbiter instrument's deep charging and the order of magnitude for energetic particles crossing the images of Metis and other instruments such as STIX and EUI.

Variable Ion Compositions of Solar Energetic Particle Events in the Inner Heliosphere: A Field-line Braiding Model with Compound Injections

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ApJ **924** 22 **2022**

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https://iopscience.iop.org/article/10.3847/1538-4357/ac3233/pdf
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We propose a model for interpreting highly variable ion composition ratios in solar energetic particles (SEP) events recently observed by Parker Solar Probe (PSP) at 0.3−0.45 astronomical unit. We use numerical simulations to calculate SEP propagation in a turbulent interplanetary magnetic field with a Kolmogorov power spectrum from large scale down to the gyration scale of energetic particles. We show that when the source regions of different species are offset by a distance comparable to the size of the source regions, the observed energetic particle composition He/H can be strongly variable over more than two orders of magnitude, even if the source ratio is at the nominal value. Assuming a 3He/4He source ratio of 10% in impulsive 3He-rich events and the same spatial offset of the source regions, the 3He/4He ratio at observation sites also vary considerably. The variability of the ion composition ratios depends on the radial distance, which can be tested by observations made at different radial locations. We discuss the implication of these results on the variability of ion composition of impulsive events and on further PSP and Solar Orbiter observations close to the Sun.

The Pivot Energy of Solar Energetic Particles Affecting the Martian Surface Radiation Environment

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2019 ApJL 883 L12

https://doi.org/10.3847/2041-8213/ab3ec2

Space radiation is a major risk for humans, especially on long-duration missions to outer space, e.g., a manned mission to Mars. Galactic cosmic rays contribute a predictable radiation background; the main risk is due to the highly variable and currently unpredictable flux of solar energetic particles (SEPs). Such sporadic SEP events may induce acute health effects and are thus considered a critical mission risk for future human exploration of Mars. Therefore, it is of the utmost importance to study, model, and predict the surface radiation environment during such events. It is well known that the deep-space SEP differential energy spectrum at high energies is often given by a power law. We use a measurement-validated particle transport code to show that, for large SEP events with proton energy extending above ~500 MeV with a power-law distribution, it is sufficient to measure the SEP flux at a pivot energy of ~300 MeV above the Martian atmosphere to predict the dose rate on the Martian surface. In conjunction with a validation by in situ measurements from the Martian surface, this remarkable simplification and elegant quantification could enable instant predictions of the radiation environment on the surface of Mars upon the onset of large SEP events.

Modeling the Evolution and Propagation of 10 September 2017 CMEs and SEPs Arriving at Mars Constrained by Remote Sensing and In Situ Measurement

Jingnan **Guo**, Mateja Dumbović, Robert F. Wimmer-Schweingruber, Manuela Temmer, Henning Lohf, Yuming Wang, Astrid Veronig, Donald M. Hassler …

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http://sci-hub.se/10.1029/2018SW001973

On **10 September 2017**, solar energetic particles originating from the active region 12673 produced a ground level enhancement at Earth. The ground level enhancement on the surface of Mars, 160 longitudinally east of Earth, observed by the Radiation Assessment Detector (RAD) was the largest since the landing of the Curiosity rover in August 2012. Based on multipoint coronagraph images and the Graduated Cylindrical Shell model, we identify the initial 3-D kinematics of an extremely fast coronal mass ejection (CME) and its shock front, as well as another two CMEs launched hours earlier with moderate speeds. The three CMEs interacted as they propagated outward into the heliosphere and merged into a complex interplanetary CME (ICME). The arrival of the shock and ICME at Mars caused a very significant Forbush decrease seen by RAD only a few hours later than that at Earth, which was about 0.5 AU closer to the Sun. We investigate the propagation of the three CMEs and the merged ICME together with the shock, using the drag-based model and the WSA-ENLIL plus cone model constrained by the in situ observations. The synergistic study of the ICME and solar energetic particle arrivals at Earth and Mars suggests that to better predict potentially hazardous space weather impacts at Earth and other heliospheric locations for human exploration missions, it is essential to analyze (1) the eruption of the flare and CME at the Sun, (2) the CME kinematics, especially during their interactions, and (3) the spatially and temporally varying heliospheric conditions, such as the evolution and propagation of the stream interaction regions.

Modeling the evolution and propagation of the 2017 September 9th and 10th CMEs and SEPs arriving at Mars constrained by remote-sensing and in-situ measurement

Jingnan **Guo**, Mateja Dumbovi, Robert F. Wimmer-Schweingruber, Manuela Temmer, Henning Lohf, Yuming Wang, Astrid Veronig, Donald M. Hassler, Leila M. Mays, Cary Zeitlin, Bent Ehresmann, Oliver Witasse, Johan L. Freiherr von Forstner, Bernd Heber, Mats Holmström, Arik Posner

GRL **2018**

https://arxiv.org/pdf/1803.00461.pdf

On **2017-09-10** active region 12673 produced solar energetic particles (SEPs) which were registered as a ground level enhancement (GLE) at Earth and the biggest GLE on the sur- face of Mars as observed by the Radiation Assessment Detector (RAD) since the landing of the Curiosity rover in August 2012. Based on STA and SOHO coronagraph images, we identify the initial 3D kinematics of an extremely fast CME and its shock front as well as another 2 CMEs launched hours earlier (with moderate speeds) using the Graduated Cylindrical Shell (GCS) model. These three CMEs interacted as they propagated outwards into the heliosphere and merged into a complex interplanetary CME (ICME). The arrival of the shock and ICME at Mars caused a very significant Forbush Decrease (FD) seen by RAD and this is only a few hours later than that at Earth which is about 0.5 AU closer to the Sun. We investigate the propagations of the three CMEs and the consequent ICME together with the shock using the Drag Based Model (DBM) and the WSA-ENLIL plus cone model constrained by the in-situ SEP and FD/shock onset timing. The optimized modeling for the ICME arrival at both Earth and Mars suggests that in order to better predict the ICME arrival and its potential space weather impact at Earth and other heliospheric locations, it is essential to analyze 1) the ICME kinematics, especially during interactions of different CMEs, and 2) the spatially and temporally varying interplanetary conditions of the heliosphere.

Observation of High Iron Charge States at Low Energies in Solar Energetic Particle Events

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2014 ApJ 785 26

The ionic charge states of solar energetic particles (SEPs) provide direct information about the source plasma, the acceleration environment, and their transport. Recent studies report that both gradual and impulsive SEP events show mean iron charge states Q Fe ~ 10-14 at low energies E ≤ 0.1 MeV nuc–1, consistent with their origin from typical corona material at temperatures 1-2 MK. Observed increases of Q Fe up to 20 at energies 0.1-0.5 MeV nuc–1 in impulsive SEPs are attributed to stripping during acceleration. However, Q Fe > 16 is occasionally found in the solar wind, particularly coming from active regions, in contrast to the exclusively reported Q Fe ≤ 14 for low energy SEPs. Here we report results from a survey of all 89 SEP events observed with Advanced Composition Explorer Solar Energetic Particle Ionic Charge Analyzer (SEPICA) in 1998-2000 for iron charge states augmented at low energy with Solar and Heliospheric Observatory CELIAS suprathermal time-of-flight (STOF). Nine SEP events with Q Fe ≥ 14 throughout the entire SEPICA and STOF energy range have been identified. Four of the nine events are impulsive events identified through velocity dispersion that are consistent with source temperatures ≥2 MK up to ~4 MK. The other five events show evidence of interplanetary acceleration. Four of them involve re-acceleration of impulsive material, whose original energy dependent charge states appear re-distributed to varying extent bringing higher charge states to lower energy. One event, which shows flat but elevated Q Fe ~ 14.2 over the entire energy range, can be associated with interplanetary acceleration of high temperature material. This event may exemplify a rare situation when a second shock plows through high temperature coronal mass ejection material.

Relativistic electron acceleration during highintensity, long-duration, continuous AE activity (HILDCAA) events: Solar cycle phase dependences.
Hajra R, Tsurutani BT, Echer E, Gonzalez WD
(**2014**), GRL 41:1876

A New Model for Nowcasting the Aviation Radiation Environment With Comparisons to In Situ Measurements During GLEs

A. D. P. **Hands**, F. Lei, C. S. Davis, B. J. Clewer, C. S. Dyer, K. A. Ryden
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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003155

Significant increases to the atmospheric radiation environment are recorded by a network of ground level neutron monitors as ground level enhancements (GLEs). These space weather phenomena pose a risk to aviation via single event effects in aircraft electronics and ionizing dose to passengers and crew. Under the UK Space Weather Instrumentation, Measurement, Modeling and Risk programme, we have developed a new model to provide nowcasts of the aviation radiation environment, including both the galactic cosmic ray (GCR) background and during GLE events. The Model for Atmospheric Ionising Radiation Effects (MAIRE+) uses multiple data sources to characterize primary GCR and GLE particle spectra and combines these with precalculated geomagnetic and atmospheric response matrices to predict particle fluxes from ground level to 20 km altitude across the entire globe. Two European neutron monitors (located at Oulu in Finland and Dourbes in Belgium) are used as the primary indicators of GLE intensity in order to maximize accuracy over UK airspace. Outputs from MAIRE+ for the historical GLEs in September and October 1989 are compared to recalibrated empirical data from a solid-state detector that was carried on Concorde in that period. The model will be hosted in the UK and will provide additional capability to the Met Office Space Weather Operations Center (MOSWOC). **29 Sep, 19 Oct, 24 Oct 1989; 10 Sep 2017, 28 Oct 2021, 4-5 Nov 2021**

Detecting Ground Level Enhancements using Soil Moisture Sensor

A. D. P. **Hands**, F. Baird, K. A. Ryden, C. S. Dyer, F. Lei, J. G. Evans, J. R. Wallbank, M. Szczykulska, D. Rylett, R. Rosolem, S. Fowler, D. Power, E. M. Henley
Space Weather **Volume19, Issue8** e2021SW002800 **2021**
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Ground level enhancements (GLEs) are space weather events that pose a potential hazard to the aviation environment through single event effects (SEE) in avionics and increased dose to passengers and crew. The existing ground level neutron monitoring network provides continuous and well-characterised measurements of the radiation environment. However, there are only a few dozen active stations worldwide, and there hasn't been a UK-based station for several decades. Much smaller neutron detectors are increasingly deployed throughout the world with the purpose of using secondary neutrons from cosmic rays to monitor local soil moisture conditions (COSMOS). Space weather signals from ground level enhancements (GLEs) and Forbush decreases have been identified in COSMOS data. Monte Carlo simulations of atmospheric radiation propagation show that a single COSMOS detector is sufficient to detect the signal of a medium-strength (10-100% increase above background) ground level enhancement (GLE) at high statistical significance, including at fine temporal resolution. Use of fine temporal resolution would also provide a capability to detect Terrestrial Gamma Ray Flashes (via secondary neutrons) which are produced by certain lightning discharges and which can provide a hazard to aircraft, particularly in tropical regions. We also show how the COSMOS-UK detector network could be used to provide warnings at the International Civil Aviation Organization (ICAO) "Moderate" and "Severe" dose rate thresholds at aviation altitudes, and how multiple-detector hubs situated at strategic UK locations could detect a small GLE at high statistical significance and infer crucial information on the nature of the primary spectrum. **7-11 Sep 2017**

Spectral Properties and the Influence of Coronal Mass Ejections in 3He-rich Solar Energetic Particle Events

Samuel T. **Hart**1,2, M. A. Dayeh1,2, R. Bučík2, G. M. Mason3, M. I. Desai1,2, R. W. Ebert1,2, G. C. Ho2, and A. A. Shmies1,2
2024 ApJ 974 220
https://iopscience.iop.org/article/10.3847/1538-4357/ad6b99/pdf

We analyze the spectral properties of 3He and 4He as well as the heavy ions (oxygen, neon, magnesium, silicon, and iron) in 80 3He-rich solar energetic particle (SEP) events observed by the Ultra-Low-Energy Ion Spectrometer on board the Advanced Composition Explorer spacecraft since its launch in 1997 until 2024. We split the spectral analysis into two criteria: events with fast and wide coronal mass ejections (CMEs; called "FW events") and events with slow, narrow, or no observed CMEs (called "non-FW events"). Overall, we find that events with fast and wide

CMEs exhibit more uniform spectra across all species, and their low-energy spectral indices are strongly correlated, suggesting a CME provides an additional reacceleration mechanism for the 3He-rich SEPs. When comparing each species' low-energy spectral index for events with no associated fast-and-wide CME, we find a primary peak in the spectral hardness of 3He, and a secondary peak in Mg and Si. If we consider a plasma temperature of 1.0–1.3 MK, Mg and Si have a charge-to-mass ratio (Q/M) nearest to one-third (1/3), directly half that of 3He. Thus, our results support the results of Roth & Temerin, which suggest heavy ions resonate with the second harmonic of the same ion cyclotron waves energizing 3He. However, it is unclear why the Fe enhancement is not reflected in its spectral index, and we propose that additional acceleration and/or transport mechanisms are playing a role in the abundance enhancement of Fe and heavier ions. **2001 June 24, 2023 March 10, 2023 December 13**
Table 1 Spectral and CME Properties of the Analyzed 3He-rich SEP Events 1997-2023

Statistical Study and Live Catalogue of Multi-Spacecraft 3He-Rich Time Periods over Solar Cycles 23, 24, and 25

Samuel T. **Hart**, Maher A. Dayeh, Radoslav Bučík, Mihir I. Desai, Robert W. Ebert, George C. Ho, Gang Li, Glenn M. Mason

ApJ Supplemental Series **263** 22 **2022**
https://arxiv.org/ftp/arxiv/papers/2210/2210.11600.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/ac91c1/pdf

Using ion measurements from Ultra-Low-Energy Isotope Spectrometer (ULEIS) observations onboard Advanced Composition Explorer (ACE) and Solar Isotope Spectrometer (SIS) observations onboard the Solar Terrestrial Observatory (STEREO)-A and STEREO-B spacecraft, we have identified 854 3He-rich time periods between 1997 September and 2021 March. We include all event types with observed 3He enhancements such as corotating interaction regions (CIRs), gradual solar energetic particle (SEP) events, interplanetary shocks, and impulsive SEP events. We employ two different mass separation techniques to obtain 3He, 4He, Fe, and O fluences for each event, and we determine the 3He/4He and Fe/O abundance ratios between 0.32 to 0.45 MeV/nucleon and 0.64 to 1.28 MeV/nucleon. We find a clear correlation in the 3He/4He and Fe/O abundance ratios between both energy ranges. We find two distinct trends in the 3He/4He vs. Fe/O relation. For low 3He/4He values, there is a positive linear correlation between 3He/4He and Fe/O. However, at 3He/4He ~ 0.3, Fe/O appears to reach a limit and the correlation weakens significantly. We provide a live catalogue of 3He rich time periods that includes the robust determination of the onset and end times of the 3He enhancements in SEP-associated periods for different types of events observed my multiple spacecraft. This catalogue is available for public use. New releases will follow after major additions such as adding new periods from new missions (e.g., Parker Solar Probe and Solar Orbiter), identifying event types (impulsive SEP events, etc.), or adding new parameters such as remote observations detailing characteristics of the active regions.

Revision of the strongest solar energetic particle event of 23 February 1956 (GLE #5) based on the rediscovered original records

Hisashi **Hayakawa**1,2,3,4, Sergey Koldobskiy5,6, Alexander Mishev5,6, Stepan Poluianov5,6, Agnieszka Gil7,8, Inna Usoskina6 and Ilya Usoskin5,6

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https://www.aanda.org/articles/aa/pdf/2024/04/aa48699-23.pdf
https://doi.org/10.1051/0004-6361/202348699

Aims. Intense solar eruptions can produce solar energetic particles (SEPs), potentially detectable by ground-based instruments such as neutron monitors (NMs). These events are called ground-level enhancements (GLEs). The strongest GLE with the hardest known SEP spectrum occurred on **23 February 1956** (conventionally numbered GLE #5), providing a benchmark reference for related studies. However, the existing datasets for GLE #5 were compiled from different sources, often secondary; these datasets exhibited significant discrepancies and internal inconsistencies leading to large uncertainties or biases. Here we resolve the inconsistencies and revisit the reconstructions of the energy spectra and angular characteristics of the SEPs for that event, based on our reanalyses on (somehow forgotten) original contemporary records.
Methods. We collected, digitised, and verified the source records for NM measurements during GLE #5 based on contemporaneous publications and unpublished materials in the University of Chicago Archives. Using the revised datasets and full modelling, we critically revised the reconstruction of the energy spectra and angular characteristics of the SEPs and the event-integrated omnidirectional SEP flux (fluence) for GLE #5.
Results. The energy spectrum of the SEPs during the initial and main phases of GLE #5 was revised based on the new dataset, resulting in a slightly softer, but still agreeing within the uncertainties of the recent studies, SEP spectral estimate. The SEP flux was found to be highly anisotropic in the early phase of the event. This provides a revised reference basis for further analyses and modelling of strong and extreme SEP events and their terrestrial impacts.

New Insight into the Formation Mechanism of the Energetic Particle Reservoirs in the Heliosphere

H.-Q. **He**

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https://arxiv.org/pdf/2109.06408.pdf
https://doi.org/10.1093/mnrasl/slab094
https://watermark.silverchair.com/slab094.pdf

The concept of energetic particle reservoirs, essentially based on the assumption of the presence of outer reflecting boundaries/magnetic mirrors or diffusion barriers (deterministic) rather than on the effect of particle diffusive propagation (stochastic) in magnetic turbulence, has been used for decades to describe the space-extended decay phases of energetic particle events within the fields of space physics, solar physics, and plasma physics. Using five-dimensional time-dependent Fokker-Planck transport equation simulations, in this work we demonstrate that the so-called particle reservoirs are naturally explained and quantitatively reproduced by diffusion processes in turbulent magnetic fields, without invoking the hypothesis of reflecting boundaries. Our results strongly suggest that the so-called "reservoir" (based on deterministic structure) should be renamed "flood" (based on stochastic diffusion), which symbolizes an authentic shift in thinking and in pragmatic rationale for the studies of energetic particles and relevant plasma phenomena in heliophysics and in astrophysics.

Propagation of Solar Energetic Particles in the Outer Heliosphere: Interplay between Scattering and Adiabatic Focusing

H.-Q. **He** and W. Wan

2019 ApJL 885 L28
https://iopscience.iop.org/article/10.3847/2041-8213/ab50bd/pdf

The turbulence and spatial nonuniformity of the guide magnetic field cause two competitive effects, namely, the scattering effect and the adiabatic focusing effect, respectively. In this work, we numerically solve the five-dimensional Fokker–Planck transport equation to investigate the radial evolutions of these important effects undergone by the solar energetic particles (SEPs) propagating through interplanetary space. We analyze the interplay process between the scattering and adiabatic focusing effects in the context of three-dimensional propagation, with special attention to the scenario of the outer heliosphere, in which some peculiar SEP phenomena are found and explained. We also discuss the radial dependence of the SEP peak intensities from the inner through the outer heliosphere, and conclude that it cannot be simply described by a single functional form such as R −α (R is radial distance), which is often used.

Onsets of Solar Proton Events in Satellite and Ground Level Observations: A Comparison

Jing **He**, Juan V. Rodriguez

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https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017SW001743
http://sci-hub.tw/10.1002/2017SW001743

The early detection of solar proton event onsets is essential for protecting humans and electronics in space, as well as passengers and crew at aviation altitudes. Two commonly compared methods for observing solar proton events that are sufficiently large and energetic to be detected on the ground through the creation of secondary radiation—known as ground level enhancements (GLEs)—are (1) a network of ground-based neutron monitors (NMs) and (2) satellite-based particle detectors. Until recently, owing to the different time resolution of the two data sets, it has not been feasible to compare these two types of observations using the same detection algorithm. This paper presents a comparison between the two observational platforms using newly processed >100 MeV 1 min count rates and fluxes from National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellite (GOES) 8–12 satellites, and 1 min count rates from the Neutron Monitor Database. We applied the same detection algorithm to each data set (tuned to the different background noise levels of the instrument types). Seventeen SPEs with GLEs were studied: GLEs 55–70 from Solar Cycle 23 and GLE 71 from Solar Cycle 24. The median difference in the event detection times by GOES and NM data is 0 min, indicating no innate benefit in time of either system. The 10th, 25th, 75th, and 90th percentiles of the onset time differences (GOES minus NMs) are −7.2 min, −1.5 min, 2.5 min, and 4.2 min, respectively. This is in contrast to previous studies in which NM detections led GOES by 8 to 52 min without accounting for different alert protocols.

Table 3. List of GLE events studied in this paper GLEs (55-70), GLE 71

Propagation of Solar Energetic Particles in Three-dimensional Interplanetary Magnetic Fields: Radial Dependence of Peak Intensities

H.-Q. **He**1, G. Zhou1,2, and W. Wan1

2017 ApJ 842 71
http://iopscience.iop.org.sci-hub.cc/0004-637X/842/2/71/

https://arxiv.org/pdf/1706.05443.pdf
A functional form $I_{\max}(R) = kR^{-\alpha}$, where R is the radial distance of a spacecraft, was usually used to model the radial dependence of peak intensities $I_{\max}(R)$ of solar energetic particles (SEPs). In this work, the five-dimensional Fokker–Planck transport equation incorporating perpendicular diffusion is numerically solved to investigate the radial dependence of SEP peak intensities. We consider two different scenarios for the distribution of a spacecraft fleet: (1) along the radial direction line and (2) along the Parker magnetic field line. We find that the index α in the above expression varies in a wide range, primarily depending on the properties (e.g., location and coverage) of SEP sources and on the longitudinal and latitudinal separations between the sources and the magnetic foot points of the observers. Particularly, whether the magnetic foot point of the observer is located inside or outside the SEP source is a crucial factor determining the values of index α. A two-phase phenomenon is found in the radial dependence of peak intensities. The "position" of the break point (transition point/critical point) is determined by the magnetic connection status of the observers. This finding suggests that a very careful examination of the magnetic connection between the SEP source and each spacecraft should be taken in the observational studies. We obtain a lower limit of $R^{-1.7\pm0.1}$ for empirically modeling the radial dependence of SEP peak intensities. Our findings in this work can be used to explain the majority of the previous multispacecraft survey results, and especially to reconcile the different or conflicting empirical values of the index α in the literature.

On the East-West Longitudinally Asymmetric Distribution of Solar Proton Events

H.-Q. **He**, W. Wan
MNRAS **2016**
https://arxiv.org/pdf/1610.05489v1.pdf
A large data set of 78 solar proton events observed near the Earth's orbit during 1996-2011 is investigated. An East-West longitudinal (azimuthal) asymmetry is found to exist in the distribution of flare sources of solar proton events. With the same longitudinal separation between the flare sources and the magnetic field line footpoint of observer, the number of the solar proton events originating from solar sources located on the eastern side of the nominal magnetic footpoint of observer is larger than the number of the solar proton events from solar sources located on the western side. We emphasize the importance of this statistical investigation in two aspects. On the one hand, this statistical finding confirms our previous simulation results obtained by numerically solving five-dimensional Fokker-Planck equation of solar energetic particle (SEP) transport. On the other hand, the East-West longitudinally (azimuthally) asymmetric distribution of solar proton events accumulated over a long time period provides an observational evidence for the effects of perpendicular diffusion on the SEP propagation in the heliosphere. We further point out that, in the sense of perpendicular diffusion, our numerical simulations and statistical results of SEP events confirm each other. We discuss in detail the important effects of perpendicular diffusion on the formation of the East-West azimuthal (longitudinal) asymmetry of SEP distribution in two physical scenarios, i.e., 'multiple SEP events with one spacecraft' and 'one SEP event with multiple spacecraft'. A functional relation I_{max}(r)=kr^{-1.7} quantifying the radial dependence of SEP peak intensities is obtained and utilized in the analysis of physical mechanism. The relationship between our results and those of Dresing et al. is also discussed.

Numerical Study of Longitudinally Asymmetric Distribution of Solar Energetic Particles in the Heliosphere

H.-Q. **He**, W. Wan
ApJ **2015**
http://arxiv.org/pdf/1502.02683v1.pdf
Solar energetic particles (SEPs) affect the solar-terrestrial space environment and become a very important aspect in space weather research. In this work, we numerically investigate the transport processes of SEPs in three-dimensional interplanetary magnetic field, with emphasis on the longitudinal distribution of SEPs in the heliosphere. We find that there exists an east-west longitudinal asymmetry in the SEP intensities, i.e., with the same longitude separations between the solar source centers and the magnetic footpoint of the observer, the fluxes of SEP events originating from solar sources located at eastern side of the nominal magnetic footpoint of observer are systematically larger than those of the SEP events originating from sources located at western side. In combination with the empirical results in previous works, we discuss the formation mechanism of this phenomenon, and propose that the longitudinally asymmetric distribution of SEPs results from the east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport of SEPs in the heliosphere. Our results would be valuable in understanding the Sun-Earth relations and useful in space weather forecasting.

The Statistical and Numerical Study of the Longitudinally Asymmetric Distribution of Solar Proton Events Affecting the Earth Environment of 1996-2011

Hongqing **He**, Weixing Wan
presented at ICRC**2013**
http://arxiv.org/pdf/1502.03090v1.pdf
Large solar proton events (SPEs) affect the solar-terrestrial space environment and become a very important aspect in space weather research. In this work, we statistically investigate 78 solar proton events of 1996-2011 and find that there exists a longitudinally asymmetric distribution of flare sources of the solar proton events observed near 1 AU, namely, with the same longitude separation between magnetic field line footpoint of observer and flare sources, the number of the solar proton events originating from sources located at eastern side of the nominal magnetic footpoint of observer is much larger than that of the solar proton events originating from sources located at western side. A complete model calculation of solar energetic particle (SEP) propagation in the three-dimensional Parker interplanetary magnetic field is presented to give a numerical explanation for this longitudinally asymmetric distribution phenomenon. We find that the longitudinally asymmetric distribution of solar proton events results from the east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport of SEPs in the heliosphere. Our results would be valuable in understanding the solar-terrestrial relations and useful in space weather forecasting.

The dependence of the parallel and perpendicular mean free paths on the rigidity of the solar energetic particles: Theoretical model versus observations

H.-Q. **He**1,2,3 and W. Wan
A&A 557, A57 (**2013**)
Context. The dependence of the parallel and perpendicular mean free paths on the particle rigidity is an important topic in the studies of the diffusion and propagation of charged energetic particles in a large-scale turbulent magnetic field.
Aims. In this work, we investigate the dependence of the parallel and perpendicular mean free paths on the rigidity of solar energetic particles (SEPs) by means of both the theoretical model and spacecraft observations with regard to several typical SEP events.
Methods. A direct method developed by previous studies and derived from the focused transport equation and Taylor-Green-Kubo (TGK) formulation is applied to explicitly determine the parallel and perpendicular mean free paths of SEPs in a turbulent and spatially varying magnetic field.
Results. We find that the parallel and perpendicular mean free paths, $\lambda_\parallel$ and $\lambda_\perp$, of energetic protons monotonically decrease with increasing particle rigidity, and the ratio $\lambda_\perp/\lambda_\parallel$ monotonically increases with particle rigidity, when the magnetic turbulence is weak. Taking a series of typical SEP events together, it can also be seen that the ratio $\lambda_\perp/\lambda_\parallel$ of the perpendicular to the parallel mean free paths remains in the range of 0.001−0.2.

PROPAGATION OF SOLAR ENERGETIC PARTICLES IN THREE-DIMENSIONAL INTERPLANETARY MAGNETIC FIELDS: IN VIEW OF CHARACTERISTICS OF SOURCES

H.-Q. **He**1,2, G. Qin1 and M. Zhang
2011 ApJ 734 74
In this paper, a model of solar energetic particle (SEP) propagation in the three-dimensional Parker interplanetary magnetic field is calculated numerically. We study the effects of the different aspects of particle sources on the solar surface, which include the source location, coverage of latitude and longitude, and spatial distribution of source particle intensity, on propagation of SEPs with both parallel and perpendicular diffusion. We compute the particle flux and anisotropy profiles at different observation locations in the heliosphere. From our calculations, we find that the observation location relative to the latitudinal and longitudinal coverage of particle source has the strongest effects on particle flux and anisotropy profiles observed by a spacecraft. When a spacecraft is directly connected to the solar sources by the interplanetary magnetic field lines, the observed particle fluxes are larger than when the spacecraft is not directly connected. This paper focuses on the situations when a spacecraft is not connected to the particle sources on the solar surface. We find that when the magnetic footpoint of the spacecraft is farther away from the source, the observed particle flux is smaller and its onset and maximum intensity occur later. When the particle source covers a larger range of latitude and longitude, the observed particle flux is larger and appears earlier. There is east-west azimuthal asymmetry in SEP profiles even when the source distribution is east-west symmetric. However, the detail of particle spatial distribution inside the source does not affect the profile of the SEP flux very much. When the magnetic footpoint of the spacecraft is significantly far away from the particle source, the anisotropy of particles in the early stage of an SEP event points toward the Sun, which indicates that the first arriving particles come from outside of the observer through perpendicular diffusion at large radial distances.

Inversion Methodology of Ground Level Enhancements **Review**

B. **Heber**, N. Agueda, R. Bütikofer, D. Galsdorf, K. Herbst, P. Kühl, J. Labrenz, and R. Vainio

In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 10, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf

While it is believed that the acceleration of Solar Energetic Particles (SEPs) is powered by the release of magnetic energy at the Sun, the nature, and location of the acceleration are uncertain, i.e. the origin of the highest energy particles is heavily debated. Information about the highest energy SEPs relies on observations by ground-based Neutron Monitors (NMs). SEPs with energies above 500 MeV entering the Earth's atmosphere will lead to an increase of the intensities recorded by NMs on the ground, also known as Ground Level Event or Ground Level Enhancement (GLE). A Fokker-Planck equation well describes the interplanetary transport of near relativistic electrons and protons. An NM is an integral counter defined by its yield function. From the observations of the NM network, the additional solar cosmic ray characteristics (intensity, spectrum, and anisotropy) in the e

nergy range &500 MeV can be assessed. If the interplanetary magnetic field outside the Earth magnetosphere is known (see Sect. 10.3.2) a computation chain can be set up in order to calculate the count rate increase of an NM for a delta injection at the Sun along the magnetic field line that connects the Sun with the Earth (Sect. 10.3.3). By this computations, we define a set of Green's functions that can be fitted to an observed GLE to determine the injection time profile. If the latter is compared to remote sensing measurements like radio observations, conclusions of the most probable acceleration process can be drawn.

Observational Validation of Cutoff Models as Boundaries of Solar Proton Event Impact Area

Erkka **Heino** , Noora Partamies
JGR Volume125, Issue7 July **2020** e2020JA027935
https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1029/2020JA027935
High energy protons accelerated during solar proton events (SPEs) can access the Earth's middle atmosphere at high and middle latitudes causing large-scale ionization and chemical changes. In this study, we have compared the performance of two cutoff latitude models that predict the limit of the SPE impact area in the atmosphere during 73 SPEs from 1997 to 2010. We use observations from 13 riometer stations and the D Region Absorption Prediction (DRAP) model to test the performance of the two cutoff latitude models by Dmitriev et al. (2010, https://doi.org/10.1029/2010JA015380) and Nesse Tyssøy and Stadsnes (2015, https://doi.org/10.1002/2014JA020508). We find similar performance from the two cutoff latitude models with respect to observations, but the Dmitriev et al. (2010, https://doi.org/10.1029/2010JA015380) model performs slightly better when observations are contrasted with the DRAP model results. The better performing model is also continuous with magnetic local time and particle energy, making it more suited for future use in climate model proton forcing. SPE forcing is currently included in climate models with a single static cutoff latitude limit at 60° geomagnetic latitude. In reality, the area that the solar protons can access is not static but varies with particle rigidity and geomagnetic conditions. We estimate that the SPE impact area is overestimated 90% of the time by this single static cutoff limit and the average overestimation of the impact area is about 15–25% for protons with energies <32 MeV.
Table A1 Solar Proton Events Used in This Study (1997-2001)

Cosmic Noise Absorption During Solar Proton Events in WACCM-D and Riometer Observations

Erkka **Heino**, Pekka T. Verronen , Antti Kero, Niilo Kalakoski , Noora Partamies
JGR Volume124, Issue2 February **2019** Pages 1361-1376
sci-hub.tw/10.1029/2018JA026192
Solar proton events (SPEs) cause large-scale ionization in the middle atmosphere leading to ozone loss and changes in the energy budget of the middle atmosphere. The accurate implementation of SPEs and other particle ionization sources in climate models is necessary to understand the role of energetic particle precipitation in climate variability. We use **riometer observations** from 16 riometer stations and the Whole Atmosphere Community Climate Model with added D region ion chemistry (WACCM-D) to study the spatial and temporal extent of cosmic noise absorption (CNA) during 62 SPEs from 2000 to 2005. We also present a correction method for the nonlinear response of observed CNA during intense absorption events. We find that WACCM-D can reproduce the observed CNA well with some need for future improvement and testing of the used energetic particle precipitation forcing. The average absolute difference between the model and the observations is found to be less than 0.5 dB poleward of about 66° geomagnetic latitude, and increasing with decreasing latitude to about 1 dB equatorward of about 66° geomagnetic latitude. The differences are largest during twilight conditions where the modeled changes in CNA are more abrupt compared to observations. An overestimation of about 1° to 3° geomagnetic latitude in the extent of the CNA is

observed due to the fixed proton cutoff latitude in the model. An unexplained underestimation of CNA by the model during sunlit conditions is observed at stations within the polar cap during 18 of the studied events.

From solar to stellar flare characteristics
On a new peak size distribution for G-, K-, and M-dwarf star flares

Konstantin **Herbst**1, Athanasios Papaioannou2, Saša Banjac1 and Bernd Heber1
A&A 621, A67 (**2019**)
sci-hub.tw/10.1051/0004-6361/201832789

Context. The connection between solar energetic proton events and X-ray flares has been the focus of many studies over the past 13 yr. In the course of these investigations several peak size distribution functions based on Geostationary Operational Environmental Satellite (GOES) measurements of both quantities have been developed. In more recent studies one of these functions has been used to estimate the stellar proton fluence around the M-dwarf star AD Leonis. However, a comparison of the existing peak size distribution functions reveals strong discrepancies with respect to each other.
Aims. The aim of this paper is to derive a new peak size distribution function that can be utilized to give a more realistic estimate of the stellar proton flux of G-, K-, and M-dwarf stars.
Methods. By updating and extending the GOES-based peak size distribution down to B-class X-ray flare intensities with the help of SphinX data from the solar minimum conditions of 2009 and newly derived GOES data between 1975 and 2005, we developed a new power-law peak size distribution function for solar proton fluxes (E > 10 MeV). However, its resulting slope differs from values reported in the literature. Therefore, we also developed a double-power-law peak size distribution function. An extension to much higher X-ray flare intensities (10−1) W m−2 and above, for the first time, results in an approximation of best- and worst-case scenarios of the stellar proton flux around G-, K-, and M-dwarf stars.
Results. Investigating the impact of the newly developed peak size distribution function for G-, K-, and M-dwarf star flare intensities we show that in the worst-case scenario previous studies may underestimate the stellar proton flux by roughly one to five orders of magnitude.

Small, Low-energy, Dispersive Solar Energetic Particle Events Observed by Parker Solar Probe

M. E. **Hill**1, D. G. Mitchell1, R. C. Allen1, G. A. de Nolfo2, A. Vourlidas1, L. E. Brown1, S. I. Jones2,3, D. J. McComas4, R. L. McNutt Jr.1, J. G. Mitchell2Show full author list
2020 ApJS 246 65
https://doi.org/10.3847/1538-4365/ab643d
https://iopscience.iop.org/article/10.3847/1538-4365/ab643d/pdf

The Energetic Particle Instrument–Low Energy (EPI-Lo) experiment has detected several weak, low-energy (~30–300 keV nucleon–1) solar energetic particle (SEP) events during its first two closest approaches to the Sun, providing a unique opportunity to explore the sources of low-energy particle acceleration. As part of the Parker Solar Probe (PSP) Integrated Science Investigation of the Sun (IS⨀IS) suite, EPI-Lo was designed to investigate the physics of energetic particles; however, in the special lowest-energy "time-of-flight only" product used in this study, it also responds to solar photons in a subset of approximately sunward-looking apertures lacking special light-attenuating foils. During the first three perihelia, in a frame rotating with the Sun, PSP undergoes retrograde motion, covering a 17° heliographic longitudinal range three times during the course of the ~11-day perihelion passes, permitting a unique spatial and temporal study into the location, correlation, and persistence of previously unmeasurable SEPs. We examine the signatures of these SEPs (during the first PSP perihelion pass only) and the connection to possible solar sources using remote observations from the Solar Dynamics Observatory (SDO), the Solar TErrestrial RElations Observatory (STEREO), and the ground-based Global Oscillation Network Group (GONG). The orientation of the Sun relative to STEREO, SDO, and GONG makes such identifications challenging, but we do have several candidates, including an equatorial coronal hole at a Carrington longitude of ~335°. To analyze observations from EPI-Lo, which is a new type of particle instrument, we examine instrumental effects and provide a preliminary separation of the ion signal from the photon background.

Longitudinal Extent of 3He-rich Solar Energetic Particle Events Near 1 au

George C. **Ho**1, Glenn M. Mason2, Robert C. Allen1, Athanasios Kouloumvakos2, Robert F. Wimmer-Schweingruber3, and Javier Rodrígzuez-Pacheco4
2024 ApJ 974 68
https://iopscience.iop.org/article/10.3847/1538-4357/ad67ce/pdf

Multispacecraft observations of 3He-rich solar energetic particle (SEP) events are scarce, but much needed in order to understand and properly constrain the source and transport of these remarkably enriched 3He SEP events. In this paper, we report 15 3He-rich SEP events that were detected by the Advanced Composition Explorer, the Solar Terrestrial Relations Observatory, and Solar Orbiter near 1 au during Solar Orbiter's aphelion pass at the end of 2022 and early 2023. Three (five) of these events were detected simultaneously by at least two (three) spacecraft at

up to ∼40° longitudinal separation, while seven events were detected by only a single spacecraft, even though an adjacent spacecraft was less than 20° apart. Using a magnetic connectivity tool, we show statistically that there is a >50% probability of detection when the spacecraft-modeled footpoints have an angular separation angle of <24° to the potential source region back at the Sun. This supports previous studies suggesting that the source of these 3He-rich SEP events is narrow in longitudinal extent. On the other hand, the magnetic connectivity due to the presence of coronal mass ejections, footpoint motion, and/or field-line meandering may also lead to difference in a detection at 1 au. **2022 November 14–18, 2022 December 8–20, 2023 January 5–9, 2023 March 10**
Table 1 List of 3He-rich SEP Events with Onset Times and Spacecraft Relative Locations During the Event

Interplanetary Ion Flux Dropouts Across Multiple 3He-rich Events

George **Ho**, G Mason, Robert Allen, R Wimmer-Schweingruber, J Rodríguez-Pacheco, and R Gómez-Herrero

Front. Astron. Space Sci. 9:939799. **2022**

https://www.frontiersin.org/articles/10.3389/fspas.2022.939799/pdf

Solar Orbiter, a joint ESA/NASA mission, is studying the Sun and inner heliosphere in greater detail than ever before. Launched in February 2020, Solar Orbiter has already completed its first three orbits, reaching perihelia of 0.5 au from the Sun in June 2020, February and August 2021. During the first 2 years in orbit, Solar Orbiter observed multiple 3He-rich Solar Energetic Particle (SEP) events inside 1 au. Even though these events were small, their spectral forms, 3He content, and association with energetic electrons and type III bursts convincingly identifies them as 3He-rich SEP events with properties similar to those previously observed at 1 au, and promising new insights as Solar Orbiter moves much closer to the Sun in 2022. In May 2021, we observed six 3He-rich SEP events in close succession within 48 h when Solar Orbiter was at 0.95 au. These events were likely released from the same active region at the Sun, and the particles arrived at Solar Orbiter in two batches with various abundances and intensities, showing strong anisotropies throughout. Multiple ion flux dropouts were also observed with these six 3He-rich SEP events. The fact that we observed so many ion injections in such a short period of time indicates the 3He enrichment and acceleration mechanism can produce SEP from the same region very efficiently and with varying enrichment levels and intensities. In addition, we report for the first-time dropout features that spanned multiple ion events simultaneously. This implies the field line random walk that we observe at 1 au still maintains magnetic connections to a small region back at the Sun up to the entire duration of these events (∼48 h). **May 21-25, 2021**

Energetic Particle Measurements with Solar Orbiter

George C. **Ho**

Fleishman's webinar 19 June **2020**

https://youtu.be/zyuMlQh6_Sw

3He-Rich Solar Energetic Particle Events with No Measurable 4He Intensity Increases

George C. **Ho**, Glenn M. Mason, Robert C. Allen

Solar Physics February **2019**, 294:33

https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1420-z.pdf

sci-hub.tw/10.1007/s11207-019-1420-z

We investigated 3He-rich solar energetic particle (SEP) events in the current solar cycle starting in 2009 through 2017. Both “impulsive” (flare-related) 3He-rich and CME-related “gradual” events are included. In the former solar cycle, we found the number of observed 3He-rich events correlated with solar activity. The same correlation is seen again in Cycle 24. Because of the comparatively weak activity, both the occurrence of 3He-rich events and their intensities are significantly less than those from Cycle 23. Interestingly, we found in several of the 3He-rich events that there is no measurable 4He intensity increase above the instrument background. Previously, we found that there is a limit on the number of 3He ions that can be released from the Sun in an impulsive SEP event, while there is no such limit on the 4He ions (Ho, Roelof, and Mason in Astrophys. J., 621, L862, 2005). In this paper, we examine several of these 3He-rich events in detail and discuss the lack of observable 4He intensity increases and the implications for the enhancement and acceleration mechanism of this special type of SEP events. **2 Sep 2010, 26 July 2013, 30 July 2013, 4 Feb 2016**

Correction Solar Phys (**2019**) 294:39 https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1437-3.pdf

Toward Enhanced Prediction of High-Impact Solar Energetic Particle Events Using Multimodal Time Series Data Fusion Models

Pouya **Hosseinzadeh**, Soukaina Filali Boubrahimi, Shah Muhammad Hamdi

Space Weather Volume22, Issue6 June **2024** e2024SW003982

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003982

Solar energetic particle (SEP) events, originating from solar flares and Coronal Mass Ejections, present significant hazards to space exploration and technology on Earth. Accurate prediction of these high-energy events is essential for safeguarding astronauts, spacecraft, and electronic systems. In this study, we conduct an in-depth investigation into the application of multimodal data fusion techniques for the prediction of high-energy SEP events, particularly ∼100 MeV events. Our research utilizes six machine learning (ML) models, each finely tuned for time series analysis, including Univariate Time Series (UTS), Image-based model (Image), Univariate Feature Concatenation (UFC), Univariate Deep Concatenation (UDC), Univariate Deep Merge (UDM), and Univariate Score Concatenation (USC). By combining time series proton flux data with solar X-ray images, we exploit complementary insights into the underlying solar phenomena responsible for SEP events. Rigorous evaluation metrics, including accuracy, F1-score, and other established measures, are applied, along with K-fold cross-validation, to ensure the robustness and generalization of our models. Additionally, we explore the influence of observation window sizes on classification accuracy.

Table 1List of Solar Energetic Particle Events Associated With ∼100 MeV Energy Band and Their Corresponding Solar FlareCharacteristics Based on GSEP Catalog 1997-2012

Improving Solar Energetic Particle Event Prediction through Multivariate Time Series Data Augmentation

Pouya **Hosseinzadeh**1, Soukaina Filali Boubrahimi1, and Shah Muhammad Hamdi

2024 ApJS 270 31

https://iopscience.iop.org/article/10.3847/1538-4365/ad1de0/pdf

Solar energetic particles (SEPs) are associated with extreme solar events that can cause major damage to space- and ground-based life and infrastructure. High-intensity SEP events, particularly ∼100 MeV SEP events, can pose severe health risks for astronauts owing to radiation exposure and affect Earth's orbiting satellites (e.g., Landsat and the International Space Station). A major challenge in the SEP event prediction task is the lack of adequate SEP data because of the rarity of these events. In this work, we aim to improve the prediction of ∼30, ∼60, and ∼100 MeV SEP events by synthetically increasing the number of SEP samples. We explore the use of a univariate and multivariate time series of proton flux data as input to machine-learning-based prediction methods, such as time series forest (TSF). Our study covers solar cycles 22, 23, and 24. Our findings show that using data augmentation methods, such as the synthetic minority oversampling technique, remarkably increases the accuracy and F1-score of the classifiers used in this research, especially for TSF, where the average accuracy increased by 20%, reaching around 90% accuracy in the ∼100 MeV SEP prediction task. We also achieved higher prediction accuracy when using the multivariate time series data of the proton flux. Finally, we build a pipeline framework for our best-performing model, TSF, and provide a comprehensive hierarchical classification of the ∼100, ∼60, and ∼30 MeV and non-SEP prediction scenarios.

Calibration of the GOES 6–16 high-energy proton detectors based on modelling of ground level enhancement energy spectra

Shaowen **Hu**1* and Edward Semones2

J. Space Weather Space Clim. **2022**, **12**, 5

https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc210063.pdf

https://doi.org/10.1051/swsc/2022003

For several decades, the Geostationary Operational Environmental Satellites (GOES) series have provided both real-time and historical data for radiation exposure estimation and solar proton radiation environment modelling. Recently, several groups conducted calibration studies that significantly reduced the uncertainties on the response of GOES proton detectors, thus improving the reliability of the spectral observations of solar energetic particle events. In this work, the long-established Band function fitting set for past ground level enhancements (GLEs) and their recent revision are used as references to estimate the best matching energies of proton channels of GOES 6–16, with emphasis on comparing with previous calibration studies on the high energetic proton measurements. The calculated energies for different missions in the same series (GOES 8, 10, 11) show overall consistency but with small variations, and differences among missions of different series are noticeable for measurements crossing the past three solar cycles, though the results are sensitive to the method used to subtract background fluxes. The discrepancy and agreement with previous calibration efforts are demonstrated with other independent analyses. It is verified that the integral channel P11 of GOES 6–16 can be reliably used as a differential proton channel with an effective energy of about 1 GeV. Therefore, the multi-decade in situ measurements of the GOES series can be utilized with more extensive energy coverage to improve space radiation environment models. **15-22 Jan 2005, 14 Dec 2006, 27 Jan 2012, 17 May 2012, 6 Jan 2014**

Table A.1. Spectral parameters of GLEs since 1986 as compiled from the works of Raukunen et al. (2018) and Koldobskiy et al. (2021)

Extreme energetic particle events by superflare-associated CMEs from solar-like stars

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SCIENCE ADVANCES 25 Mar **2022** Vol 8, Issue 12 , 8, eabi9743
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https://www.science.org/doi/pdf/10.1126/sciadv.abi9743
Discovery of frequent superflares on active cool stars opened a new avenue in understanding the properties of eruptive events and their impact on exoplanetary environments. Solar data suggest that coronal mass ejections (CMEs) should be associated with superflares on active solar-like planet hosts and produce solar/stellar energetic particle (SEP/StEP) events. Here, we apply the 2D Particle Acceleration and Transport in the Heliosphere model to simulate the SEPs accelerated via CME-driven shocks from the Sun and young solar-like stars. We derive the scaling of SEP fluence and hardness of energy spectra with CME speed and associated flare energy. These results have crucial implications for the prebiotic chemistry and expected atmospheric biosignatures from young rocky exoplanets as well as the chemistry and isotopic composition of circumstellar disks around infant solar-like stars.

Modeling a Single SEP Event from Multiple Vantage Points Using the iPATH Model

Junxiang **Hu**1, Gang Li1, Shuai Fu1, Gary Zank1, and Xianzhi Ao1
2018 ApJL 854 L19
http://sci-hub.tw/http://iopscience.iop.org/2041-8205/854/2/L19/
Using the recently extended 2D improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, we model an example gradual solar energetic particle event as observed at multiple locations. Protons and ions that are energized via the diffusive shock acceleration mechanism are followed at a 2D coronal mass ejection-driven shock where the shock geometry varies across the shock front. The subsequent transport of energetic particles, including cross-field diffusion, is modeled by a Monte Carlo code that is based on a stochastic differential equation method. Time intensity profiles and particle spectra at multiple locations and different radial distances, separated in longitudes, are presented. The results shown here are relevant to the upcoming Parker Solar Probe mission.

Modeling Particle Acceleration and Transport at a 2-D CME-Driven Shock

Junxiang **Hu**, Gang Li, Xianzhi Ao, Gary P. Zank, Olga Verkhoglyadova
JGR November **2017** Vol: 122, Pages: 10,921–10,937
http://sci-hub.tw/10.1002/2017JA024077
We extend our earlier Particle Acceleration and Transport in the Heliosphere (PATH) model to study particle acceleration and transport at a coronal mass ejection (CME)-driven shock. We model the propagation of a CME-driven shock in the ecliptic plane using the ZEUS-3D code from 20 solar radii to 2 AU. As in the previous PATH model, the initiation of the CME-driven shock is simplified and modeled as a disturbance at the inner boundary. Different from the earlier PATH model, the disturbance is now longitudinally dependent. Particles are accelerated at the 2-D shock via the diffusive shock acceleration mechanism. The acceleration depends on both the parallel and perpendicular diffusion coefficients $\kappa_{||}$ and $\kappa_{\perp}$ and is therefore shock-obliquity dependent. Following the procedure used in Li, Shalchi, et al. (2012), we obtain the particle injection energy, the maximum energy, and the accelerated particle spectra at the shock front. Once accelerated, particles diffuse and convect in the shock complex. The diffusion and convection of these particles are treated using a refined 2-D shell model in an approach similar to Zank et al. (2000). When particles escape from the shock, they propagate along and across the interplanetary magnetic field. The propagation is modeled using a focused transport equation with the addition of perpendicular diffusion. We solve the transport equation using a backward stochastic differential equation method where adiabatic cooling, focusing, pitch angle scattering, and cross-field diffusion effects are all included. Time intensity profiles and instantaneous particle spectra as well as particle pitch angle distributions are shown for two example CME shocks.

Segmental interpolating spectra for solar particle events and in situ validation

S. **Hu**, C. Zeitlin, W. Atwell, D. Fry, J.E. Barzilla, E. Semones
Space Weather Volume 14, Issue 10 October **2016** Pages 742–753
http://sci-hub.cc/doi/10.1002/2016SW001476
It is a delicate task to accurately assess the impact of solar particle events (SPEs) on future long-duration human exploration missions. In the past, researchers have used several functional forms to fit satellite data for radiation exposure estimation. In this work we present a segmental power law interpolating algorithm to stream satellite data and get time series of proton spectra, which can be used to derive dosimetric quantities for any short period during which a single SPE or multiple SPEs occur. Directly using the corrected High Energy Proton and Alpha Detector

fluxes of GOES, this method interpolates the intensity spectrum of a typical SPE to hundreds of MeV and extrapolates to the GeV level as long as sufficient particles are recorded in the high-energy sensors. The high-energy branch of the **May 2012** SPE is consistent with the Band functional fitting, which is calibrated with ground level measurement. Modeling simulations indicate that the input spectrum of an SPE beyond 100 MeV is the major contributor for dose estimation behind the normal shielding thickness of spacecraft. Applying this method to the three SPEs that occurred in 2012 generates results consistent with two sets of in situ measurements, demonstrating that this approach could be a way to perform real-time dose estimation. This work also indicates that the galactic cosmic ray dose rate is important for accurately modeling the temporal profile of radiation exposure during an SPE.
2012-Jan-23, 2012-Mar-7, 2012-May-17-18

Relationship between Intensity of White-light Flares and Proton Flux of Solar Energetic Particles

Nengyi **Huang**1,2, Yan Xu1,2, and Haimin Wang
2018 Res. Notes AAS 2 7
http://iopscience.iop.org/article/10.3847/2515-5172/aaa602
https://arxiv.org/pdf/1801.04316.pdf
In summary, our preliminary results show that most ($>83\%$) of WLFs and SEP events have no correspondence.
Solar energetic particles (SEPs), including protons and heavy ions, are believed to be accelerated either by CME shock or by magnetic reconnection. The latter also produces solar flares, in which the white light flares (WLFs) are among the most energetic ones. Magnetic reconnections occur in the corona and the accelerated particles propagate both downward and upward along the magnetic loops. The former is the source of flare emission and the latter is thought to be SEPs. Therefore, a comparison between flare emission and SEP events provides valuable constraint in determining the acceleration site of SEPs. We collect 43 SEP events, observed from 2010 to 2017, and investigate their correlation with WL emission and SXR flus, observed by SDO/HMI and GOES, respectively. Our preliminary results show: 1) Among 47 SEP events, 39 of which do not have detectable flare emissions in white light and SXR. 2) Most strong WLFs are not associated with SEPs. 3) No clear correlation is found between the proton flux and the equivalent area, a quantity that measures the magnitude of WLF emission. A straightforward speculation is that the acceleration process could be different for SEPs and the energetic electrons powering WLFs in the events analyzed.
4.8. 2011, 9.8.2011, 23.01.2012, 13.03.2012, 2012 March 7 , 6.7.2012, 25-Jun 2015, 4.9.2017, 2017 September 6

Ensemble prediction model of solar proton events associated with solar flares and coronal mass ejections

Huang, Xin; Wang, Hua-Ning; Li, Le-Ping
Research in Astronomy and Astrophysics, Volume 12, Issue 3, pp. 313-321 (**2012**).
An ensemble prediction model of solar proton events (SPEs), combining the information of solar flares and coronal mass ejections (CMEs), is built. In this model, solar flares are parameterized by the peak flux, the duration and the longitude. In addition, CMEs are parameterized by the width, the speed and the measurement position angle. The importance of each parameter for the occurrence of SPEs is estimated by the information gain ratio. We find that the CME width and speed are more informative than the flare's peak flux and duration. As the physical mechanism of SPEs is not very clear, a hidden naive Bayes approach, which is a probability-based calculation method from the field of machine learning, is used to build the prediction model from the observational data. As is known, SPEs originate from solar flares and/or shock waves associated with CMEs. Hence, we first build two base prediction models using the properties of solar flares and CMEs, respectively. Then the outputs of these models are combined to generate the ensemble prediction model of SPEs. The ensemble prediction model incorporating the complementary information of solar flares and CMEs achieves better performance than each base prediction model taken separately.

Study of the Impact of past extreme Solar Events on the modern air traffic

G. **Hubert**, S. Aubry
Space Weather e2020SW002665 **2021**
https://doi.org/10.1029/2020SW002665
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002665
The ancient SEP events of AD **774/775** and AD **993/994** were characterized thanks to radionuclide productions stored in environmental archives as ice cores or tree rings. Primary cosmic ray spectra deduced from these cosmogenic isotope data indicate that the impact of these extreme SEP events would have been much more significant than any of the ones observed during the modern era. However, the impact of these should be studied more accurately in the framework of the ambient dose equivalent impacting aircrew and passengers in the air traffic context by considering physical parameters such as time profile or anisotropy properties. In this paper the impact that AD 774/775 and AD 993/994 past extreme SEP events could have had on modern air traffic is discussed. Possible event spectra for these ancient events are derived from the spectra **GLE 5** and **GLE 69**, which have been observed during the modern era and have been widely studied/characterized using measurements. The investigations

include the impact of the SEP activity on ambient dose equivalent, including detailed analyses considering route, airplane characteristics (departure, arrival, continent, airplane type), and the time occurrence of the SEP event. Statistical analyses show that additional dose levels can reach values on the order of 70 mSv, which is absolutely significant considering the current air traffic recommendations. The orders of magnitude of the ambient dose equivalent induced during past extreme SEP events raises a number of issues, both for aircrews and for avionics hardware. This paper demonstrates that simulations can be useful for the evaluation of risks in case of extreme SEP events. **23 Feb 1956, 20 Jan 2005**

Analysis of the Forbush Decreases and Ground-Level Enhancement on September 2017 Using Neutron Spectrometers Operated in Antarctic and Midlatitude Stations

G. **Hubert**, M. T. Pazianotto C. A. Federico P. Ricaud
JGR Volume124, Issue1 January **2019** Pages 661-673
sci-hub.tw/10.1029/2018JA025834

This work investigates solar events occurred in September 2017 characterized by a series of Forbush decreases and a ground level enhancement (GLE). Forbush decreases is a rapid decrease in the observed https://en.wikipedia.org/wiki/Galactic_cosmic_rayintensity following a coronal mass ejection while GLE is induced by a strong solar event for which the flux of high-energy solar particles is sufficient to enhance the radiation level on the ground. These investigations were performed using data recorded by a neutron spectrometer network composed of a Bonner sphere system. Two instruments located at Pic-du-Midi Observatory (+2,885 m above sea level) and at Concordia station (Antarctica, +3,233 m) record simultaneously and continuously the neutron spectra, allowing to consider short-term variations during solar events. The main objective is to analyze neutron spectral properties including their energy distributions and dynamics. This paper presents cosmic ray-induced neutron spectra during active solar event leading to changes in the local cosmic ray spectrum (Forbush decreases and a GLE). Concerning the GLE, analyses show that neutrons in the evaporation domain are particularly amplified during the GLE, while other energetic domains increase uniformly.

Carrington events.

Hudson HS
(**2021**) Annu Rev Astron Astrophys 59:445.
https://doi.org/10.1146/annurev-astro-112420-023324

The Carrington event in 1859, a solar flare with an associated geomagnetic storm, has served as a prototype of possible superflare occurrence on the Sun. Recent geophysical (^{14}C signatures in tree rings) and precise time-series photometry [the bolometric total solar irradiance (TSI) for the Sun, and the broadband photometry from *Kepler* and *Transiting Exoplanet Survey Satellite*, for the stars] have broadened our perspective on extreme events and the threats that they pose for Earth and for Earth-like exoplanets. This review assesses the mutual solar and/or stellar lessons learned and the status of our theoretical understanding of the new data, both stellar and solar, as they relate to the physics of the Carrington event. The discussion includes the event's implied coronal mass ejection, its potential “solar cosmic ray” production, and the observed geomagnetic disturbances based on the multimessenger information already available in that era. Taking the Carrington event as an exemplar of the most extreme solar event, and in the context of our rich modern knowledge of solar flare and/or coronal mass ejection events, we discuss the aspects of these processes that might be relevant to activity on solar-type stars, and in particular their superflares.

Cosmic-Ray Interactions in the Solar Atmosphere

Hugh S. **Hudson**1,2 , Alec MacKinnon1 , Mikolaj Szydlarski3 , and Mats Carlsson3
MNRAS Volume 491, Issue 4, February **2020** Pages 4852–4856,
https://doi.org/10.1093/mnras/stz3373
https://arxiv.org/pdf/1910.01186.pdf

High-energy particles enter the solar atmosphere from Galactic or solar coronal sources, producing an "albedo" source from the quiet Sun, now observable across a wide range of photon energies. The interaction of high-energy particles in a stellar atmosphere depends essentially upon the joint variation of the magnetic field and the gas, which heretofore has been characterized parametrically as P ~ B^alpha with P the gas pressure and B the magnitude of the magnetic field. We re-examine that parametrization by using a self-consistent 3D MHD model (Bifrost) and show that this relationship tends to P ~ B^{2.9+-0.1} based on the visible portions of the sample of open-field flux tubes in such a model, but with large variations from point to point. This scatter corresponds to the strong meandering of the open-field flux tubes in the lower atmosphere, which will have a strong effect on the prediction of the emission anisotropy (limb brightening). The simulations show that much of the open flux in coronal holes originates in weak-field regions within the granular pattern of the convective motions seen in the simulations.
RHESSI Nuggets #366 Dec **2019**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Cosmic_Rays_over_the_Rainbow_Bridge

The Relationship between Long-Duration Gamma-Ray Flares and Solar Cosmic Rays
Hugh S. **Hudson**
Space Weather of the Heliosphere: Processes and Forecasts (eds. Claire Foullon and Olga Malandraki), IAU Symposium 335, **2017** V. 13,
https://arxiv.org/pdf/1711.05583.pdf
sci-hub.se/10.1017/S1743921317009681
https://www.cambridge.org/core/services/aop-cambridge-core/content/view/AA110058A9A4D2D8F8AB885CD9D86A28/S1743921317009681a.pdf/relationship_between_longduration_gammaray_flares_and_solar_cosmic_rays.pdf
A characteristic pattern of solar hard X-ray emission, first identified in SOL1969-03-30 by Frost & Dennis (1971), turns out to have a close association with the prolonged high-energy gamma-ray emission originally observed by Forrest et al. (1985). This identification has become clear via the observations of long-duration gamma-ray flares by the Fermi/LAT experiment, for example in the event SOL2014-09-01. The distinctive features of these events include flat hard X-ray spectra extending well above 100 keV, a characteristic pattern of time development, low-frequency gyrosynchrotron peaks, CME association, and gamma-rays identifiable with pion decay originating in GeV ions. The identification of these events with otherwise known solar structures nevertheless remains elusive, in spite of the wealth of EUV imagery available from SDO/AIA. The quandary is that these events have a clear association with SEPs in the high corona, and yet the gamma-ray production implicates the photosphere itself, despite the strong mirror force that should focus the particles \textit{away} from the Sun We discuss the morphology of these phenomena and propose a solution to this problem. **1969-03-30, 1982-06-03, 2014-09-01**

Solar extreme events **Review**
Hugh S. **Hudson**
24th European Cosmic Ray Symposium, Kiel, September 2014, **2015**
http://arxiv.org/pdf/1504.04755v1.pdf
Solar flares and CMEs have a broad range of magnitudes. This review discusses the possibility of "extreme events," defined as those with magnitudes greater than have been seen in the existing historical record. For most quantitative measures, this direct information does not extend more than a century and a half into the recent past. The magnitude distributions (occurrence frequencies) of solar events (flares/CMEs) typically decrease with the parameter measured or inferred (peak flux, mass, energy etc. Flare radiation fluxes tend to follow a power law slightly flatter than S^{-2}, where S represents a peak flux; solar particle events (SPEs) follow a still flatter power law up to a limiting magnitude, and then appear to roll over to a steeper distribution, which may take an exponential form or follow a broken power law. This inference comes from the terrestrial 14C record and from the depth dependence of various radioisotope proxies in the lunar regolith and in meteorites. Recently major new observational results have impacted our use of the relatively limited historical record in new ways: the detection of actual events in the 14C tree-ring records, and the systematic observations of flares and "superflares" by the Kepler spacecraft. I discuss how these new findings may affect our understanding of the distribution function expected for extreme solar events. 2003-11-04,

Solar Cosmic Rays, Neutrons, and Fermi Gamma-Rays,
Hugh **Hudson** and Alec MacKinnon
RHESSI Science Nuggets, No. 227, May, **2014**:
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Solar_Cosmic_Rays,_Neutrons,_and_Fermi_Gamma-Rays
Exciting new solar high-energy observations.
In this Nugget we discuss the remote-sensing observations of two solar flares by the Large Area Detector on board the Fermi gamma-ray observatory. These events were simultaneously detected by ground-based detectors of high-energy particles at a high-altitude site in the Argentinian Andes, and also by direct measurement of solar neutrons arriving at the International Space Station [Ref. 2]. RHESSI's Browser provides an overview of one of the event featured in this Nugget, **2011-03-07, 2011-01-23**

Remote sensing of low-energy SEPs via charge exchange
Hudson, H. S.; MacKinnon, A. L.; Badnell, N. R.
E-print, Feb **2014**; SOLAR WIND 13: Proceedings of the Thirteenth International Solar Wind Conference. AIP Conference Proceedings, Volume 1539, pp. 19-21 (**2013**)
Charge-exchange reactions at high energies provide new channels for the remote sensing of solar high-energy particles, as demonstrated by the recent detection of 1.8-5 MeV hydrogen atoms from a solar flare. Orrall and Zirker had earlier proposed the detection of low-energy protons via charge-exchange atomic reactions in the solar atmosphere, leading in the simplest case to extended red-wing emission in the Lymanα line. We discuss the analogous process for the He II 304 A line (forα particles) and also assess the feasibility of the analogous process in

the solar wind, whereby ambient He and (C, N, O) ions allow low-energyα particles to undergo resonant charge exchange in the ambient corona and thereby produce 304 A wing emission close to the acceleration region.

Cross-Field Diffusion Effects on Particle Transport in a Solar Coronal Flux Rope

Edin **Husidic**, Nicolas Wijsen, Luis Linan, Michaela Brchnelova, Rami Vainio, Stefaan Poedts

ApJL **2024**

https://arxiv.org/pdf/2411.00738

Solar energetic particles (SEPs) associated with solar flares and coronal mass ejections (CMEs) are key agents of space weather phenomena, posing severe threats to spacecraft and astronauts. Recent observations by Parker Solar Probe (PSP) indicate that the magnetic flux ropes of a CME can trap energetic particles and act as barriers, preventing other particles from crossing. In this paper, we introduce the novel COCONUT+PARADISE model to investigate the confinement of energetic particles within a flux rope and the effects of cross-field diffusion (CFD) on particle transport in the solar corona, particularly in the presence of a CME. Using the global magnetohydrodynamic coronal model COCONUT, we generate background configurations containing a CME modeled as a Titov-Démoulin flux rope (TDFR). We then utilize the particle transport code PARADISE to inject monoenergetic 100 keV protons inside one of the TDFR legs near its footpoint and evolve the particles through the COCONUT backgrounds. To study CFD, we employ two different approaches regarding the perpendicular proton mean free path (MFP): a constant MFP and a Larmor radius-dependent MFP. We contrast these results with those obtained without CFD. While particles remain fully trapped within the TDFR without CFD, we find that even relatively small perpendicular MFP values allow particles on the outer layers to escape. In contrast, the initially interior trapped particles stay largely confined. Finally, we highlight how our model and this paper's results are relevant for future research on particle acceleration and transport in an extended domain encompassing both the corona and inner heliosphere.

Energetic particle acceleration and transport with the novel Icarus + PARADISE model

Edin **Husidic**1,2, Nicolas Wijsen1, Tinatin Baratashvili1, Stefaan Poedts1,3 and Rami Vainio2

J. Space Weather Space Clim. **2024**, 14, 11

https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc230063.pdf

With the rise of satellites and mankind's growing dependence on technology, there is an increasing awareness of space weather phenomena related to high-energy particles. Shock waves driven by coronal mass ejections (CMEs) and corotating interaction regions (CIRs) occasionally act as potent particle accelerators, generating hazardous solar energetic particles (SEPs) that pose risks to satellite electronics and astronauts. Numerical simulation tools capable of modelling and predicting large SEP events are thus highly demanded. We introduce the new Icarus + PARADISE model as an advancement of the previous EUHFORIA + PARADISE model. Icarus, based on the MPI-AMRVAC framework, is a three-dimensional magnetohydrodynamic code that models solar wind configurations from 0.1 au onwards, encompassing transient structures like CMEs or CIRs. Differing from EUHFORIA's uniform-only grid, Icarus incorporates solution adaptive mesh refinement (AMR) and grid stretching. The particle transport code PARADISE propagates energetic particles as test particles through these solar wind configurations by solving the focused transport equation in a stochastic manner. We validate our new model by reproducing EUHFORIA + PARADISE results. This is done by modelling the acceleration and transport of energetic particles in a synthetic solar wind configuration containing an embedded CIR. Subsequently, we illustrate how the simulation results vary with grid resolution by employing different levels of AMR. The resulting intensity profiles illustrate increased particle acceleration with higher levels of AMR in the shock region, better capturing the effects of the shock.

Modelling shock-like injections of solar energetic particles with 3D test particle simulations

A. **Hutchinson**, S. Dalla, T. Laitinen and C. O. G. Waterfall

A&A 670, A178 (**2023**)

https://arxiv.org/pdf/2210.15587.pdf

https://www.aanda.org/articles/aa/pdf/2023/02/aa45313-22.pdf

Context. Solar energetic particle (SEP) acceleration and injection into interplanetary space during gradual SEP events is thought to take place at coronal mass ejection (CME)-driven shocks. Various features of measured intensity profiles at 1 au have been attributed to properties of the radial, longitudinal, and latitudinal SEP injections at the shock. Focussed transport models are typically used to model acceleration at a CME-shock and subsequent propagation. Test particle simulations are an alternative approach but so far they have been carried out only with instantaneous injection near the Sun.

Aims. We develop the first temporally extended shock-like injection for our 3D test particle code and investigate how the spatial features of injection at a shock affect SEP intensity and anisotropy profiles for observers at 0.3 and 1.0 au.

Methods. We conducted simulations of a monoenergetic population of 5 MeV protons considering three different radial injection functions and two longitudinal and latitudinal injection functions. We considered a range of

scattering conditions with scattering mean free path values ranging from $\lambda = 0.1 - 1.0$ au, and determined intensity and anisotropy profiles at six observers at different longitudinal locations.
Results. We find that the radial, longitudinal, and latitudinal injection functions play a relatively minor role in shaping the SEP intensity profiles. The dependence of intensity profiles on the value of the scattering mean free path is also weak, unlike what is found from 1D focussed transport models. Spatial factors, such as the times of observer-shock connection and disconnection as well as the time of shock passage have a much stronger influence on SEP intensities and anisotropies. Persistent anisotropies, until shock passage, are seen in our simulations. Comparing instantaneous and shock-like injections, we find that the link between the duration of injection and the duration of the SEP event is very weak, unlike what is commonly assumed.

The impact of corotation on gradual solar energetic particle event intensity profiles

Adam **Hutchinson**, Silvia Dalla, Timo Laitinen, Charlotte O. G. Waterfall

A&A Lett 670, L24 **2023**

https://arxiv.org/pdf/2210.15464.pdf

https://www.aanda.org/articles/aa/pdf/2023/02/aa45312-22.pdf

Context. The corotation of particle-filled magnetic flux tubes is generally thought to have a minor influence on the time-intensity profiles of gradual solar energetic particle (SEP) events. For this reason, many SEP models solve the focussed transport equation within the corotating frame, thus neglecting corotation effects.

Aims. We use simulations to study the effects of corotation on gradual SEP intensity profiles at a range of observer longitudinal positions relative to the solar source. We study how corotation affects the duration and decay time constant of SEP events as well as the variation in the peak intensity with the observer's position.

Methods. We used a 3D full-orbit test particle code with time-extended SEP injection via a shock-like source. In contrast to the case of focussed transport models, the test particle approach enables us to easily switch corotation on and off. While shock acceleration and downstream features are not modelled directly, our methodology allows us to study how corotation and the time-varying observer-shock magnetic connection influence the intensity profiles detected at several observers.

Results. We find that corotation has a strong effect on the SEP intensity profiles for a monoenergetic population of 5 MeV protons, having a dominant influence during the decay phase. Simulations that include corotation display dramatically shortened durations for western events, compared to ones where it is not included. When corotation effects are taken into account, for both eastern and western events, the decay time constant is reduced and its dependence on the value of the scattering mean free path becomes negligible. Corotation reduces the SEP peak intensity for western events and enhances it for eastern ones, thus making the east-west asymmetry in peak intensity stronger, compared to the non-corotation case. Modelling SEP intensity profiles without carefully accounting for the effects of corotation leads to artificially extended decay phases during western events, leading to profiles with a similar shape regardless of the observer's longitudinal position.

Multi-spacecraft observations of the decay phase of solar energetic particle events

R. A. **Hyndman**, S. Dalla, T. Laitinen, A. Hutchinson, C. M. S. Cohen, R. F. Wimmer-Schweingruber

A&A **2024**

https://arxiv.org/pdf/2411.07903

Context: Parameters of solar energetic particle (SEP) event profiles such as the onset time and peak time have been researched extensively to obtain information on acceleration and transport of SEPs. Corotation of particle-filled magnetic flux tubes with the Sun is generally thought to play a minor role in determining intensity profiles. However recent simulations have suggested that corotation has an effect on SEP decay phases, depending on the location of the observer with respect to the active region (AR) associated with the event. Aims: We aim to determine whether signatures of corotation are present in observations of decay phases of SEP events and study how the parameters of the decay phase depend on the properties of the flares and coronal mass ejections (CMEs) associated with the events. Methods: We analyse multi-spacecraft observations of SEP intensity profiles from 11 events between 2020 and 2022, using data from SOLO, PSP, STEREO-A, and SOHO. We determine the decay time constant, \tau in 3 energy channels; electrons ~ 1 MeV, protons ~ 25 MeV, and protons ~ 60 MeV. We study the dependence of \tau on the longitudinal separation, \Delta \phi, between source active region (AR) and the spacecraft magnetic footpoint on the Sun.
Results: Within individual events there is a tendency for the decay time constant to decrease with increasing $\Delta\phi$, in agreement with test particle simulations. The intensity of the associated flare and speed of the associated CMEs have a strong effect on the measured τ values and are likely the cause of the observed large inter-event variability.
Conclusions: We conclude that corotation has a significant effect on the decay phase of a solar energetic particle event and should be included in future simulations and interpretations of these events**. 09-10- 2021, 28-10-2021, 2022-02-15**

Table 1: Associated flare and CME properties for SEP events analysed. 2020-2022

Detection of the temporal variation of the Sun's cosmic ray shadow with the IceCube detector

IceCube Collaboration: M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D ....

2018

https://arxiv.org/pdf/1811.02015.pdf

We report on the observation of a deficit in the cosmic ray flux from the directions of the Moon and Sun with five years of data taken by the IceCube Neutrino Observatory. Between May 2010 and May 2011 the IceCube detector operated with 79 strings deployed in the glacial ice at the South Pole, and with 86 strings between May 2011 and May 2015. A binned analysis is used to measure the relative deficit and significance of the cosmic ray shadows. Both the cosmic ray Moon and Sun shadows are detected with high statistical significance (>10σ) for each year. The results for the Moon shadow are consistent with previous analyses and verify the stability of the IceCube detector over time. This work represents the first observation of the Sun shadow with the IceCube detector. We show that the cosmic ray shadow of the Sun varies with time. These results open the possibility to study cosmic ray transport near the Sun with future data from IceCube.

Reconstruction of the magnetic connection from Mercury to the solar corona during enhancements in the solar proton fluxes at Mercury

A. **Ippolito**1,2, C. Plainaki1, G. Zimbardo3, T. Alberti4, S. Massetti4, A. Milillo4 and S. Orsini4

A&A 660, A50 (**2022**)

https://www.aanda.org/articles/aa/pdf/2022/04/aa42328-21.pdf

Aims. We study the magnetic connection between Mercury and the solar corona based on energetic proton events measured near Mercury by MESSENGER during 2011−2013 in order to identify the possible source of the accelerated particles on the solar surface.

Methods. The transport of the magnetic field lines in the heliosphere was evaluated with a Monte Carlo code that gives a random displacement at each step of the integration along the Parker magnetic field model. The simulation was tailored to each specific event by using the magnetic fluctuation levels obtained at Mercury by MESSENGER and the values of the solar wind velocity measured at 1 AU by the Advanced Composition Explorer satellite. We selected seven case studies for which an increase in the proton fluxes of at least two orders of magnitude with respect to the background level was observed. For each selected case, we took the background magnetic field map (magnetogram) at the source surface of the solar wind ($r = 2.5\,R_\odot$) into account. By considering the relative position of Mercury and the Earth on the day on which the enhancement in the proton fluxes was observed by MESSENGER, we obtained the position of the active regions on the solar surface as seen by Mercury.

Results. The footpoint of the Parker spiral passing Mercury was reconstructed for all of the selected events. By considering the values of the fluctuation levels of the interplanetary magnetic field recorded by MAG-MESSENGER two days before the event and the values of the fluctuation levels of the interplanetary magnetic field on the day on which the event was observed, we are also able to appreciate the effects on the solar wind magnetic field perturbations induced by the shock of the coronal mass ejection. This technique will also be useful for the interpretation of energetic particle observations by BepiColombo. **5 June 2011, 27 January 2012, 4 March 2012, 26 May 2012, 12 July 2012, 20 September 2012, and 21 June 2013**

Proton Flares in Solar Activity Complexes: Possible Origins and Consequences

E. S. **Isaeva**, V. M. Tomozov & S. A. Yazev

Astronomy Reports March **2018**, Volume 62, Issue 3, pp 243–250

http://sci-hub.tw/http://link.springer.com/10.1134/S1063772918030058

Solar flares observed during the 24th solar-activity cycle and accompanied by fluxes of particles detected at the Earth's orbit with intensities exceeding 10 particles cm^{-2} s^{-1} and energies of more than 10 MeV per particle mainly occurred in activity complexes (82% of cases), with 80% of these occurring no more than 20 heliographic degrees from the nearest coronal holes. The correlation between the X-ray classes of flares and the proton fluxes detected at the Earth's orbit is weak. The work presented here supports the hypothesis that the leakage of particles into the heliosphere is due to the existence of long-lived magnetic channels, which facilitate the transport of flare-accelerated particles into the boundary regions of open magnetic structures of coronal holes. The possible contribution of exchange reconnection in the formation of such channels and the role of exchange reconnection in the generation of flares are discussed.

Dependence of the SCR Proton Flux Estimate on Radio Burst Parameters

E. A. **Isaeva**a, *, V. F. Melnikovb, and L. I. Tsvetkova,

Bulletin of the Crimean Astrophysical Observatory, 2010, Vol. 106, pp. 26–30. © Allerton Press, Inc., **2010, File**.
Original Russian Text © E.A. Isaeva, V.F. Melnikov, L.I. Tsvetkov, 2010, published in Izvestiya Krymskoi Astrofizicheskoi Observatorii, 2010, Vol. 106, pp. 42–48.

We present results suggesting that the accuracy of estimating the solar cosmic_ray (SCR) proton flux from μ_burst parameters is much higher for proton events characterized by a low level of post_burst increase (PBI) in the μ_burst flux, a powerful decametric (DCM) component, and a small time shift ($\Delta t < 9$ min) of the DCM burst maximum relative to the μ_burst maximum. These three parameters are probably related between themselves, since events characterized by a small Δt have a very low PBI level. We show that the accuracy of estimating the proton flux depends to a greater extent on Δt than on the intensity of the DCM component. For approximately half of the events from the investigated sample, the accuracy of estimating the proton flux approaches the maximum possible accuracy from μ_burst parameters.

Particle Acceleration and Heating in Regions of Magnetic Flux Emergence

Heinz **Isliker**, Vasilis Archontis, Loukas Vlahos

ApJ **2019**

https://arxiv.org/pdf/1907.04296.pdf

The interaction between emerging and pre-existing magnetic fields in the solar atmosphere can trigger several dynamic phenomena, such as eruptions and jets. A key element during this interaction is the formation of large scale current sheets and, eventually, their fragmentation that leads to the creation of a strongly turbulent environment. In this paper, we study the kinetic aspects of the interaction (reconnection) between emerging and ambient magnetic fields. We show that the statistical properties of the spontaneously fragmented and fractal electric fields are responsible for the efficient heating and acceleration of charged particles, which form a power law tail at high energies on sub-second time scales. A fraction of the energized particles escapes from the acceleration volume, with a super-hot component with temperature close to 150MK, and with a power law high energy tail with index between -2 and -3. We estimate the transport coefficients in energy space from the dynamics of the charged particles inside the fragmented and fractal electric fields, and the solution of a fractional transport equation, as appropriate for a strongly turbulent plasma, agrees with the test particle simulations. We also show that the acceleration mechanism is not related to Fermi acceleration, and the Fokker Planck equation is inconsistent and not adequate as a transport model. Finally, we address the problem of correlations between spatial transport and transport in energy space. Our results confirm the observations reported for high energy particles (hard X-rays, type III bursts and solar energetic particles) during the emission of solar jets.

Spectral Structures of Type II Solar Radio Bursts and Solar Energetic Particles

Kazumasa **Iwai**, Seiji Yashiro, Nariaki V. Nitta, Yuki Kubo

ApJ **888** 50 **2020**

https://arxiv.org/ftp/arxiv/papers/1911/1911.05897.pdf

sci-hub.si/10.3847/1538-4357/ab57ff **File**

We investigated the relationship between the spectral structures of type II solar radio bursts in the hectometric and kilometric wavelength ranges and solar energetic particles (SEPs). To examine the statistical relationship between type II bursts and SEPs, we selected 26 coronal mass ejection (CME) events with similar characteristics (e.g., initial speed, angular width, and location) observed by the Large Angle and Spectrometric Coronagraph (LASCO), regardless of the characteristics of the corresponding type II bursts and the SEP flux. Then, we compared associated type II bursts observed by the Radio and Plasma Wave Experiment (WAVES) onboard the Wind spacecraft and the SEP flux observed by the Geostationary Operational Environmental Satellite (GOES) orbiting around the Earth. We found that the bandwidth of the hectometric type II bursts and the peak flux of the SEPs has a positive correlation (with a correlation coefficient of 0.64). This result supports the idea that the nonthermal electrons of type II bursts and the nonthermal ions of SEPs are generated by the same shock and suggests that more SEPs may be generated for a wider or stronger CME shock with a longer duration. Our result also suggests that considering the spectral structures of type II bursts can improve the forecasting accuracy for the peak flux of gradual SEPs. **2006-12-13, 2013-08-18, 2013 October 28, 2017 September 4**

Table 1. CME events and associated X-ray flares, SEPs, and type II bursts used in the statistical analysis in this study (2006-2019).

CESRA nugget #2514 Mar **2020** http://www.astro.gla.ac.uk/users/eduard/cesra/?p=2514

Advancing Solar Energetic Particle Event Prediction through Survival Analysis and Cloud Computing. I. Kaplan–Meier Estimation and Cox Proportional Hazards Modeling

India **Jackson**1 and Petrus Martens

2024 ApJS 272 37

https://iopscience.iop.org/article/10.3847/1538-4365/ad3fba/pdf

Solar energetic particles (SEPs) pose significant challenges to technology, astronaut health, and space missions. This initial paper in our two-part series undertakes a comprehensive analysis of the time to detection for SEPs, applying advanced statistical techniques and cloud-computing resources to deepen our understanding of SEP event probabilities over time. We employ a range of models encompassing nonparametric, semiparametric, and parametric approaches, such as the Kaplan–Meier estimator and Cox Proportional Hazards models. These are complemented by various distribution models—including exponential, Weibull, lognormal, and log-logistic distributions—to effectively tackle the challenges associated with "censored data," a common issue in survival analysis. Employing Amazon Web Services and Python's "lifelines" and "scikit-survival" libraries, we efficiently preprocess and analyze large data sets. This methodical approach not only enhances our current analysis, but also sets a robust statistical foundation for the development of predictive models, which will be the focus of the subsequent paper. In identifying the key determinants that affect the timing of SEP detection, we establish the vital features that will inform the machine-learning (ML) techniques explored in the second paper. There, we will utilize advanced ML models—such as survival trees and random survival forests—to evolve SEP event prediction capabilities. This research is committed to advancing space weather, strengthening the safety of space-borne technology, and safeguarding astronaut health.

Preferential acceleration of heavy ions in magnetic reconnection: Hybrid-kinetic simulations with electron inertia

Neeraj **Jain**1, Jörg Büchner1, Miroslav Bárta2 and Radoslav Bučík3

A&A, 686, A28 (**2024**)

https://doi.org/10.1051/0004-6361/202348573

https://www.aanda.org/articles/aa/pdf/2024/06/aa48573-23.pdf

Context. Solar energetic particles (SEPs) in the energy range 10 s KeV nucleon−1–100s MeV nucleon−1 originate from the Sun. Their high flux near Earth may damage the space-borne electronics and generate secondary radiation that is harmful for life on Earth. Thus, understanding their energization on the Sun is important for space weather prediction. Impulsive (or 3He-rich) SEP events are associated with the acceleration of charge particles in solar flares by magnetic reconnection and related processes. The preferential acceleration of heavy ions and the extraordinary abundance enhancement of 3He in the impulsive SEP events are not understood yet.

Aims. In this paper we study the acceleration of heavy ions and its consequences for their abundance enhancements by magnetic reconnection, an established acceleration source for impulsive SEP events in which heavy-ion enhancement is observed

Methods. We employed a two-dimensional hybrid-kinetic plasma model (kinetic ions and inertial electron fluid) to simulate magnetic reconnection. All the ion species are treated self-consistently in our simulations.

Results. We find that heavy ions are preferentially accelerated to energies many times higher than their initial thermal energies by a variety of acceleration mechanisms operating in reconnection. The most efficient acceleration takes place in the flux pileup regions of magnetic reconnection. Heavy ions with sufficiently low values of charge-to-mass ratio (Q/M) can be accelerated by pickup mechanism in outflow regions even before any magnetic flux is piled up. The energy spectra of heavy ions develop a shoulder-like region, a nonthermal feature, as a result of the acceleration. The spectral index of the power-law fit to the shoulder region of the spectra varies approximately as (Q/M)−0.64. The abundance enhancement factor, defined as the number of particles above a threshold energy normalized to the total number of particles, scales as (Q/M)−α, where α increases with the energy threshold. We discuss our simulation results in the light of the SEP observations.

The evolution of coronal shock wave properties and their relation with solar energetic particles

Manon **Jarry**, Nina Dresing, Alexis P. Rouillard, Illya Plotnikov, Rami Vainio, Christian Palmroos, Athanasios Kouloumvakos, Laura Vuorinen

A&A **2024**

https://arxiv.org/pdf/2406.07058

Context. Shock waves driven by fast and wide coronal mass ejections (CMEs) are considered to be very efficient particle accelerators and are involved in the production of solar energetic particle (SEP) events. These events cause space weather phenomena by disturbing the near-Earth radiation environment. In past studies, we have analysed statistically the relation between the maximum intensity of energetic electrons and protons and the properties of coronal shocks inferred at the point of magnetic connectivity. The present study focuses on a gradual SEP event measured by STEREO-A and B on **October 11, 2013**. This event had the interesting properties that it (1) occurred in isolation with very low background particle intensities measured before the event, (2) was associated with a clear onset of SEPs measured in situ allowing detailed timing analyses, and (3) was associated with a fast CME event that was magnetically connected with STEREO-A and B. These three properties allowed us to investigate at a high cadence the temporal connection between the rapidly evolving shock properties and the SEPs measured in situ.

Aims. The present study aims to investigate the relative roles of fundamental shock parameters such as compression ratio, Mach number and geometry, in the intensity and composition of the associated SEP event measured in situ.

Methods. We use shock reconstruction techniques and multi-viewpoint imaging data obtained by STEREO-A and B, SOHO, and SDO spacecraft to determine the kinematic evolution of the expanding shock wave. We then exploit 3D magneto-hydrodynamic modelling to model the geometry and Mach number of the shock wave along an ensemble of magnetic field lines connected to STEREO-A and B, estimating also the uncertainties of the shock parameters. Using a velocity dispersion analysis of the available SEP data we time shift the SEP time series and analyse the relations between observed SEP properties and the modelled shock properties. We also study the energy dependence of these relations. Results. We find a very good temporal agreement between the formation of the modelled shock wave and the estimated release times for both electrons and protons. The simultaneous release of protons and electrons suggests a common acceleration process. This early phase is marked at both STEREOs by elevated electron-to-proton ratios that coincide with the highly quasi-perpendicular phase of the shock. These findings suggest that the rapid evolution of the shock as it transits from the low to the high corona modifies the conditions under which particles are accelerated. We discuss these findings in terms of basic geometry and acceleration processes.

Acceleration of Electrons and Ions by an "Almost" Astrophysical Shock in the Heliosphere

Immanuel Christopher **Jebaraj**1, Oleksiy Agapitov2, Vladimir Krasnoselskikh2,3, Laura Vuorinen1, Michael Gedalin4, Kyung-Eun Choi2, Erika Palmerio5, Nicolas Wijsen6, Nina Dresing1, Christina Cohen7Show full author list

2024 ApJL 968 L8

https://iopscience.iop.org/article/10.3847/2041-8213/ad4daa/pdf

https://arxiv.org/pdf/2405.07074

Collisionless shock waves, ubiquitous in the Universe, are crucial for particle acceleration in various astrophysical systems. Currently, the heliosphere is the only natural environment available for their in situ study. In this work, we showcase the collective acceleration of electrons and ions by one of the fastest in situ shocks ever recorded, observed by the pioneering Parker Solar Probe at only 34.5 million km from the Sun. Our analysis of this unprecedented, near-parallel shock shows electron acceleration up to 6 MeV amidst intense multiscale electromagnetic wave emissions. We also present evidence of a variable shock structure capable of injecting and accelerating ions from the solar wind to high energies through a self-consistent process. The exceptional capability of the probe's instruments to measure electromagnetic fields in a shock traveling at 1% the speed of light has enabled us, for the first time, to confirm that the structure of a strong heliospheric shock aligns with theoretical models of strong shocks observed in astrophysical environments. This alignment offers viable avenues for understanding astrophysical shock processes and the self-consistent acceleration of charged particles. **2023 March 13**

Relativistic electron beams accelerated by an interplanetary shock

Immanuel C. **Jebaraj**, Nina Dresing, Vladimir Krasnoselskikh, Oleksiy V.Agapitov, +++

A&A 680, L7 **2023**

https://arxiv.org/pdf/2311.05765.pdf

https://www.aanda.org/articles/aa/pdf/2023/12/aa48120-23.pdf

Collisionless shock waves have long been considered amongst the most prolific particle accelerators in the universe. Shocks alter the plasma they propagate through and often exhibit complex evolution across multiple scales. Interplanetary (IP) traveling shocks have been recorded in-situ for over half a century and act as a natural laboratory for experimentally verifying various aspects of large-scale collisionless shocks. A fundamentally interesting problem in both helio and astrophysics is the acceleration of electrons to relativistic energies (more than 300 keV) by traveling shocks. This letter presents first observations of field-aligned beams of relativistic electrons upstream of an IP shock observed thanks to the instrumental capabilities of Solar Orbiter. This study aims to present the characteristics of the electron beams close to the source and contribute towards understanding their acceleration mechanism. On **25 July 2022**, Solar Orbiter encountered an IP shock at 0.98 AU. The shock was associated with an energetic storm particle event which also featured upstream field-aligned relativistic electron beams observed 14 minutes prior to the actual shock crossing. The distance of the beam's origin was investigated using a velocity dispersion analysis (VDA). Peak-intensity energy spectra were anaylzed and compared with those obtained from a semi-analytical fast-Fermi acceleration model. By leveraging Solar Orbiter's high-time resolution Energetic Particle Detector (EPD), we have successfully showcased an IP shock's ability to accelerate relativistic electron beams. Our proposed acceleration mechanism offers an explanation for the observed electron beam and its characteristics, while we also explore the potential contributions of more complex mechanisms.

Solar Orbiter Nugget #27 Jan 2024 *https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-relativistic-electrons-accelerated-by-an-interplanetary-shock-wave*

Multiple injections of energetic electrons associated with the flare/CME event on 9 October 2021

Immanuel Christopher **Jebaraj**, Athanasios Kouloumvakos, Nina Dresing, Alexander Warmuth, Nicolas Wijsen, Christian Palmroos, Jan Gieseler, Rami Vainio, Vratislav Krupar, Jasmina Magdalenic, Thomas Wiegelmann, Frederic Schuller, Andrea Battaglia, Annamaria Fedeli
A&A 675, A27 **2023 File**
https://arxiv.org/pdf/2301.03650.pdf
https://www.aanda.org/articles/aa/pdf/2023/07/aa45716-22.pdf
We study the solar energetic particle (SEP) event observed on **9 October 2021**, by multiple spacecraft including Solar Orbiter (SolO). The event was associated with an M1.6 flare, a coronal mass ejection (CME) and a shock wave. During the event, high-energy protons and electrons were recorded by multiple instruments located within a narrow longitudinal cone. An interesting aspect of the event was the multi-stage particle energization during the flare impulsive phase and also what appears to be a separate phase of electron acceleration detected at SolO after the flare maximum. We aim to investigate and identify the multiple sources of energetic electron acceleration. We utilize SEP electron observations from the Energetic Particle Detector (EPD) and hard X-ray (HXR) observations from the Spectrometer/Telescope for Imaging X-rays (STIX) on-board SolO, in combination with radio observations at a broad frequency range. We focus on establishing an association between the energetic electrons and the different HXR and radio emissions associated with the multiple acceleration episodes. We have found that the flare was able to accelerate electrons for at least 20 minutes during the nonthermal phase observed in the form of five discrete HXR pulses. We also show evidence that the shock wave has contributed to the electron acceleration during and after the impulsive flare phase. The detailed analysis of EPD electron data shows that there was a time difference in the release of low- and high-energy electrons, with the high-energy release delayed. Also, the observed electron anisotropy characteristics suggest different connectivity during the two phases of acceleration.
See Introduction

Forecast of solar proton flux profiles for well-connected events†

Eun-Young **Ji**1, Yong-Jae Moon2,* and Jinhye Park
JGR, Volume 119, Issue 12, pages 9383–9394, December **2014**
http://onlinelibrary.wiley.com/doi/10.1002/2014JA020333/pdf
We have developed a forecast model of solar proton flux profiles (>10 MeV channel) for well-connected events. Among 136 solar proton events (SPEs) from 1986 to 2006, we select **49 well-connected ones** that are all associated with single X-ray flares stronger than M1 class and start to increase within four hours after their X-ray peak times. These events show rapid increments in proton flux. By comparing several empirical functions, we select a modified Weibull curve function to approximate a SPE flux profile, which is not far from the particle injection rate. The parameters (peak flux, rise time, and decay time) of this function are determined by the relationship between X-ray flare parameters (peak flux, impulsive time, and emission measure) and SPE parameters. For 49 well-connected SPEs, the linear correlation coefficient between the predicted and the observed proton peak fluxes is 0.65 with the RMS error of 0.55 log10(pfu). In addition, we determine another forecast model based on flare and CME parameters using 22 SPEs. The used CME parameters are linear speed and angular width. As a result, we find that the linear correlation coefficient between the predicted and the observed proton peak fluxes is 0.83 with the RMS error of 0.35 log10(pfu). From the relationship between error of model and CME acceleration, we find that CME acceleration is an important factor for predicting proton flux profiles. **Table**

In Situ Data and Effect Correlation During September 2017 Solar Particle Event

P. **Jiggens**, C. Clavie, H. Evans, T. P. O'Brien, O. Witasse, A. L. Mishev …….
Space Weather 17(1) 99-117 **2019**
https://doi.org/10.1029/2018SW001936
Solar energetic particles are one of the main sources of particle radiation seen in space. In the first part of September 2017 the most active solar period of cycle 24 produced four large X-class flares and a series of (interplanetary) coronal mass ejections, which gave rise to radiation storms seen over all energies and at the ground by neutron monitors. This paper presents comprehensive cross comparisons of in situ radiation detector data from near-Earth satellites to give an appraisal on the state of present data processing for monitors of such particles. Many of these data sets have been the target of previous cross calibrations, and this event with a hard spectrum provides the opportunity to validate these results. As a result of the excellent agreement found between these data sets and the use of neutron monitor data, this paper also presents an analytical expression for fluence spectrum for the event. Derived ionizing dose values have been computed to show that although there is a significant high-energy component, the event was not particularly concerning as regards dose effects in spacecraft electronics. Several sets of spacecraft data illustrating single event effects are presented showing a more significant impact in this regard. Such a hard event can penetrate thick shielding; human dose quantities measured inside the International Space Station and derived through modeling for aircraft altitudes are also presented. Lastly, simulation results of coronal mass ejection propagation through the heliosphere are presented along with data from Mars-orbiting spacecraft in addition to data from the Mars surface.

Updated Model of the Solar Energetic Proton Environment in Space
Piers **Jiggens**, Daniel Heynderickx, Ingmar Sandberg, Pete Truscott, Osku Raukunen, Rami Vainio
Journal of Space Weather and Space Climate 8, A31 **2018**
https://arxiv.org/pdf/1801.05422.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170082.pdf
The Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) model provides environment specification outputs for all aspects of the Solar Energetic Particle (SEP) environment. The model is based upon a thoroughly cleaned and carefully processed data set. Herein the evolution of the solar proton model is discussed with comparisons to other models and data. This paper discusses the construction of the underlying data set, the modelling methodology, optimisation of fitted flux distributions and extrapolation of model outputs to cover a range of proton energies from 0.1 MeV to 1 GeV. The model provides outputs in terms of mission cumulative fluence, maximum event fluence and peak flux for both solar maximum and solar minimum periods. A new method for describing maximum event fluence and peak flux outputs in terms of 1-in-x-year SPEs is also described. SAPPHIRE proton model outputs are compared with previous models including CREME96, ESP-PSYCHIC and the JPL model. Low energy outputs are compared to SEP data from ACE/EPAM whilst high energy outputs are compared to a new model based on GLEs detected by Neutron Monitors (NMs).

The magnitude and effects of extreme solar particle events
Piers **Jiggens***, Marc-Andre Chavy-Macdonald, Giovanni Santin, Alessandra Menicucci, Hugh Evans and Alain Hilgers
J. Space Weather Space Clim. 4 (**2014**) A20
http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130038.pdf
The solar energetic particle (SEP) radiation environment is an important consideration for spacecraft design, spacecraft mission planning and human spaceflight. Herein is presented an investigation into the likely severity of effects of a very large Solar Particle Event (SPE) on technology and humans in space. Fluences for SPEs derived using statistical models are compared to historical SPEs to verify their appropriateness for use in the analysis which follows. By combining environment tools with tools to model effects behind varying layers of spacecraft shielding it is possible to predict what impact a large SPE would be likely to have on a spacecraft in Near-Earth interplanetary space or geostationary Earth orbit. Also presented is a comparison of results generated using the traditional method of inputting the environment spectra, determined using a statistical model, into effects tools and a new method developed as part of the ESA SEPEM Project allowing for the creation of an effect time series on which statistics, previously applied to the flux data, can be run directly. The SPE environment spectra is determined and presented as energy integrated proton fluence (cm^{-2}) as a function of particle energy (in MeV). This is input into the SHIELDOSE-2, MULASSIS, NIEL, GRAS and SEU effects tools to provide the output results. In the case of the new method for analysis, the flux time series is fed directly into the MULASSIS and GEMAT tools integrated into the SEPEM system. The output effect quantities include total ionising dose (in rads), non-ionising energy loss (MeV g^{-1}), single event upsets (upsets/bit) and the dose in humans compared to established limits for stochastic (or cancer-causing) effects and tissue reactions (such as acute radiation sickness) in humans given in grey-equivalent and sieverts respectively.

Time distributions of solar energetic particle events: Are SEPEs really random?
Jiggens, P. T. A.; Gabriel, S. B.
J. Geophys. Res., Vol. 114, No. A10, A10105, **2009**, http://dx.doi.org/10.1029/2009JA014291
Solar energetic particle events (SEPEs) can exhibit flux increases of several orders of magnitude over background levels and have always been considered to be random in nature in statistical models with no dependence of any one event on the occurrence of previous events. We examine whether this assumption of randomness in time is correct. Engineering modeling of SEPEs is important to enable reliable and efficient design of both Earth-orbiting and interplanetary spacecraft and future manned missions to Mars and the Moon. All existing engineering models assume that the frequency of SEPEs follows a Poisson process. We present analysis of the event waiting times using alternative distributions described by Lévy and time-dependent Poisson processes and compared these with the usual Poisson distribution. The results show significant deviation from a Poisson process and indicate that the underlying physical processes might be more closely related to a Lévy-type process, suggesting that there is some inherent “memory” in the system. Inherent Poisson assumptions of stationarity and event independence are investigated, and it appears that they do not hold and can be dependent upon the event definition used. SEPEs appear to have some memory indicating that events are not completely random with activity levels varying even during solar active

periods and are characterized by clusters of events. This could have significant ramifications for engineering models of the SEP environment, and it is recommended that current statistical engineering models of the SEP environment should be modified to incorporate long-term event dependency and short-term system memory.

Exploring the Dynamics of CME-Driven Shocks by Comparing Numerical Modeling and Observations

Meng **Jin**, Gang Li, Nariaki Nitta, Wei Liu, Vahe Petrosian, Ward Manchester, Christina Cohen, Frederic Effenberger, Zheyi Ding, Melissa Pesce-Rollins, Nicola Omodei, Nat Gopalswamy

Proceedings of IAU Symposium No. 388 - Solar and Stellar Coronal Mass Ejections **2024**

https://arxiv.org/pdf/2409.18020

Shocks driven by coronal mass ejections (CMEs) are primary drivers of gradual solar energetic particle (SEP) events, posing significant risks to space technology and astronauts. Concurrently, particles accelerated at these shocks may also propagate back to the Sun, potentially generating gamma-ray emissions through pion decay. We incorporated advanced modeling and multi-messenger observations to explore the role of CME-driven shocks in gamma-ray emissions and SEPs. Motivated by Fermi-LAT long-duration solar flares, we used the AWSoM MHD model to investigate the connection between the shocks and the properties of observed gamma-ray emissions. By coupling the AWSoM with iPATH model, we evaluate the impact of shock evolution complexity near the Sun on SEP intensity and spectra. Our result points to the importance of accurate background coronal and solar wind modeling, as well as detailed observations of CME source regions, in advancing our understanding of CME-driven shocks and the dynamics of associated energetic particles. **7 Mar 2012, 17 May 2012, 11 Apr 2013, 1 Sep 2014, 17 Jul 2021, 28 Oct 2021**

Assessing the Influence of Input Magnetic Maps on Global Modeling of the Solar Wind and CME-driven Shock in the 2013 April 11 Event

Meng **Jin**, Nariaki V. Nitta, Christina M. S. Cohen

Space Weather **2022**

https://arxiv.org/pdf/2202.07214.pdf

In the past decade, significant efforts have been made in developing physics-based solar wind and coronal mass ejection (CME) models, which have been or are being transferred to national centers (e.g., SWPC, CCMC) to enable space weather predictive capability. However, the input data coverage for space weather forecasting is extremely limited. One major limitation is the solar magnetic field measurements, which are used to specify the inner boundary conditions of the global magnetohydrodynamic (MHD) models. In this study, using the Alfven wave solar model (AWSoM), we quantitatively assess the influence of the magnetic field map input (synoptic/diachronic vs. synchronic magnetic maps) on the global modeling of the solar wind and the CME-driven shock in the **2013 April 11** solar energetic particle (SEP) event. Our study shows that due to the inhomogeneous background solar wind and dynamical evolution of the CME, the CME-driven shock parameters change significantly both spatially and temporally as the CME propagates through the heliosphere. The input magnetic map has a great impact on the shock connectivity and shock properties in the global MHD simulation. Therefore this study illustrates the importance of taking into account the model uncertainty due to the imperfect magnetic field measurements when using the model to provide space weather predictions.

Effects of adiabatic focusing and free-escape boundaries in coronal shock acceleration

Lidiya Annie **John**1,2*, Seve Nyberg1, Laura Vuorinen1, Rami Vainio1, Alexandr Afanasiev1, Stefaan Poedts2,3 and Nicolas Wijsen2

J. Space Weather Space Clim. **2024**, 14, 15

https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc230068.pdf

Solar energetic particles (SEPs) are considered a serious radiation threat to space technologies and humans in space. SEPs are accelerated to high energies by solar explosive phenomena such as solar flares and in particular by shocks driven by coronal mass ejections (CMEs). We aim to better understand the effects of magnetic field gradient-induced adiabatic focusing on the coronal acceleration of SEPs and to test whether free-escape boundaries produce the same effects as focusing. We present results from a one-dimensional oblique shock model with a mean free path similar to Bell's (1978) theory using Monte Carlo simulations. We show that the momentum spectrum at a shock and far upstream will attain a steady state in a model with adiabatic focusing, whereas it does not in a non-focusing model. However, the effects of focusing can be mimicked in a non-focused simulation by introducing a free-escape boundary ahead of the shock close to the position where the particles will escape from the shock by focusing in a focused transport simulation. This provides a promising avenue for constructing computationally efficient codes that can model the particle emission from shocks.

A Multi-wavelength Study of Eruptive Events on January 23, 2012 associated with a Major Solar Energetic Particle Event.

Joshi NC, Uddin W, Srivastava AK, Chandra R, Gopalswamy N, Manoharan PK, Aschwanden M,

Choudhary DP, Jain R, Nitta NV, Xie H, Yashiro S, Akiyama S, Mäkelä, P, Kayshap P, Awasthi AK, Dwivedi VC, Mahalakshmi, K
(**2013**), AdSR 52:1

Energetic Particle Observations from the Parker Solar Probe Using Combined Energy Spectra from the IS⨀IS Instrument Suite

C. J**. Joyce**1, D. J. McComas1, E. R. Christian2, N. A. Schwadron1,3, M. E. Wiedenbeck4, R. L. McNutt Jr.5, C. M. S. Cohen6, R. A. Leske6, R. A. Mewaldt6, E. C. Stone6Show full author list
2020 ApJS 246 41
https://iopscience.iop.org/article/10.3847/1538-4365/ab5948/pdf
The Integrated Science Investigations of the Sun (IS⨀IS) instrument suite includes two Energetic Particle instruments: EPI-Hi, designed to measure ions from ~1 to 200 MeV nuc−1, and EPI-Lo, designed to measure ions from ~20 to ~15 MeV nuc−1. We present an analysis of eight energetic proton events observed across the energy range of both instruments during Parker Solar Probe's (PSP) first two orbits in order to examine their combined energy spectra. Background corrections are applied to help resolve spectral breaks between the two instruments and are shown to be effective. In doing so we demonstrate that even in the early stages of calibration, IS⨀IS is capable of producing reliable spectral observations across broad energy ranges. In addition to making groundbreaking measurements very near the Sun, IS⨀IS also characterizes energetic particle populations over a range of heliocentric distances inside 1 au. During the first two orbits, IS⨀IS observed energetic particle events from a single corotating interaction region (CIR) at three different distances from the Sun. The events are separated by two Carrington rotations and just 0.11 au in distance; however, the relationship shown between proton intensities and proximity of the spacecraft to the source region shows evidence of the importance of transport effects on observations of energetic particles from CIRs. Future IS⨀IS observations of similar events over larger distances will help disentangle the effects of CIR-related acceleration and transport. We apply similar spectral analyses to the remaining five events, including four that are likely related to stream interaction regions (SIRs) and one solar energetic particle (SEP) event.

Spatial Evolution of 20 MeV Solar Energetic Proton Events

S. W. **Kahler**1, A. G. Ling2, and D. V. Reames3
2023 ApJ 942 68
https://iopscience.iop.org/article/10.3847/1538-4357/aca7c0/pdf **File**
The longitudinal extents of solar energetic (E > 10 MeV) particle (SEP) events in the heliosphere are a characteristic important for understanding SEP acceleration and transport as well as their space weather effects. SEP detectors on the STEREO A and B spacecraft launched in 2008, combined with those on Earth-orbiting spacecraft, have enabled recent studies of this characteristic for many events. Each SEP event distribution has been characterized by a single central longitude, width, and amplitude derived from Gaussian fits to peak intensities or fluences at each spacecraft. To capture dynamic changes of those parameters through SEP events, we apply Gaussian fits in solar-based Carrington longitude coordinates with 1 hr resolution to four selected large 20 MeV proton events. The limitations of single-Gaussian fits for very extended events is discussed. In all four examples the widths are increasing throughout the event, as expected, while the projected Gaussian centers at SEP onset start from 30° to 100° east of the associated flare, move westward, then remain stationary well east of the flare for several days before moving west as the event amplitudes decrease. Late decay phases can be characterized by eastward movements away from the flare longitudes. We introduce schematic Buffett plots to show successive snapshots of event longitudes and amplitudes. **2012 Jan 23, 2012 Jan 27, 2012 Jul 23, 2014 Feb 25**

Spatial and Temporal Variations of 2 – 10 MeV nuc−1 He/H in Gradual Solar Energetic Particle Events

S. W. **Kahler**, D. Brown & A. G. Ling
Solar Physics volume 297, Article number: 51 (**2022**)
https://doi.org/10.1007/s11207-022-01971-0
In a previous work (Kahler and Brown, 2021; henceforth KB21) we found that 4 – 53 MeV nuc−1 He/H ratios measured at peak intensities of 43 gradual solar energetic-particle (SEP) events were significantly correlated with solar-wind (SW) He/H ratios and with SEP event peak intensities. Here, we extend that work by examining He/H ratios from onsets through peaks of 12 large 1.8 – 10.0 MeV nuc−1 SEP events observed with the Low Energy Telescope (LET) on both STEREO A and B (STA/B) spacecraft when their longitudinal separation angle was < 90∘ in 2013 – 2014. We discuss the challenges of choosing matching five 1-hour periods of STA/B SEP profiles to characterize He/H in the LET energy ranges 1.8 – 3.6, 4.0 – 6.0, and 6.0 – 10.0 MeV nuc−1. The roles of rigidity-dependent transport or of anomalous He production in large variations of He/H are assessed with 6.0 – 10.0 MeV nuc−1 O/He. The STA/B SW data do not include He/H, but we confirm the KB21 results that SEP He/H extends over a range of 0.001 to 0.1, decreasing with increasing energy, and increasing with event peak H

intensities. Differences of STA/B log He/H are not correlated with STA/B angular separations. The six cases of SEP events occurring within interplanetary coronal mass ejections (ICMEs) show somewhat higher H peak intensities and He/H than those outside ICMEs. We interpret the low He/H events as predominately SEP3 and high He/H as SEP4 events in the Reames (2020) SEP event-classification system.

Exploring Contingency Skill Scores Based on Event Sizes

S. W. **Kahler** , H. Darsey

Space Weather **Volume19, Issue5** e2020SW002604 **2021 File**

https://doi.org/10.1029/2020SW002604

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002604

Space weather forecasts are generally made for events with an arbitrary size threshold imposed on an event statistical size distribution which is likely described by a power law. This is the case for solar energetic ($E > 10$ MeV) particle (SEP) events, which have a differential power law exponent of $\gamma = 1.2$. Event forecasts are usually evaluated by skill scores using a contingency table that matches the forecasted events against observed events independently of the event sizes. Each observed event is either a forecasted hit or a miss, and each forecasted event is either an observed hit or a false alarm. However, for SEP events and most other space weather parameters the event size is a critical factor for the user. It is more important that large events be well forecasted than threshold events. In addition, false alarms may be useful when they match observed events just below the forecast threshold. We explore a forecast evaluation scheme to incorporate the event size within the usual format of a binary contingency table to evaluate model performance. The scheme is applied to three different input options of a recently published evaluation of the Proton Prediction System (PPS) for SEP events to show differences between numbers-based and intensity-based skill scores of the PPS. We demonstrate how identical skill scores can result from models with extremely different performances of event intensity forecasts. The scheme requires model validation and would benefit from testing with other space weather applications.

Variations of Peak He/H Ratios in Solar Energetic (E > 4 MeV) Particle Events and Comparisons with Solar Wind He/H Ratios

S. W. **Kahler**1 and D. Brown2

2021 ApJ 908 214

https://iopscience.iop.org/article/10.3847/1538-4357/abd481/pdf

https://doi.org/10.3847/1538-4357/abd481

We determine solar energetic particle (SEP) event He/H peak intensity ratios AHe observed in the four energy channels of the SOHO EPHIN detector covering 4–53 MeV nuc^{-1}. Those SEP AHe values range over two orders of magnitude for 43 large western hemisphere SEP events through the period 1997–2017. AHe of each SEP event are compared with average solar wind (SW) AHe values measured for 8 hr after the SEP event onsets with the solar wind experiment Faraday Cup instrument on Wind. AHe in the 4–8 and 8–21 MeV nuc^{-1} range are significantly correlated with SW AHe (CC = 0.45 and 0.41), but less so in the 21–41 and 41–53 MeV nuc^{-1} range, where uncertainties of the AHe values are higher. Median SEP AHe values decline slightly with increasing energy and are ≤0.5 their associated SW values. Both median SEP and SW AHe decline by a factor of ~2 from the 27 events of cycle 23 to the 16 of cycle 24. Those results suggest a connection between the SW and the seed population of SEP events. An unexpected result is that SEP AHe increases with event peak intensities in our 43 events as He peak intensities increase faster than those of H in larger events. **1998 May 6, 2012 May 17**

Table 1 SEP Events and Associated Solar Wind h/p Abundances 1998-2017

The Role of Peak Temperatures in Solar X-Ray Flare Associations with CME Speeds and Widths and in Flare Size Distributions

S. W. **Kahler**1 and A. G. Ling2

2020 ApJ 901 63

https://doi.org/10.3847/1538-4357/abae5e

Recently, we reported that solar X-ray flares with relatively low peak (0.05–0.3 nm)/(0.1–0.8 nm) ratios R, a proxy for peak flare temperature T, were preferentially associated not only with solar energetic ($E > 10$ MeV) particle (SEP) events, but also with fast ($V_{cme} \geq 1000$ km s^{-1}) coronal mass ejections (CMEs) that produce the SEP events. Flares associated with a characteristic CME speed Vcme range from small and cool to large and hot, and cooler X-ray flares were preferentially associated with broader CME widths. Here we increase the list of analyzed Geostationary Operational Environmental Satellite flares from the previous 450 to 588 and validate the earlier results with flare peak X-ray temperatures T from the TEBBS (Temperature and Emission measure-based Background Subtraction) method catalog. Power-law size distributions of flare peak fluxes Fp are increasingly steeper for X-ray flares with (1) fast ($V_{cme} \geq 1000$ km s^{-1}); (2) slow ($V_{cme} < 1000$ km s^{-1}); and (3) no CMEs; in each case flares of larger Fp are characteristically hotter. The power-law size distribution of SEP event peak intensities Ip is flatter than any of the X-ray Fp distributions or a distribution formed from the product of the steep SEP Ip dependence on Vcme and the Vcme number distributions.

Temperatures of Large Solar X-ray Events and Associated CME Speeds

S. **Kahler**,* A. Ling

36th International Cosmic Ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A.

https://pos.sissa.it/358/1089/pdf

Recently we [1] repeated an earlier analysis by [2,3] showing that large (> M3) solar X-ray flares associated with solar energetic particle (SEP) events have significantly lower peak X-ray flux ratios R of 0.04-0.5/0.1-0.8 nm, proxies for flare peak temperatures, than those without SEP events. Since we expect SEP events to be produced by shocks ahead of fast coronal mass ejections (CMEs), this would imply that an X-ray flare of a given peak flux is more likely to have a fast CME and associated SEP event when it has a relatively smaller R. We examine the role played by the ratios R in correlations between X-ray peak flare fluxes and CME speeds Vcme, and then compare CMEs widths W, speeds Vcme, X-ray flare durations ΔT, and R with each other. We resolve the apparent conflict between a global scaling model of eruptive events showing Vcme scaling with higher R and our confirmation that the [2,3] analysis implies faster CMEs are associated with flares of lower R.

Ratios of SEP/Suprathermal Intensities and Associated CME Speeds

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36th International Cosmic Ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A.

https://pos.sissa.it/358/1091/pdf

Recently [1] have found correlations between peak intensities Ip of E > 10 MeV SEP events and suprathermal H and He ion intensities observed in situ at 1 AU around the onsets of SEP events. The correlations depend on the solar source longitudes of the driver CMEs and the kind of solar wind (SW) (transient or normal) at the SEP event onset. How the 1 AU suprathermals are related to the solar coronal seed population of SEPs is not known. In a previous study [2] with a similar result, the ratio R of 20-MeV Ip to the 2-MeV H suprathermal backgrounds were plotted against CME speeds Vcme. In contrast to the usual strong correlations between Ip and Vcme, [2] found the dependence of R on Vcme to be very weak, suggesting that the primary factor determining Ip of SEP events may be the source seed population, rather than Vcme. We extend that work [1,2] by plotting both R and log Ip against log Vcme for various types of SW and different source longitudes to look for the dependences of R on Vcme. We confirm the lower correlations found for R and Vcme, but Vcme retains its role as an independent factor in SEP production. The better R correlation using 1.28-2.56 MeV H suggests a more significant role for lower energy 0.16-0.32 MeV H as shock seed particles. Conclusions of variations of R correlations among different SW types and solar longitudes are limited by the statistics of the SEP events.

Are Solar Energetic Particle Events and Type II Bursts Associated with Fast and Narrow Coronal Mass Ejections?

S. W. **Kahler**, A. G. Ling, N. Gopalswamy

Solar Physics September **2019**, 294:134 **File**

https://doi.org/10.1007/s11207-019-1518-3

sci-hub.ru/10.1007/s11207-019-1518-3

Gradual solar energetic (E>10 MeV) particle (SEP) events and metric through kilometric wavelength type II radio bursts are usually associated with shocks driven by fast (V≥900 kms−1) and wide (W≥60∘) coronal mass ejections (FW CMEs). This criterion was established empirically by several studies from solar cycle 23. The characteristic Alfvén speed in the corona, which ranges over 500 – 1500 km s−1 at heights ≥2 Ro, provides the minimum V requirement for a CME to drive a shock, but the general absence of SEP events or type II bursts with fast and narrow (W<60∘) CMEs has not been explained. We review and confirm the earlier studies with a more comprehensive comparison of SEP events and type II bursts with fast and narrow (FN) CMEs. We offer an explanation for the lack of SEP event and type II burst associations with FN CMEs in terms of recent heuristic arguments and modeling that show that the response of a magnetized plasma to the propagation of a CME depends on the CME geometry as well as on its speed. A clear distinction is made between a projectile that propagates through the medium to produce a bow shock, and a 3D piston that everywhere accumulates material to produce a broad shock and sheath. The bow shock is unfavorable for producing SEP events and type II bursts, but the 60∘ cut-off is not explained.

CESRA #2423 Dec **2019** http://www.astro.gla.ac.uk/users/eduard/cesra/?p=2423

Suprathermal Ion Backgrounds of Solar Energetic Particle Events

S. W. **Kahler**1 and A. G. Ling2

2019 ApJ 872 89

https://doi.org/10.3847/1538-4357/aafb03

Gradual solar energetic particle (SEP) events result from the acceleration of low-energy suprathermal seed particles to high (E > 10 MeV nuc−1) energies by shocks driven by coronal mass ejections (CMEs). Several studies suggest connections between suprathermal particles measured in situ at 1 au and the seed particles accelerated near the Sun to E > 10 MeV. We correlate E > 10 MeV SEP event peak intensities (Ip) with suprathermal H and He intensities at each of two energies averaged over four periods around the SEP onsets in the Geostationary Operational Environmental Satellitespacecraft during the period of 1998–2016. The 201 SEP events are sorted into four groups by their associated solar source longitudes and are further separated between events in transient CMEs and in normal solar wind (SW). The mean Ip in CME SW that is larger than in normal SW that was found earlier is confirmed. The suprathermals significantly correlate (correlation coefficients CCs ≈ 0.4–0.6) with the SEP Ip from the 0° to W40° range, but only weakly (CC ≈ 0.0–0.3) with SEP events from the well-connected W41° to W83° range. Eastern hemisphere SEP intensities are uncorrelated (CC ≃ 0.0) with suprathermals in normal SW but are well correlated (CC ≈ 0.4–0.7) for those in transient CME SW, which we interpret with a simple model involving perpendicular shock acceleration of the suprathermals. The in situ B field magnitude shows no correlation with SEP intensities for any longitude range or timescale. These results confirm that tracking suprathermal intensities at 1 au can be useful in forecasting the Ip of SEP events.

Forecasting Solar Energetic Particle (SEP) events with Flare X-ray peak ratios

Stephen W. **Kahler** and Alan. G. Ling

J. Space Weather Space Clim. **2018**, 8, A47

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180013.pdf

Solar flare X-ray peak fluxes and fluences in the 0.1–0.8 nm band are often used in models to forecast solar energetic particle (SEP) events. Garcia (2004) [Forecasting methods for occurrence and magnitude of proton storms with solar soft X rays, Space Weather, 2, S02002, 2004] used ratios of the 0.05–0.4 and 0.1–0.8 nm bands of the X-ray instrument on the GOES spacecraft to plot inferred peak flare temperatures versus peak 0.1–0.8 nm fluxes for flares from 1988 to 2002. Flares associated with E > 10 MeV SEP events of >10 proton flux units (pfu) had statistically lower peak temperatures than those without SEP events and therefore offered a possible empirical forecasting tool for SEP events. We review the soft and hard X-ray flare spectral variations as SEP event forecast tools and repeat Garcia's work for the period 1998–2016, comparing both the peak ratios and the ratios of the preceding 0.05–0.4 nm peak fluxes to the later 0.1–0.8 nm peak fluxes of flares >M3 to the occurrence of associated SEP events. We divide the events into eastern and western hemisphere sources and compare both small (1.2–10 pfu) and large (≥300 pfu) SEP events with those of >10 pfu. In the western hemisphere X-ray peak ratios are statistically lower for >10 pfu SEP events than for non-SEP events and are even lower for the large (>300 pfu) events. The small SEP events, however, are not distinguished from the non-SEP events. We discuss the possible connections between the flare X-ray peak ratios and associated coronal mass ejections that are presumed to be the sources of the SEPs.

Relating Solar Energetic Particle Event Fluences to Peak Intensities

Stephen W. **Kahler**, Alan G. Ling

Solar Physics February **2018**, 293:30

https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1249-x.pdf

Recently we (Kahler and Ling, Solar Phys.292, 59, 2017: KL) have shown that time–intensity profiles [I(t)] of 14 large solar energetic particle (SEP) events can be fitted with a simple two-parameter fit, the modified Weibull function, which is characterized by shape and scaling parameters [α and β]. We now look for a simple correlation between an event peak energy intensity [Ip] and the time integral of I(t) over the event duration: the fluence [F]. We first ask how the ratio of F/Ip varies for the fits of the 14 KL events and then examine that ratio for three separate published statistical studies of SEP events in which both F and Ip were measured for comparisons of those parameters with various solar-flare and coronal mass ejection (CME) parameters. The three studies included SEP energies from a 4 – 13 MeV band toE>100 MeV. Within each group of SEP events, we find a very robust correlation (CC>0.90) in log–log plots of F versus Ip over four decades of Ip. The ratio increases from western to eastern longitudes. From the value of Ip for a given event, F can be estimated to within a standard deviation of a factor of ≤2. Log–log plots of two studies are consistent with slopes of unity, but the third study shows plot slopes of <1 and decreasing with increasing energy for their four energy ranges from E>10 MeV to >100 MeV. This difference is not explained.

Flare magnetic reconnection fluxes as possible signatures of flare contributions to gradual SEP events

S.W. **Kahler**, M. Kazachenko, B.J. Lynch and B.T. Welsch

Journal of Physics: Conference Series, Volume 900, Number 1 012011 **2017**

http://iopscience.iop.org/article/10.1088/1742-6596/900/1/012011/pdf

The primary sources of solar energetic (E > 20 MeV) particle (SEP) events are flares and CME-driven shocks. Some studies claim that even up to GeV energies solar flares are major contributors to SEP events. There are several candidate flare processes for producing SEPs, but acceleration in magnetic reconnection regions is probably the most efficient. Previous studies have relied on flare radiation signatures to determine the times and locations of SEP injections. An alternative approach is to use the amount of magnetic flux that gets reconnected during solar flares. The photospheric magnetic flux swept out by flare ribbons is thought to be directly related to the amount of magnetic reconnection in the corona and is therefore a key diagnostic tool for understanding the physical processes in flares and CMEs. We use the database of flare magnetic reconnection fluxes to compare these parameters with peak intensities of SEP events. We find that while sizes of 15 ~25-MeV SEP events in the western hemisphere correlate with both CME speeds and reconnection fluxes, there are many cases of large reconnection fluxes with no observed SEP events. The occurrence of large reconnection fluxes accompanied by slow CMEs but no SEP events suggests that the CME shocks are the primary, if not the only, sources of high energy (E > 100 MeV) SEP events.

Forecasting E > 50-MeV proton events with the proton prediction system (PPS)

Stephen W. **Kahler**1*, Stephen M. White1 and Alan G. Ling

J. Space Weather Space Clim. **2017**, 7, A27

https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170016.pdf

Forecasting solar energetic (E > 10-MeV) particle (SEP) events is an important element of space weather. While several models have been developed for use in forecasting such events, satellite operations are particularly vulnerable to higher-energy (≥50-MeV) SEP events. Here we validate one model, the proton prediction system (PPS), which extends to that energy range. We first develop a data base of E ≥ 50-MeV proton events >1.0 proton flux units (pfu) events observed on the GOES satellite over the period 1986–2016. We modify the PPS to forecast proton events at the reduced level of 1 pfu and run PPS for four different solar input parameters: (1) all ≥M5 solar X-ray flares; (2) all ≥200 sfu 8800-MHz bursts with associated ≥M5 flares; (3) all ≥500 sfu 8800-MHz bursts; and (4) all ≥5000 sfu 8800-MHz bursts. The validation contingency tables and skill scores are calculated for all groups and used as a guide to use of the PPS. We plot the false alarms and missed events as functions of solar source longitude, and argue that the longitude-dependence employed by PPS does not match modern observations. Use of the radio fluxes as the PPS driver tends to result in too many false alarms at the 500 sfu threshold, and misses more events than the soft X-ray predictor at the 5000 sfu threshold.

Table 1. The E > 50 MeV 10-pfu events, flare associations, and PPS outcomes (1986-2014)

Characterizing Solar Energetic Particle Event Profiles with Two-Parameter Fits

Stephen W. **Kahler**, Alan G. Ling

Solar Physics   April **2017**, 292:59

http://link.springer.com/content/pdf/10.1007%2Fs11207-017-1085-4.pdf

The intensity–time profiles of solar energetic (\(E>10~\mbox{MeV}\)) particle (SEP) events observed at 1 AU reflect a number of physical processes involving solar injection and interplanetary transport. In addition to energy spectral and composition studies, SEP intensity–time profiles are the basis for diagnostic timescales needed for describing and modeling the acceleration and transport of SEPs. We briefly review commonly used timescales and point out the absence of holistic descriptions of the SEP profiles. We define the requirements for such a description and select a modified Weibull function from among three candidates as one which provides a reasonable two-parameter fit for most observed SEP events. In addition to the peak intensity, \(I_{\mathrm{p}}\), each event energy range can be described by shape and duration parameters \(\alpha\) and \(\beta\). Fits are applied to the profiles of 14 recent large SEP events observed in three integral energy ranges by the Geostationary Operational Environmental Satellite (GOES) spacecraft. The fits are generally robust, with \({<}\,1\%\) uncertainties in the parameters, but they can be very dependent on the choices of fit end times. We show the fit parameters as functions of energy range and solar source longitude. The fit parameters can be used not only as targets for modeling efforts, but also in space weather applications. **7 Jun 2011, 4 Aug 2011, 23 Jan, 2012, Jan 27-28, 7 Mar 2012, 2012 Mar 13, 17 May 2012, 11 Apr 2013, 22 May 2013, 30 Sep 2013, 6-7 January 2014, 25 Feb 2014, 11 Sep 2014**

Using the WSA Model to Test the Parker Spiral Approximation for SEP Event Magnetic Connections

S. W. **Kahler** , C. N. Arge, D. A. Smith

Solar Phys.   Volume 291, Issue 6, pp 1829-1852   **2016**

In studies of solar energetic (E>10 MeV) particle (SEP) events the Parker spiral (PS) field approximation, based only on the measured 1 AU solar wind (SW) speed Vsw, is nearly always used to determine the coronal or photospheric source locations of the 1 AU magnetic fields. There is no objective way to validate that approximation, but here we seek guidelines for optimizing its application. We first review recent SEP studies showing the extensive use of the PS approximation with various assumptions about coronal and photospheric source fields. We then run the Wang–Sheeley–Arge (WSA) model over selected Carrington rotations (CRs) to track both the photospheric and 5 R⊙ source locations of the forecasted 1 AU SW, allowing us to compare those WSA sources with the PS sources inferred from the WSA Vsw forecast. We compile statistics of the longitude differences (WSA–PS) for all the CRs and discuss the limitations of using the WSA model to validate the PS approximation. Over nearly all of each CR the PS and WSA source longitudes agree to within several degrees. The agreement is poor only in the slow–fast SW interaction regions characterized by high-speed events (HSEs), where the longitude differences can reach several tens of degrees. This result implies that SEP studies should limit use of the PS approximation around HSEs and use magnetic field polarities as an additional check of solar source connections.

SOLAR ENERGETIC PARTICLE EVENT ONSETS: FAR BACKSIDE SOLAR SOURCES AND THE EAST–WEST HEMISPHERIC ASYMMETRY

S. W. **Kahler**

2016 ApJ 819 105

Prompt onsets and short rise times to peak intensities Ip have been noted in a few solar energetic (E > 10 MeV) particle (SEP) events from far behind (≥25°) the west limb. We discuss **15 archival and recent examples** of these prompt events, giving their source longitudes, onset and rise times, and associated coronal mass ejection (CME) speeds. Their timescales and CME speeds are not exceptional in comparison with a larger set of SEP events from behind the west limb. A further statistical comparison of observed timescales of SEP events from behind the west limb with events similarly poorly magnetically connected to the eastern hemisphere (EH) shows the longer timescales of the latter group. We interpret this result in terms of a difference between SEP production at parallel shocks on the eastern flanks of western backside events and at perpendicular shocks on the western flanks of EH events.

Filament Eruptions Outside of Active Regions as Sources of Large Solar Energetic Particle Events

Kahler, S. ; Gopalswamy, N. ; Makela, P. ; Akiyama, S. ; Yashiro, S. ; Xie, H. ; Thakur, N.

Proceedings of the 34th International Cosmic Ray Conference (ICRC2015). 30 July - 6 August, 2015. The Hague, The Netherlands. Online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=236, id.48 **2015**

https://pos.sissa.it/236/048/pdf

Gradual solar energetic (E > 10 MeV) particle (SEP) events are produced in shocks driven by fast CMEs, which are nearly always spatially associated with ARs. Several cases of SEP events associated with CMEs originating in large filament eruptions (FEs) from outside ARs have previously been known, but four more such cases from solar cycles 23 and 24 have been described by [1]. The CMEs were fast (~ 1000 km s−1), appeared as coronagraph halo CMEs, and were associated with interplanetary type II bursts over a wide wavelength range. On the basis of their observed weak post-eruption arcade X-ray flare enhancements, several more candidate large SEP events resulting from eruptions of filaments adjacent to but outside ARs were identified. Thus, large SEP events can arise not only from unobserved ARs behind the disk, but also from non-AR filament eruptions. SEP event forecasting, currently based on observations of front-side solar ARs and X-ray flares, therefore can not predict either kind of SEP event. For the two SEP events with STEREO observations we confirm that despite their good magnetic connections to Earth, the SEP longitudinal distributions are broad. Neither Ulysses SEP observations nor CMEs associated with shocks and type II bursts give any indication that high-latitude polar-crown filament eruptions may have produced SEP events.
2000/04/04, 2000/09/12, 2002/05/22, 2004/04/11, 2011/11/26, 2013/09/29

[1] N. **Gopalswamy**, P. Mäkelä, S. Akiyama, S. Yashiro, H. Xie, N. Thakur, and S.W. Kahler, **Large Solar Energetic Particle Events Associated with Filament Eruptions Outside of Active Regions,** Astrophys. J., 806, (**2015**), 8.

Dynamic SEP event probability forecasts

S. W. **Kahler** and A. Ling

Space Weather Volume 13, Issue 10 (pages 665–675) **2015** DOI: 10.1002/2015SW001222

http://sci-hub.cc/10.1002/2015SW001222

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015SW001222

The forecasting of solar energetic particle (SEP) event probabilities at Earth has been based primarily on the estimates of magnetic free energy in active regions and on the observations of peak fluxes and fluences of large (≥ M2) solar X-ray flares. These forecasts are typically issued for the next 24 h or with no definite expiration time, which can be deficient for time-critical operations when no SEP event appears following a large X-ray flare. It is therefore important to decrease the event probability forecast with time as a SEP event fails to appear. We use the NOAA listing of major (≥10 pfu) SEP events from 1976 to 2014 to plot the delay times from X-ray peaks to SEP threshold onsets as a function of solar source longitude. An algorithm is derived to decrease the SEP event probabilities with time when no event is observed to reach the 10 pfu threshold. In addition, we use known SEP event size distributions to modify probability forecasts when SEP intensity increases occur below the 10 pfu event threshold. An algorithm to provide a dynamic SEP event forecast, Pd, for both situations of SEP intensities following a large flare is derived. **04/05/2000, 12/06/2006, 02/15/2011, 08/04/2011, 09/07/2011, 07/07/2012,**

Coronal Sources of Impulsive Fe-Rich Solar Energetic Particle Events

Stephen **Kahler**, Donald Reames, Edward Cliver

34th ICRC proceedings **2015**

http://arxiv.org/pdf/1509.09260v1.pdf

We review recent work on 111 Fe-rich impulsive solar energetic (∼ 3 MeV/nuc) particle (SEP) events observed from 1994 to 2013. Strong elemental abundance enhancements scale with A/Q, the ion mass-to-charge ratio, as $(A/Q)^{\alpha}$, where $2<\alpha<8$ for different events. Most Fe-rich events are associated with both flares and coronal mass ejections (CMEs), and those with larger α are associated with smaller flares, slower and narrower CMEs, and lower SEP event fluences. The narrow equilibrium temperature range required to fit the observed A/Q enhancements is 2.5--3.2 MK, far below the characteristic flare temperatures of > 10 MK. Only a small number of SEP events slightly outside this temperature range were found in an expanded search of impulsive Fe-rich events. Event characteristics are similar for events isolated in time and those occurring in clusters. The current challenge is to determine the solar sources of the Fe-rich events. Ambient coronal regions in the 2.5--3.2 MK range are broadly distributed both in and outside active regions. We explore the possibility of acceleration from thermal plasmas at reconnecting current sheets in the context of observed standard and blowout jets. Recent current sheet reconnection modelling provides a basis for the A/Q enhancements.

Forecasting SEP events with same active region prior flares

S. W. **Kahler**1,*, A. Ling2 and S. M. White

Space Weather Volume 13, Issue 2, pages 116–123, February **2015**

Forecasting large solar energetic (E > 10 MeV) particle (SEP) events is currently based on observed solar X-ray flare peak fluxes or fluences. Recent work has indicated that the probability of a solar eruptive event in an active region (AR) is enhanced when a large flare has occurred in that AR during the previous day. In addition, peak intensities Sp of SEP events associated with fast coronal mass ejections (CMEs) are larger for CMEs with prior CMEs from the same associated ARs in the previous day. This suggests that the associated SEP event probability and/or Sp may be higher for a given solar X-ray flare with a recent prior major flare in the same AR. We use data sets of NOAA flares and SEP events from solar cycles 22–24 to test this idea statistically for periods of prior flares ranging from 12 to 48 h. The occurrence probabilities and Sp of large SEP events for flares with prior same AR major (≥ M2) flares are not significantly higher than for flares without the prior flares; hence, prior flare occurrence is not a useful SEP event forecasting tool. The flare-based occurrence probabilities are higher for cycle 24 than for cycles 22 and 23, but the dependence of Sp on X-ray fluence appears unchanged. We show an example of a recent flare-prolific AR for which the SEP-associated flares are spatially distinct from the numerous non-SEP associated flares, indicating how prior AR flares may be unrelated to SEP-associated flares.

Solar Energetic Particle Events in Different Types of Solar Wind

S. W. **Kahler**1 and A. Vourlidas

2014, ApJ 791, 4; **File**

We examine statistically some properties of 96 20-MeV gradual solar energetic proton (SEP) events as a function of three different types of solar winds (SWs) as classified by Richardson and Cane (2012). Gradual SEP (E > 10 MeV) events are produced in shocks driven by fast (V _ 900 km/s) and wide (W >60 ◦) coronal mass ejections (CMEs). We find no differences between transient and fast or slow SW streams for SEP 20-MeV event timescales. It has recently been found that the peak intensities Ip of these SEP events scale with the ∼2-MeV proton background intensities, which may be a proxy for the near-Sun shock seed particles. Both the intensities Ip and their 2-MeV backgrounds are significantly enhanced in transient SW compared to those of fast and slow SW streams, and the values of Ip normalized to the 2-MeV backgrounds only weakly correlate with CME V for all SW types. This result implies that forecasts of SEP events could be improved by monitoring both the Sun and the local SW stream properties and that the well known power-law size distributions of Ip may differ between transient and long-lived SW streams. We interpret an observed correlation between CME V and the 2-MeV background for SEP events in transient SW as a manifestation of enhanced solar activity.

Do Interacting Coronal Mass Ejections Play a Role in Solar Energetic Particle Events?

S. W. **Kahler**1 and A. Vourlidas

2014 ApJ 784 47; **File**

Gradual solar energetic (E > 10 MeV) particle (SEP) events are produced in shocks driven by fast and wide coronal mass ejections (CMEs). With a set of western hemisphere 20 MeV SEP events, we test the possibility that SEP peak intensities, Ip, are enhanced by interactions of their associated CMEs with preceding CMEs (preCMEs) launched during the previous 12 hr. Among SEP events with no, 1, or 2 or more (2+) preCMEs, we find enhanced Ip for the groups with preCMEs, but no differences in TO+TR, the time from CME launch to SEP onset and the time from onset to SEP half-peak Ip. Neither the timings of the preCMEs relative to their associated CMEs nor the preCME widths W pre, speeds V pre, or numbers correlate with the SEP Ip values. The 20 MeV Ip of all the preCME groups correlate with the 2 MeV proton background intensities, consistent with a general correlation with possible seed particle populations. Furthermore, the fraction of CMEs with preCMEs also increases with the 2 MeV proton background intensities. This implies that the higher SEP Ip values with preCMEs may not be due primarily to CME interactions, such as the "twin-CME" scenario, but are explained by a general increase of both background seed particles and more frequent CMEs during times of higher solar activity. This explanation is not supported by our analysis of 2 MeV proton backgrounds in two earlier preCME studies of SEP events, so the relevance of CME interactions for larger SEP event intensities remains unclear.

Do Solar Coronal Holes Affect the Properties of Solar Energetic Particle Events?

S. W. **Kahler**, C. N. Arge, S. Akiyama, N. Gopalswamy

Solar Physics, February **2014**, Volume 289, Issue 2, pp 657-673; **File**

The intensities and timescales of gradual solar energetic particle (SEP) events at 1 AU may depend not only on the characteristics of shocks driven by coronal mass ejections (CMEs), but also on large-scale coronal and interplanetary structures. It has long been suspected that the presence of coronal holes (CHs) near the CMEs or near the 1-AU magnetic footpoints may be an important factor in SEP events. We used a group of 41 E≈ 20 MeV SEP events with origins near the solar central meridian to search for such effects. First we investigated whether the presence of a CH directly between the sources of the CME and of the magnetic connection at 1 AU is an important factor. Then we searched for variations of the SEP events among different solar wind (SW) stream types: slow, fast, and transient. Finally, we considered the separations between CME sources and CH footpoint connections from 1 AU determined from four-day forecast maps based on Mount Wilson Observatory and the National Solar Observatory synoptic magnetic-field maps and the Wang–Sheeley–Arge model of SW propagation. The observed in-situ magnetic-field polarities and SW speeds at SEP event onsets tested the forecast accuracies employed to select the best SEP/CH connection events for that analysis. Within our limited sample and the three analytical treatments, we found no statistical evidence for an effect of CHs on SEP event peak intensities, onset times, or rise times. The only exception is a possible enhancement of SEP peak intensities in magnetic clouds. **Table**

A COMPARISON OF THE INTENSITIES AND ENERGIES OF GRADUAL SOLAR ENERGETIC PARTICLE EVENTS WITH THE DYNAMICAL PROPERTIES OF ASSOCIATED CORONAL MASS EJECTIONS

S. W. **Kahler**1 and A. Vourlidas

2013 ApJ 769 143; **File**

https://iopscience.iop.org/article/10.1088/0004-637X/769/2/143/pdf

Gradual solar energetic particle (SEP) events observed at 1 AU are produced by shocks driven by coronal mass ejections (CMEs). Characterizations of the remotely imaged CMEs and of their associated SEP events observed in situ can be used to increase our ability to forecast SEP events and to understand better the physical connections between the two phenomena. We carry out a statistical comparison of the peak intensities Ip20, of 120 western-hemisphere 20 MeV SEP events with those of their associated CMEs observed by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph over the past solar cycle. For a subset of 96 events observed with the EPACT instrument on the Wind spacecraft we also compare the SEP 2 MeV peak intensities Ip2, power-law energy spectral exponents γ, total SEP energies Esep, and 2 MeV nuc–1 H/He ratios with CME properties. New analyses of white-light CME images enable us to improve calculations of the CME masses and potential energies and then to determine two values of their kinetic energies based on frontal V (fr) and center-of-mass V (cm) speeds. Despite considerable scatter in the SEP and CME data, the large dynamical ranges of both the SEP and CME parameters allow us to determine statistical trends in the comparisons of the logs of the parameters. Ip2, Ip20, and Esep are significantly correlated with CME kinetic energies, masses, and speeds, while γ trends lower (harder). Those correlations are higher with V (fr) than with V (cm) parameters, indicating a less significant role for the body of the CME than for the CME front in SEP production. The high ratios (≥10%) of Esep to CME energies found by Mewaldt et al. are confirmed, and the fits are consistent with a linear relationship between the two energies. The 2 MeV nuc–1 H/He ratios decrease with increasing CME speeds, which may be an effect of shock geometry. We discuss several factors that limit the estimates of both the SEP and CME energies.

A COMPARISON OF SOLAR ENERGETIC PARTICLE EVENT TIMESCALES WITH PROPERTIES OF ASSOCIATED CORONAL MASS EJECTIONS

S. W. **Kahler**

2013 ApJ 769 110; **File**

The dependence of solar energetic proton (SEP) event peak intensities Ip on properties of associated coronal mass ejections (CMEs) has been extensively examined, but the dependence of SEP event timescales is not well known. We define three timescales of 20 MeV SEP events and ask how they are related to speeds v CME or widths W of their associated CMEs observed by LASCO/SOHO. The timescales of the EPACT/Wind 20 MeV events are TO, the onset time from CME launch to SEP onset; TR, the rise time from onset to half the peak intensity (0.5Ip); and TD, the duration of the SEP intensity above 0.5Ip. This is a statistical study based on 217 SEP-CME events observed during 1996-2008. The large number of SEP events allows us to examine the SEP-CME relationship in five solar-source longitude ranges. In general, we statistically find that TO declines slightly with v CME, and TR and TD increase with both v CME and W. TO is inversely correlated with log Ip, as expected from a particle background effect. We discuss the implications of this result and find that a background-independent parameter TO+TR also increases with v CME and W. The correlations generally fall below the 98% significance level, but there is a significant correlation between v CME and W which renders interpretation of the timescale results uncertain. We suggest that faster (and wider) CMEs drive shocks and accelerate SEPs over longer times to produce the longer TR and TD SEP timescales.
Table 1: Properties of CMEs and Associated SEP Events, 1996-2008

DOES A SCALING LAW EXIST BETWEEN SOLAR ENERGETIC PARTICLE EVENTS AND SOLAR FLARES?

S. W. **Kahler**

2013 ApJ 769 35; **File**

Among many other natural processes, the size distributions of solar X-ray flares and solar energetic particle (SEP) events are scale-invariant power laws. The measured distributions of SEP events prove to be distinctly flatter, i.e., have smaller power-law slopes, than those of the flares. This has led to speculation that the two distributions are related through a scaling law, first suggested by Hudson, which implies a direct nonlinear physical connection between the processes producing the flares and those producing the SEP events. We present four arguments against this interpretation. First, a true scaling must relate SEP events to all flare X-ray events, and not to a small subset of the X-ray event population. We also show that the assumed scaling law is not mathematically valid and that although the flare X-ray and SEP event data are correlated, they are highly scattered and not necessarily related through an assumed scaling of the two phenomena. An interpretation of SEP events within the context of a recent model of fractal-diffusive self-organized criticality by Aschwanden provides a physical basis for why the SEP distributions should be flatter than those of solar flares. These arguments provide evidence against a close physical connection of flares with SEP production.

DEFLECTIONS OF FAST CORONAL MASS EJECTIONS AND THE PROPERTIES OF ASSOCIATED SOLAR ENERGETIC PARTICLE EVENTS

S. W. **Kahler**1, S. Akiyama2, and N. Gopalswamy

2012 ApJ 754 100, **File**

The onset times and peak intensities of solar energetic particle (SEP) events at Earth have long been thought to be influenced by the open magnetic fields of coronal holes (CHs). The original idea was that a CH lying between the solar SEP source region and the magnetic footpoint of the 1 AU observer would result in a delay in onset and/or a decrease in the peak intensity of that SEP event. Recently, Gopalswamy et al. showed that CHs near coronal mass ejection (CME) source regions can deflect fast CMEs from their expected trajectories in space, explaining the appearance of driverless shocks at 1 AU from CMEs ejected near solar central meridian (CM). This suggests that SEP events originating in CME-driven shocks may show variations attributable to CH deflections of the CME trajectories. Here, we use a CH magnetic force parameter to examine possible effects of CHs on the timing and intensities of 41 observed gradual E ~ 20 MeV SEP events with CME source regions within 20° of CM. We find no systematic CH effects on SEP event intensity profiles. Furthermore, we find no correlation between the CME leading-edge measured position angles and SEP event properties, suggesting that the widths of CME-driven shock sources of the SEPs are much larger than the CMEs. Independently of the SEP event properties, we do find evidence for significant CME deflections by CH fields in these events.

A Comparison of Ground Level Event e/p and Fe/O Ratios with Associated Solar Flare and CME Characteristics

S. W. **Kahler**, E. W. Cliver, A. J. Tylka and W. F. Dietrich

Space Science Reviews, 171, Numbers 1-4, 121-139, **2012**

https://link.springer.com/content/pdf/10.1007/s11214-011-9768-x.pdf

Solar energetic particle (SEP) events reaching rigidities >1 GV are observed at 1 AU as ground-level events (GLEs). They are considered to be extreme cases of gradual SEP events, produced by shocks driven by wide and fast CMEs that are usually associated with long-duration (>1 hour) soft X-ray (SXR) flares. However, some large gradual SEP events, including GLEs, are associated with flares of short-duration (<1 hour) timescales comparable to those of flares seen with impulsive, low-energy SEP events with enhanced charge states, heavy-element abundances, and e/p ratios. The association of some GLEs with short-duration SXR events challenges us to understand the GLE event-to-event variation with SXR durations and whether it truly reflects the nature of the particle acceleration processes or simply the characteristics of the solar regions from which large, fast CMEs arise. We examine statistically the associated flare, active region (AR), and CME characteristics of ~40 GLEs observed since 1976 to determine how the GLE e/p and Fe/O ratios, each measured in two energy ranges, depend on those characteristics. The abundance ratios trend weakly to lower, more coronal, and less scattered values with increasing flare timescales, thermal and nonthermal peak fluxes, and measures of source AR sizes. These results and the wide range of solar longitude connections for GLEs with high abundance ratios argue against a significant role for flare effects in the GLEs. We suggest that GLE SEPs are accelerated predominately in CME-driven shocks and that a coupling of flare size and timescales with CME properties could explain the SEP abundance correlations with flare properties.

Table 1 GLE SEP Fluence Ratios and Flare, AR and CME Properties

SOLAR ENERGETIC PARTICLE EVENTS AND THE KIPLINGER EFFECT

S. W. **Kahler**

2012 ApJ 747 66, **File**

The Kiplinger effect is an observed association of solar energetic (E > 10 MeV) particle (SEP) events with a "soft-hard-harder" (SHH) spectral evolution during the extended phases of the associated solar hard (E > 30 keV) X-ray (HXR) flares. Besides its possible use as a space weather predictor of SEP events, the Kiplinger effect has been interpreted as evidence of SEP production in the flare site itself, contradicting the widely accepted view that particles of large SEP events are predominately or entirely accelerated in shocks driven by coronal mass ejections (CMEs). We review earlier work to develop flare soft X-ray (SXR) and HXR spectra as SEP event forecast tools and then examine recent Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) evidence supporting the association of SHH HXR flares with large SEP events. We point out that ad hoc prediction criteria using the CME widths and SXR flare durations of associated RHESSI hard X-ray bursts (HXBs) can yield results comparable to those of the SHH prediction criteria. An examination of the RHESSI dynamic plots reveals several ambiguities in the determination of whether and when the SHH criteria are fulfilled, which must be quantified and applied consistently before an SHH-based predictive tool can be made. A comparative HXR spectral study beginning with the large population of relatively smaller SEP events has yet to be done, and we argue that those events will not be so well predicted by the SHH criteria. SHH HXR flares and CMEs are both components of large eruptive flare events, which accounts for the good connection of the SHH HXR flares with SEP events.

A COMPARISON OF ELEMENTAL ABUNDANCE RATIOS IN SEP EVENTS IN FAST AND SLOW SOLAR WIND REGIONS

S. W. **Kahler**[1], A. J. Tylka[2], and D. V. Reames[3]

Astrophysical Journal, 701:561–570, **2009; File**

The solar energetic (E > 1 MeV nucleon^{-1}) particles (SEPs) observed in gradual events at 1 AU are assumed to be accelerated by coronal/interplanetary shocks from ambient thermal or suprathermal seed particles. If so, then the elemental abundances of SEPs produced in different solar wind (SW) stream types (transient, fast, and slow) might be systematically distinguished from each other. We look for these differences in SEP energy spectra and in elemental abundance ratios (including Mg/Ne and Fe/C, which compare low/high first ionization potential elements), in a large number of SEP time intervals over the past solar cycle. The SW regions are characterized by the three-component stream classification of Richardson et al. Our survey shows no significant compositional or energy spectral differences in the 5–10 MeV nucleon^{-1} range for SEP events of different SW stream types. This result extends the earlier finding that SEP events are observed frequently in fast SW streams, although their higher Alfven and SW flow speeds should constrain SEP production by coronal mass ejection-driven shocks in those regions. We discuss the implications of our results for shock seed populations and cross-field propagation.

Variation of SEP event occurrence with heliospheric magnetic field magnitudes

S.W. **Kahler**

Advances in Space Research

Volume 43, Issue 9, 1 May **2009**, Pages 1423-1428

Recent work based on nitrate abundances in polar ice cores has shown that large fluence solar energetic E>30 MeV particle (LSEP) events during the spacecraft era of observations (1960–present) are diminished in comparison with those of some preceding eras detected in the ice cores dating back to 1561. McCracken et al. [McCracken, K.G., Dreschhoff, G.A.M., Smart, D.F., Shea, M.A. A study of the frequency of occurrence of large-fluence solar proton events and the strength of the interplanetary magnetic field, Sol. Phys., 224, 359–372, 2004] have reported an inverse correlation between LSEP events and the magnitudes of the associated reconstructed heliospheric magnetic fields (HMF). A physical working model by McCracken [McCracken, K.G. Changes in the cosmic ray and heliomagnetic components of space climate, 1428–2005, including the variable occurrence of solar energetic particle events, Adv. Space Res., 40, 1070–1077, 2007a; McCracken, K.G. High frequency of occurrence of large solar energetic particle events prior to 1958 and a possible repetition in the near future, Space Weather, 5, S07004, 2007b] is that the lower HMF and coronal magnetic field B imply that fast coronal mass ejections (CMEs) produce shocks with enhanced Alfvenic Mach numbers MA and higher compression ratios r, leading to shock production of more numerous and energetic LSEP events. From a possible decline of the HMF over the next several solar cycles he has urged a watch for a return to the environment of high-frequency, high-fluence LSEP events preceding the current spacecraft era. His LSEP event watch involves three independent questions about (1) the physical model, (2) the prediction of decreasing solar-cycle sunspot numbers and heliomagnetic fields, and (3) the inferred anti-correlation between LSEP events and HMFs. Here we discuss observational evidence bearing on the last question and find little support for the claimed LSEP-HMF anticorrelation.

Prospects for future enhanced solar energetic particle events and the effects of weaker heliospheric magnetic fields,

Kahler, S. W.

J. Geophys. Res., 113, A11102, (**2008**), http://dx.doi.org/10.1029/2008JA013168

Recent work based on nitrate abundances in ice cores has shown that large solar energetic (E > 30 MeV) particle (LSEP) events during the spacecraft era of observations (1960–present) are diminished in comparison with those of some preceding eras and that LSEP events have occurred during low cycles of solar activity. McCracken et al. (2004) have reported an inverse correlation between those LSEP events and the magnitude of the associated reconstructed heliospheric magnetic field (HMF). A physical explanation by McCracken (2007a, 2007b) is that the lower HMF and coronal magnetic field B imply that fast coronal mass ejections (CMEs) produce shocks with enhanced Alfvenic Mach numbers M A and higher compression ratios r, leading to more numerous and energetic LSEP events. From a possible decline of the HMF over the next several solar cycles, he has warned of a return to the environment of the more intense LSEP events preceding the current spacecraft era. We formulate and discuss seven questions using recent published observational, modeling, and theoretical work to assess the assumptions and the validity of his explanation and watch. We conclude that a return to more intense LSEP events is certainly possible, but (1) the inferred large increase in HMF characterizing the spacecraft era is in doubt; (2) there is no good evidence to connect more intense LSEP events with weaker HMFs; (3) a new Gleissberg minimum, with lower HMF, may not be imminent; (4) a lower active region B should result in slower CME speeds V less likely to produce shocks; (5) the average CME V increases significantly with SSN; (6) a lower coronal B likely results in a lower V A as the explanation requires; and (7) the lower coronal B leads to weaker, not more intense, LSEP events because of decreased spectral cutoff energies.

Solar Sources of Heliospheric Energetic Electron Events - Shocks or Flares? **Review**

Kahler, S. W.

Space Sci. Rev. 129, 359-390 (**2007**). **File**

Electrons with near-relativistic (E≳30 keV, NrR) and relativistic (E≳0.3 MeV) energies are often observed as discrete events in the inner heliosphere following solar transient activity. Several acceleration mechanisms have been proposed for the production of those electrons. One candidate is acceleration at MHD shocks driven by coronal mass ejections (CMEs) with speeds ≳1000 km s−1. Many NrR electron events are temporally associated only with flares while others are associated with flares as well as with CMEs or with radio type II shock waves. Since CME onsets and associated flares are roughly simultaneous, distinguishing the sources of electron events is a serious challenge. On a phenomenological basis two classes of solar electron events were known several decades ago, but recent observations have presented a more complex picture. We review early and recent observational results to deduce different electron event classes and their viable acceleration mechanisms, defined broadly as shocks versus flares. The NrR and relativistic electrons are treated separately. Topics covered are: solar electron injection delays from flare impulsive phases; comparisons of electron intensities and spectra with flares, CMEs and accompanying solar energetic proton (SEP) events; multiple spacecraft observations; two-phase electron events; coronal flares; shock-associated (SA) events; electron spectral invariance; and solar electron intensity size distributions. This evidence suggests that CME-driven shocks are statistically the dominant acceleration mechanism of relativistic events, but most NrR electron events result from flares. Determining the solar origin of a given NrR or relativistic electron event remains a difficult proposition, and suggestions for future work are given.

Validating the proton prediction system (PPS)

S.W. **Kahler,** E.W. Cliver, A.G. Ling

Journal of Atmospheric and Solar-Terrestrial Physics 69 (**2007**) 43–49, **File**

The proton prediction system (PPS) is a program developed at the Air Force Research Laboratory (AFRL) to predict solar energetic Ep>5 MeV proton (SEP) intensities at 1AU following solar flares. It is based on average observed SEP intensity-time profiles, peak intensities, and event durations. The input parameters are solar flare peak or time-integrated X-ray or radio fluxes and their times of onsets and maxima, and solar flare locations. We do a limited validation of the PPS using 78 GOES solar X-ray flares of peak intensity XM5 with well associated Ha flare locations. Predicted peak proton intensities Jp>10 MeV and event onset and rise times are compared with SEP events observed by GOES. We also select all GOES >10MeV SEP events above 10 proton flux units (pfu) during the same time period to compare with those predicted by the PPS. With our M5 X-ray flare threshold the PPS yields approximately equal numbers of correct predictions, false predictions, and missed 10-pfu SEP events.

SOLAR RADIO BURST AND SOLAR WIND ASSOCIATIONS WITH INFERRED NEAR-RELATIVISTIC ELECTRON INJECTIONS

S. W. **Kahler**, H. Aurass, G. Mann, A. Klassen

The Astrophysical Journal, 656:567Y576, **2007, File**

The solar injections of near-relativistic (NR) electron events observed at 1 AU appear to be systematically delayed by ~10 minutes from the associated flare impulsive phases.

Electron events with long (_2 hr) beaming times at 1 AU are preferentially associated with type II bursts, which supports the possibility of a class of shock-accelerated NR electron events.

Solar Sources of Heliospheric Energetic Electron Events—Shocks or Flares?

S. W. **Kahler**

Space Science Reviews, Volume 129, Number 4, p. 359 – 390, **2007, File**

Since CME onsets and associated flares are roughly simultaneous, distinguishing the sources of electron events is a serious challenge. On a phenomenological basis two classes of solar electron events were known several decades ago, but recent observations have presented a more complex picture. We review early and recent observational results to deduce different electron event classes and their viable acceleration mechanisms, defined broadly as shocks versus flares. The NrR and relativistic electrons are treated separately.

This evidence suggests that CME-driven shocks are statistically the dominant acceleration mechanism of relativistic events, but most NrR electron events result from flares. Determining the solar origin of a given NrR or relativistic electron event remains a difficult proposition, and suggestions for future work are given.

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CHARACTERISTIC TIMES OF GRADUAL SOLAR ENERGETIC PARTICLE EVENTS AND THEIR DEPENDENCE ON ASSOCIATED CORONAL MASS EJECTION PROPERTIES

S. W. **Kahler**

Astrophysical Journal, 628:1014–1022, **2005**

We use 20MeV proton intensities from the EPACT instrument on Wind and coronal mass ejections (CMEs) from the LASCO coronagraph on SOHO observed during 1998–2002 to statistically determine three characteristic times of gradual solar energetic particle (SEP) events as functions of solar source longitude: (1) TO, the time from associated CME launch to SEP onset at 1 AU, (2) TR, the rise time from SEP onset to the time when the SEP intensity is a factor of 2 below peak intensity, and (3) TD, the duration over which the SEP intensity is within a factor of 2 of the peak intensity. Those SEP event times are compared with associated CME speeds, accelerations, and widths to determine whether and how the SEP event times may depend on the formation and dynamics of coronal/interplanetary shocks driven by the CMEs. Solar source longitudinal variations are clearly present in the

SEP times, but TR and TD are significantly correlated with CME speeds only for SEP events in the best-connected longitude range. No significant correlations between the SEP times and CME accelerations are found except for TD in one longitude range, but there is a weak correlation of TR and TD with CME widths.We also find no correlation of any SEP times with the solar wind Oю7/Oю6 values, suggesting no dependence on solar wind stream type. The SEP times of the small subset of events occurring in interplanetary CMEs may be slightly shorter than those of all events.

Onsets of Solar Cycle 23 Ground Level Events as Probes of Solar Energetic Particle Injections at the Sun

Kahler S. W. Simnett G. M. & Reiner M. J.

Proceedings of the 28th International Cosmic Ray Conference, **2003**, p. 3415.

The correlation between solar energetic particle peak intensities and speeds of coronal mass ejections: Effects of ambient particle intensities and energy spectra.

Kahler, S.W.:

2001, J. Geophys. Res. 106, 20947 – 20956.

https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2000JA002231

The correlation of peak intensities of solar energetic particle (SEP) events with the speeds of the associated coronal mass ejections (CMEs) is understood to be a result of SEP acceleration at shocks driven by the CMEs. However, the peak SEP intensities associated with CMEs of a given speed vary over ∼ 4 orders of magnitude. We examine a database of 71 E > 10 MeV SEP events observed with the GOES satellite to determine whether enhanced ambient SEP intensities at the times of the CMEs and/or variations among SEP event spectra contribute to the large range of peak SEP event intensities. A statistical analysis shows that enhanced ambient SEP intensities may be a contributing factor to the range of SEP events of higher peak intensities, probably by providing sources of energetic seed particles for the shock acceleration process. Another factor is the variation of energy spectra among the SEP events, which generally have harder spectra with increasing peak intensities. The observed increase of peak SEP intensities and hardening of peak SEP spectra with increasingly westward solar source regions is only a minor factor in the range of SEP peak intensities in the CME speed correlation.

Coronal mass ejections associated with impulsive solar energetic particle events.

Kahler, D.V. Reames, N.R. Sheeley Jr.,

Astrophys. J. 562, 558 (**2001**).

sci-hub.si/10.1086/323847

https://iopscience.iop.org/article/10.1086/323847/pdf

An impulsive solar energetic particle (SEP) event observed on the W ind spacecraft on **2000 May 1** was associated with an impulsive solar active region M1 X-ray flare. The timing and position of a fast (v\ 960 km s~1), narrow CME observed in the LASCO coronagraph on SOHO make clear the connection between the CME and the flare and SEP event. Impulsive SEP events have long been associated with impulsive flares, but only gradual SEP events have thus far been found to be associated with CMEs. A comparison of impulsive SEP events with CME observations from the Solwind and LASCO coronagraphs revealed further good cases of narrow (10¡È40¡) CMEs associated with impulsive SEP events. A recent model of impulsive flares includes jets or plasmoids that are ejected upward from magnetic reconnection sites over active regions and might therefore be expected to appear in exceptional cases as faint and narrow CMEs in coronagraphs. We suggest that this model allows us to understand better SEP production and propagation in impulsive flares.

Origin and Properties of Solar Energetic Particles in Space Review

S. W. **Kahler**

Space Weather Geophysical Monograph 125 **2001** pages 109–122

http://onlinelibrary.wiley.com/doi/10.1029/GM125p0109/pdf

http://sci-hub.si/10.1029/GM125p0109

Transient energetic (E > 10 MeV) particle events from the Sun have been observed at the Earth for half a century using several detection techniques. We review these observations and the change in focus from solar flares to fast coronal mass ejections (CMEs) and shocks as the causal agents of solar energetic particle (SEP) events. We review the properties of SEP events that are important for space weather: 1) the number distributions of peak SEP intensities and of SEP fluences; 2) the relationship of SEP intensities to CME speeds; 3) when SEP events occur during the solar cycle; and 4) where SEP events occur relative to the CME-driven shocks. We conclude with a discussion of two cases of direct negative effects of SEPs on space experiments.

A Search for Interplanetary Energetic Particle Events from Solar Posteruptive Arcades

S. W. **Kahler**1, A. H. McAllister2, and H. V. Cane3,4

2000 ApJ 533 1063

https://iopscience.iop.org/article/10.1086/308680/pdf

While the E > 10 MeV ions observed in gradual solar energetic particle (SEP) events in space are attributed to acceleration at shocks driven by coronal mass ejections (CMEs), it has been suggested that such SEPs may also be produced in the magnetic reconnection of coronal arcades following CMEs. The arcade SEPs could escape the corona along open field lines and provide additional contributions to observed gradual SEP events. We searched for SEP events associated with large, bright solar soft X-ray arcades and intense metric noise storms in the western hemisphere, which should be favorable for the production of arcade SEP events observed at 1 AU. Five arcades/storms were possibly or definitely associated with IMP-8 24-28 MeV proton increases, but the latter appear to be shock accelerated. We also found 30 arcades (14 in active regions and 16 outside active regions) with no detectable SEP increases, suggesting that those arcades were not sources of escaping SEPs. This result provides evidence against the possibility of coronal arcade contributions to gradual SEP events.

Solar filament eruptions and energetic particle events

Kahler, S. W.; Cliver, E. W.; Cane, H. V.; McGuire, R. E.; Stone, R. G.; Sheeley, N. R., Jr.

Astrophysical Journal, Part, vol. 302, March 1, **1986**, p. 504-510

http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?db_key=AST&bibcode=1986ApJ...302..504K&letter=.&classic=YES&defaultprint=YES&whole_paper=YES&page=504&epage=504&send=Send+PDF&filetype=.pdf

The **1981 December 5** solar filament eruption that is associated with an energetic (E greater than 50 MeV) particle event observed at 1 AU. The eruption was photographed in H-alpha and was observed by the Solwind whitelight coronagraph on P78-1. It occurred well away from any solar active region and was not associated with an impulsive microwave burst, indicating that magnetic complexity and a detectable impulsive phase are not required for the production of a solar energetic particle (SEP) event. No metric type II or IV emission was observed, but an associated interplanetary type II burst was detected by the low-frequency radio experiment on ISEE 3. The December 5 and two other SEP events lacking evidence for low coronal shocks had unusually steep energy spectra (gamma greater than 3.5). In terms of shock acceleration, this suggests that shocks formed relatively high in the corona may produce steeper energy spectra than those formed at lower altitudes. It is noted that the filament itself maybe one source of the ions accelerated to high energies, since it is the only plausible coronal source of the He(+) ions observed in SEP events.

The relationship of shock-associated kilometric radio emission with metric type II bursts and energetic particles

Kahler, S. W.; Cliver, E. W.; Cane, H. V.

Advances in Space Research, Volume 6, Issue 6, p. 319-322. **1986**

Shock-associated (SA) events are a class of kilometric wavelength solar radio bursts first observed with the ISEE-3 Radio Astronomy Experiment. Cane et al. /1/ noted that these fast drift events are typically associated with metric type II bursts and hypothesized that the SA events were due to electrons accelerated by coronal shocks. We compare SA events from 1978 to 1982 with metric type II bursts and solar energetic particle (SEP) events. Most metric type II bursts are not obviously associated with SA events at 1980 kHz. Metric type II bursts associated with magnetically well connected flares and SA emission are well correlated with SEP events; those without SA emission are poorly correlated with SEP events. The largest SEP events from flares at any longitude are well correlated with SAs. These results are consistent with the hypothesis that the escaping electrons giving rise to SA emission are accelerated in coronal shocks.

Associations between coronal mass ejections and solar energetic proton events.

Kahler, N.R. Sheeley Jr., R.A. Howard, M.J. Koomen, D.J. Michels, R.E. McGuire, T.T. von Rosenvinge, D.V. Reames,

J. Geophys. Res. 89, 9683 (**1984**). **File**

sci-hub.tw/10.1029/JA089iA11p09683

We have used data from the Naval Research Laboratory (NRL) white light coronagraph on the P78-1 spacecraft and energetic (œ > 4 MeV) proton data from the Goddard Space Flight Center (GSFC) detectors on the IMP 8 and ISEE 3 spacecraft to investigate the association between proton events originating in flares and coronal mass ejections (CME's). The primary data were 50 prompt proton events observed between April 1979 and February 1982 for which reduced coronagraph data were available. H alpha flares could be confidently associated with 27 of these events, and in 26 of these 27 cases an associated CME was found, indicating a high but not perfect association of

prompt protøn events with CME's. Peak proton fluxes correlate with both the speeds and the angular sizes of the associated CME's. We show that the CME speeds do not significantly correlate with CME angular sizes, so that the peak proton fluxes are correlated with two independent CME parameters. With larger angular sizes, CME's are more likely to be loops and fans rather than jets and spikes and are more likely to intersect the ecliptic. Which of these factors is important to the peak proton flux correlation cannot be determined from the data. We find weak evidence that steeper proton spectra are associated with faster and wider CME's. Two of the 50 proton events of the study and two additional events, all with no associated CME's, share common characteristics: relatively short duration (• 1 day) proton events with low fluxes, parent flares with short (• 10 min) soft X ray duration, close magnetic connection to the earth, and gamma ray and metric type II emission.
After many years, Kahler et al. (1984) showed that SEPs had a strong (96%) association with wide, fast coronal mass ejections (CMEs), only discovered a few years before, and thus with the extensive shock waves that they drive out from the Sun.

The role of the big flare syndrome in correlations of solar energetic proton fluxes and associated microwave burst parameters.
Kahler, S.W.:
1982, J. Geophys. Res. 87, 3439 – 3448.
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/JA087iA05p03439
A hypothesis based on the big flare syndrome (BFS) is proposed which attempts to explain the observed correlations between solar energetic proton fluxes and microwave burst parameters in terms of the statistical correlation between solar flare energy release and the magnitude of flare energy manifestations in general. Correlations between peak prompt proton fluxes and associated microwave burst parameters are examined for the period from June 1973 to August 1979 based on IMP 7 and 8 data for protons of energies 20-40 and 40-80 MeV. Correlation coefficients for proton and microwave data are found not to exceed those expected for the BFS hypothesis with the exception of the relation of peak proton fluxes to the time-integrated flux densities at 8800 and 15,400 MHz, which may be explained by the concurrent production of the energetic electrons responsible for the microwave bursts and the energetic protons. Results thus indicate that most correlations between proton fluxes and microwave and hard X-ray parameters can be accounted for by the BFS.

Radio burst characteristics of solar proton flares.
Kahler, S. W.
Astrophys. J., 261, 710–719, **1982**a. 10.1086/160381.
http://articles.adsabs.harvard.edu/pdf/1982ApJ...261..710K
To isolate the properties of solar radio bursts indicative of energetic (F > 20 MeV) proton acceleration, we compare several groups of solar bursts. Intense centimetric bursts and metric type II bursts associated with solar flares at magnetically well-connected longitudes, but not resulting in detected prompt proton events, are compared with the radio bursts of proton flares. The type II bursts not associated with proton flares are distinguished from those of proton flares by their short durations, associations with small Ha flares, and lack of associated type IV metric bursts. We find that, contrary to the claim of Svestka and Fritzova-Svestkova, the appearance of a type II burst, indicating a coronal shock, is not a sufficient condition for the occurrence of an interplanetary proton event. We further conclude that interplanetary energetic protons are not significantly produced in most type II burst shocks. The centimetric bursts were examined in detail using records from the Sagamore Hill Observatory. The distinguishing difference between the proton and nonproton centimetric bursts is that the proton-event burst durations ranged from 1 minute to 1 hour, but the burst durations of nonproton flares were less than 10 minutes. We argue that energetic electrons produced in postflare loop systems are the sources of the stationary metric and decimetric type IV bursts associated with proton flares

Prompt solar proton events and coronal mass ejections,
Kahler, S. W., Hildner, E., and van Hollebeke, M. A. I.,
Solar Phys. 57, 429, **1978**
https://link.springer.com/content/pdf/10.1007/BF00160116.pdf
We have used data from the HAO white light coronagraph and AS&E X-ray telescope on Skylab to investigate the coronal manifestations of 18 prompt solar proton events observed with the GSFC detectors on the IMP-7 spacecraft during the Skylab period. We find evidence that a mass ejection event is a necessary condition for the occurrence of a prompt proton event. Mass ejection events can be observed directly in the white light coronagraph when they occur near the limb and inferred from **the presence of a long decay X-ray** event when they occur on the disk. We suggest that: (1) **the occurrence of mass ejection events facilitates the escape of protons - whether accelerated at low or high altitudes - to the interplanetary medium;** and (2) there may exist a proton acceleration region above or around the outward moving ejecta far above the flare site.
Although SEP events are known for several decades, it was Kahler et al. (1978) who recognized the importance of CMEs for the occurrence of SEP events.

Analysis of type II and type III radio bursts associated with SEPs from non-interacting/interacting radio-loud CMEs

P Pappa **Kalaivani**, O Prakash, A Shanmugaraju, Li Feng, Lei Lu, Weiqun Gan, G Michalek
Astrophysics **2021**
https://arxiv.org/pdf/2107.09955.pdf

We analyze radio bursts observed in events with interacting/non-interacting CMEs that produced major SEPs (Ip > 10 MeV) fromApril 1997 to December 2014.We compare properties of meter (m), deca-hectometer (DH) type II as well as DH type III bursts, and time lags for interacting-CME-associated (IC) events and non-interacting-CME-associated (NIC) events. About 70\% of radio emissions were observed in events of both types from meters to kilometers. We found high correlations between the drift rates and mid-frequencies of type II radio bursts calculated as the mean geometric between their starting and ending frequencies for both NIC and IC-associated events (Correlation coefficient \textit{R}2 = 0.98, power-law index ε = 1.68 ± 0.16 and \textit{R}2 = 0.93, ε = 1.64 ± 0.19 respectively).We also found a correlation between the frequency drift rates of DH type II bursts and space speeds of CMEs in NIC-associated events. The absence of such correlation for IC-associated events confirms that the shock speeds changed in CME--CME interactions. For the events with western source locations, the mean peak intensity of SEPs in IC-associated events is four times larger than that in NIC-associated SEP events. From the mean time lags between the start times of SEP events and the start of m, DH type II, and DH type III radio bursts, we inferred that particle enhancements in NIC-associated SEP events occurred earlier than in IC-associated SEP events. The difference between NIC events and IC events in the mean values of parameters of type II and type III bursts is statistically insignificant. **18 Apr 2014**

Statistical characteristics on SEPs, radio-loud CMEs, low frequency type II and type III radio bursts associated with impulsive and gradual flares

P. Pappa **Kalaivani**, A. Shanmugaraju, O. Prakash, R.-S. Kim
Earth Moon and Planets, [104, 295 ?] (**2020**)
https://arxiv.org/pdf/2007.05726.pdf
https://sci-hub.tw/https://link.springer.com/article/10.1007/s11038-020-09533-9

We have statistically analyzed a set of 115 low frequency (Deca- Hectometer wavelengths range) type II and type III bursts associated with major Solar Energetic Particle (SEP: Ep > 10 MeV) events and their solar causes such as solar flares and coronal mass ejections (CMEs) observed from 1997 to 2014. We classified them into two sets of events based on the duration of the associated solar flares:75 impulsive flares (duration < 60 min) and 40 gradual flares (duration > 60 min).The impulsive flare-associated SEP events (Rt = 989.23 min: 2.86 days) are short lived and they quickly reach their peak intensity (shorter rise time) when compared with gradual flares associated events (Rt =1275.45 min: 3.34 days). We found a good correlation between the logarithmic peak intensity of all SEPs and properties of CMEs (space speed: cc = 0.52, SEcc = 0.083), and solar flares (log integrated flux: cc = 0.44, SEcc = 0.083). This particular result gives no clear cut distinction between flare-related and CME-related SEP events for this set of major SEP events. We derived the peak intensity, integrated intensity, duration and slope of these bursts from the radio dynamic spectra observed by Wind/WAVES. Most of the properties (peak intensity, integrated intensity and starting frequency) of DH type II bursts associated with impulsive and gradual flare events are found to be similar in magnitudes. In addition, we also found a significant correlation between the properties of SEPs and key parameters of DH type III bursts. This result shows a closer association of peak intensity of the SEPs with the properties of DH type III radio bursts than with the properties DH type II radio bursts, at least for this set of 115 major SEP events. **17 May 2012, 31 Aug 2012**

A study on radio-loud interacting/non-interacting CMEs-associated SEPs and solar flares

P. Pappa **Kalaivani**, O. Prakash, Li Feng, A. Shanmugaraju, ... Weiqun Gan
Advances in Space Research Volume 63, Issue 10, 15 May **2019**, Pages 3390-3403
sci-hub.se/10.1016/j.asr.2019.01.019

We have established a data set of 58 major hybrid SEP events associated with meter-to-decahectometer wavelength (m-to-DH) type II bursts, solar flares, and radio-load CMEs during the period of 1997–2014. The main focus of our study is to address the following two questions: Does the interaction of CMEs play a role in the enhancement of SEP intensity? Is there any difference in the seed population, and parent eruptions in the SEP events with and without CME interactions? Hence, the sample of 58 events is classified into two sets: (i) 35 non-interacting-CME-associated SEP events; (ii) 23 interacting-CME-associated SEP events. All the characteristics of SEPs, their associated CMEs/flares and the relationships between them are statistically analyzed and compared. Some of the basic attributes and relative elemental abundances (Fe/O ratios) of the both the sets are also compared. The results indicate that the seed particles in non-interacting-CME-associated SEP events are mostly from solar wind/coronal materials. But in the case of interacting-CME-associated SEP events, it may be associated with both flare material from preceding flares and coronal materials from solar wind/preceding CMEs. The correlation studies reveal that there are clear correlations between logarithmic peak intensity of SEP events and properties of CMEs (space speed: cc = 0.56) and solar flares (peak intensity: cc = 0.40; integrated flux: cc = 0.52) for non-interacting-CME-associated SEP events. But these correlations are absent for the interacting-CME-associated events. In addition, the results suggest that interaction of primary CMEs with their preceding CMEs plays an important role in the enhancement of peak intensity of SEPs at least for a set of m-to-DH type II bursts associated SEP events. **May 22, 2013, April 18, 2014**

Table 1 Basic characteristics of SEPs, CMEs, flares in non-interacting-CME and interacting-CME associated events.

Magnetospheric access for solar protons during the January 2005 SEP event

Vladimir V. **Kalegaev**1*, Natalia A. Vlasova1, Ilya S. Nazarkov1 and Sophia A. Melkova2

J. Space Weather Space Clim. **2018**, 8, A55

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170051.pdf

The early phase of the extraordinary solar energetic particle **20 January, 2005** event having the highest peak flux of any SEP in the past 50 years of protons with energies > 100 MeV is studied. Solar energetic particles (>16 MeV) entry to the Earth's magnetosphere on January 20, 2005 under northward interplanetary magnetic field conditions is considered based on multi-satellite data analysis and magnetic field simulation. Solar wind parameters and interplanetary magnetic field data, as well as calculations in terms of the A2000 magnetospheric magnetic field model were used to specify conditions in the Earth's environment corresponding to solar proton event. It was shown that during the early phase of the event energetic particle penetration into the magnetosphere took place in the regions on the magnetopause where the magnetospheric and interplanetary magnetic field vectors are parallel. Complex analysis of the experimental data on particle fluxes in the interplanetary medium (data from ACE spacecraft) and on low-altitude (POES) and geosynchronous (GOES) orbits inside the Earth's magnetosphere show two regions on the magnetopause responsible for particle access to the magnetosphere: the near equatorial day-side region and open field lines window at the high-latitude magnetospheric boundary. Calculations in terms of A2000 magnetospheric magnetic field model and comparison with SuperDARN images support the link between high-latitude solar energetic particle precipitations and the region at the magnetopause where the magnetospheric field is coupled with northward IMF, allowing solar particles entrance into the magnetosphere and access to the northern polar cap.

Current views on impulsive and gradual solar energetic particle events

M-B **Kallenrode**

J. Phys. G: Nucl. Part. Phys. **29** (**2003**) 965–981, **File**

Solar energetic particles (SEPs) are one manifestation of violent energy releases on the Sun. The study of their acceleration and propagation reveals information about basic plasma-physical processes, such as reconnection, shock acceleration and wave-particle interaction, in astrophysical objects, such as stars, magnetospheres or the diluted plasma of the interstellar or interplanetary medium. This paper introduces the current classification scheme for solar energetic particle events, its relation to the underlying acceleration processes, and addresses open questions regarding the better understanding of SEPs as well as the underlying physical processes. Modifications to the current paradigm considering more recent observations will be suggested.

Neutral lines and azimuthal 'transport' of solar energetic particles.

Kallenrode, M.:

1993, J. Geophys. Res. 98, 5573 – 5591.

Composition and azimuthal spread of solar energetic particles from impulsive and gradual flares.

Kallenrode, M.-B., Cliver, E.W., Wibberenz, G.:

1992, Astrophys. J. 391, 370. DOI. ADS.

http://articles.adsabs.harvard.edu/pdf/1992ApJ...391..370K

A list of 77 flare-associated solar energetic particle (SEP) parent flares are classified as impulsive (25 cases) or gradual (52 cases) on the basis of their soft X-ray durations. The intensities of the prompt component of about 0.5 MeV electrons, about 10 MeV protons, and about 10 MeV per nucleon helium for the two classes of SEP flares are compared. SEPs from gradual flares have higher intensities than SEPs from impulsive flares. These differences are most pronounced for protons (about two orders of magnitude), and less for electrons (about one order of magnitude), and helium (about a factor of 5). The SEPs from impulsive flares have a 'cone of emission' of +/- 50 deg vs +/- 120 deg for gradual flares.

Solar Neutrons Observed from September 4 to 10, 2017 by SEDA-FIB

K. **Kamiya**, K. Koga, H. Matsumoto, S. Masuda, Y. Muraki, H. Tajima, S. Shibata

Proceeding of Science, **2019**

https://arxiv.org/ftp/arxiv/papers/1907/1907.09154.pdf **File**
PoS(**ICRC2019**)1150 pdf

The SEDA-FIB is a detector designed to measure solar neutrons. This solar neutron detector was operated onboard the ISS on July 16, 2009 and March 31, 2018. Eighteen large solar flares were later observed by the GOES satellite in solar active region 12673 that appeared on September 4 and lasted until September 10, 2017, with intensity higher than > M2. In nine of those solar flares, the SEDA-FIB detected clear signals of solar neutrons, along with five minor excesses. Among these events, we focus on two associated with the flares of X2.2 (**SOL2017-09-06**) and X8.2 (**SOL2017-09-10**) that share a common feature: a process of accelerating electrons into high energies as clearly recorded by the FERMI-GBM detector. These events may provide us with useful information to elucidate the ion acceleration process. The X8.2 event was a limb flare that proved adequate for fixing the parameters needed to explain the process of particle acceleration into high energies. According to our analysis, the electron acceleration process may possibly be explained by the shock acceleration model. However, we found that it would be difficult to explain the simultaneous acceleration of ions with electrons, unless the ions were preheated prior to their rapid acceleration.

Table 1. List of Solar Neutrons

Proton Acceleration by Very Impulsive Flare on June 3, 2012

K. **Kamiya**, 1) K. Koga, 1) S. Masuda, 2) H. Matsumoto, 1) Y. Muraki, 2) T. Obara, 3) O. Okudaira, 4) Y. Tanaka, 5) S. Shibata, 6) and T. Goka1)

Proc. of 35th International Cosmic Ray Conference — ICRC2017 10–20 July, **2017** Bexco, Busan, Korea

https://pos.sissa.it/301/115/pdf

On **June 3, 2012**, a very impulsive solar flare was observed by the GOES, RHESSI and FERMILAT satellites. The intensity of the flare was M3.3. The hard X-ray intensity (> 100 keV) rose ≥ 1000 times within one minute and then decayed immediately to the background level (in less than one minute). It was an extremely impulsive flare. By chance, the SEDA-FIB solar neutron detector onboard the International Space Station detected a 5.1σ enhancement due to solar neutrons. Therefore, it provided a good opportunity to investigate the mechanism of instantaneous proton acceleration to a few GeV. Based on the results of a new Monte Carlo calculation, we will show a reasonable proton acceleration model for the June 3, 2012 event. We also reexamined another very impulsive flare observed on **June 12, 2010**.

Lags and Hysteresis Loops of Cosmic Ray Intensity *Versus* Sunspot Numbers: Quantitative Estimates for Cycles 19 – 23 and a Preliminary Indication for Cycle 24

R.P. **Kane**

Solar Phys., **2014**

Hysteresis plots between cosmic-ray (CR) intensity (recorded at the Climax station) and sunspot relative number R_Z show broad loops in odd cycles (19, 21, and 23) and narrow loops in even cycles (20 and 22). However, in the even cycles, the loops are not narrow throughout the whole cycle; around the sunspot-maximum period, a broad loop is seen. Only in the rising and declining phases, the loops are narrow in even cycles. The CR modulation is known to have a delay with respect to R_Z, and the delay was believed to be longer in odd cycles (19, 21, and 23; about 10 months) than the delay in even cycles (20 and 22; about 3 – 5 months). When this was reexamined, it was found that the delays are different during the sunspot-minimum periods (2, 6, and 14 months for odd cycles and 7 and 9 months for even cycles) and sunspot-maximum periods (0, 4, and 7 months for odd cycles and 5 and 8 months for even cycles). Thus, the differences between odd and even cycles are not significant throughout the whole cycle. In the recent even cycle 24, hysteresis plots show a preliminary broadening near the sunspot maximum, which occurred recently (February 2012). The CR level (recorded at Newark station) is still high in 2013, indicating a long lag (exceeding 10 months) with respect to the sunspot maximum.

A Mechanism for the Fractionation of Isotopes in 3He-rich Solar Energetic Particle Events

Y. Y. **Kartavykh**1,2, W. Dröge1, B. Klecker3, G. A. Kovaltsov2, and V. M. Ostryakov4

2021 ApJ 906 6

https://iopscience.iop.org/article/10.3847/1538-4357/abc62a/pdf

https://doi.org/10.3847/1538-4357/abc62a

By employing our charge-consistent acceleration model we demonstrate a possibility to explain the isotopic ratios observed in a number of 3He-rich events. We investigate the dependence of isotopic ratios of heavy ions on the energy of the particles, the acceleration efficiency, the product of acceleration time, and the number density of ambient electrons, of the plasma temperature, and of the spectral index of the magnetic fluctuations by which the ions are energized in the acceleration region. On the basis of the energy spectra of heavy ions and their isotopic ratios observed in the event of **2002 August 20** by the Solar Isotope Spectrometer on board the Advanced Composition Explorer (SIS/ACE) we put constraints on the plasma parameters in the acceleration region. Our investigation gives evidence that the spectral index of the fluctuations with which the ions interact is greater than 2, and that the plasma temperature is about 1 MK.

A Possible Enrichment of Heavy and Ultraheavy Ions in Solar Energetic Particle Events Due to a Combined Effect of Stochastic Acceleration and Coulomb Losses

Y. Y. **Kartavykh**1,2, W. Dröge1, B. Klecker3, G. A. Kovaltsov2, and V. M. Ostryakov4

2020 ApJ 888 48

https://doi.org/10.3847/1538-4357/ab584e

Solar particle events that are rich in 3He typically also exhibit large overabundances of heavy and ultraheavy ions that increase with the mass of the ions. To explain these observations we apply our charge-consistent acceleration model, which takes into account the acceleration efficiency as a function of the charge to mass ratio of the ion, as well as the charge-dependent Coulomb energy losses, to consider the acceleration of ions within a wide range of their nuclear charge. Because the considerations of particle acceleration were restricted so far by tabulated values of ionization and recombination coefficients that were available only for a limited set of ions, we make use of our method developed earlier and calculate the rates of ions resembling the three representative mass groups of ultraheavy ions. We demonstrate that smaller Coulomb losses together with higher acceleration efficiency result in the enhancements of heavy and ultraheavy ions, in accordance with recent observations. We also conclude that the existing measurements of ultraheavy ions in impulsive solar energetic particle events provide evidence in favor of a magnetic turbulence in the acceleration region with spectral index $S \geq 2$.

SIMULATION OF ENERGETIC PARTICLE TRANSPORT AND ACCELERATION AT SHOCK WAVES IN A FOCUSED TRANSPORT MODEL: IMPLICATIONS FOR MIXED SOLAR PARTICLE EVENTS

Y. Y. **Kartavykh1**,2, W. Dröge1, and M. Gedalin

2016 ApJ 820 24

We use numerical solutions of the focused transport equation obtained by an implicit stochastic differential equation scheme to study the evolution of the pitch-angle dependent distribution function of protons in the vicinity of shock waves. For a planar stationary parallel shock, the effects of anisotropic distribution functions, pitch-angle dependent spatial diffusion, and first-order Fermi acceleration at the shock are examined, including the timescales on which the energy spectrum approaches the predictions of diffusive shock acceleration theory. We then consider the case that a flare-accelerated population of ions is released close to the Sun simultaneously with a traveling interplanetary shock for which we assume a simplified geometry. We investigate the consequences of adiabatic focusing in the diverging magnetic field on the particle transport at the shock, and of the competing effects of acceleration at the shock and adiabatic energy losses in the expanding solar wind. We analyze the resulting intensities, anisotropies, and energy spectra as a function of time and find that **our simulations can naturally reproduce the morphologies of so-called mixed particle events in which sometimes the prompt and sometimes the shock component is more prominent**, by assuming parameter values which are typically observed for scattering mean free paths of ions in the inner heliosphere and energy spectra of the flare particles which are injected simultaneously with the release of the shock.

Bimodal fluxes of near-relativistic electrons during the onset of solar particle events

Y. Y. **Kartavykh**, W. Dröge and B. Klecker

JGR, **2013**, Volume 118, Issue 7, pages 4005–4020

[1] We report for several solar energetic particle events (SEPs) intensity and anisotropy measurements of energetic electrons in the energy range ~27 to ~500 keV as observed with the *Wind* and ACE spacecraft in June 2000. The observations onboard *Wind* show bi-modal pitch angle distributions (PAD), whereas ACE shows PADs with one peak, as usually observed for impulsive injection of electrons at the Sun. During the time of observation *Wind* was located upstream of the Earth's bow shock, in the dawn - noon sector, at distances of ~40 to ~70 R_E from the Earth, and magnetically well connected to the quasi-parallel bow shock, whereas ACE, located at the libration point L1, was not connected to the bow shock. The electron intensity-time profiles and energy spectra show that the backstreaming electrons observed at *Wind* are not of magnetospheric origin. The observations rather suggest that the bi-modal electron PADs are due to reflection or scattering at an obstacle located at a distance of less than ~150 R_E in the anti-sunward direction, compatible with the bow shock or magnetosheath of the magnetosphere of the Earth. For a modeling of the observations we have performed transport simulations which include the effects of pitch angle diffusion, adiabatic focusing, and reflection at a boundary close to the point of observation. The results of the simulations demonstrate that the bimodal PADs are compatible with the reflection of electrons at a nearby boundary, at distances of ~70 R_E.This finding is supported by the orbital configuration and the magnetic field direction: whereas ACE is not connected, *Wind* is well connected to the magnetosphere of the Earth.

Forecasting SEP Events During Solar Cycles 23 and 24 Using Interpretable Machine Learning

Spiridon **Kasapis**, Irina N. Kitiashvili, Paul Kosovich, Alexander G. Kosovichev, Viacheslav M. Sadykov, Patrick O'Keefe, Vincent Wang
ApJ **974** 131 **2024**
https://arxiv.org/pdf/2403.02536.pdf **File**
https://iopscience.iop.org/article/10.3847/1538-4357/ad6f0e/pdf
Prediction of the Solar Energetic Particle (SEP) events garner increasing interest as space missions extend beyond Earth's protective magnetosphere. These events, which are, in most cases, products of magnetic reconnection-driven processes during solar flares or fast coronal-mass-ejection-driven shock waves, pose significant radiation hazards to aviation, space-based electronics, and particularly, space exploration. In this work, we utilize the recently developed dataset that combines the Solar Dynamics Observatory/Helioseismic and Magnetic Imager's (SDO/HMI) Space weather HMI Active Region Patches (SHARP) and the Solar and Heliospheric Observatory/Michelson Doppler Imager's (SoHO/MDI) Space Weather MDI Active Region Patches (SMARP). We employ a suite of machine learning strategies, including Support Vector Machines (SVM) and regression models, to evaluate the predictive potential of this new data product for a forecast of post-solar flare SEP events. Our study indicates that despite the augmented volume of data, the prediction accuracy reaches 0.7 +- 0.1, which aligns with but does not exceed these published benchmarks. A linear SVM model with training and testing configurations that mimic an operational setting (positive-negative imbalance) reveals a slight increase (+ 0.04 +- 0.05) in the accuracy of a 14-hour SEP forecast compared to previous studies. This outcome emphasizes the imperative for more sophisticated, physics-informed models to better understand the underlying processes leading to SEP events.

Interpretable Machine Learning to Forecast SEP Events for Solar Cycle 23

Spiridon **Kasapis**,Lulu Zhao,Yang Chen,Xiantong Wang,Monica Bobra,Tamas Gombosi
Space Weather **Volume20, Issue2** e2021SW002842 **2022**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002842
https://doi.org/10.1029/2021SW002842
We use machine learning methods to predict whether an active region (AR) which produces flares will lead to a solar energetic particle (SEP) event using Space-Weather Michelson Doppler Imager (MDI) Active Region Patches (SMARPs). This new data product is derived from maps of the solar surface magnetic field taken by the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory (SOHO). We survey the SMARP active regions associated with flares that appear on the solar disk between June 5, 1996 and August 14, 2010, label those that produced SEPs as positive and the rest as negative. The AR SMARP features that correspond to each flare are used to train two different types of machine learning methods, the support vector machines (SVMs) and the regression models. The results show that the SMARP data can predict whether a flare will lead to an SEP with accuracy (ACC) $\leq 0.72 \pm 0.12$ while allowing for a competitive leading time of 55.3 ± 28.6 minutes for forecasting the SEP events.

Characteristics of SEP Events and Their Solar Origin During the Evolution of Active Region NOAA 10069

L. K. **Kashapova**, R. Miteva, I. N. Myagkova, A. V. Bogomolov
Solar Physics January **2019**, 294:9
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1400-3.pdf **File**
We present the results of a comparative analysis of the properties of a series of successive solar flares, which occurred in active region (AR) 10069 in August 2002, and the associated solar energetic particle (SEP) events. The active region was extremely flare productive during its evolution. The solar flare characteristics are based on X-ray and radio emission data: maximum detected photon energies and spectral index, delays between microwave, metric-radio and, hard X-ray emissions. The coronal mass ejections (CMEs) are characterized by their projected speed. The SEP properties are described by the relative electron to proton abundance as well as by the abundance of lower relative to higher energy particles. The analysis carried out supports some previous results obtained by large statistical studies, but at the same time refutes others. For example, the set of analyzed events that occurred in the AR did not show clear evidence of the big flare syndrome though the large proton events observed near Earth were always accompanied by CMEs. Some of the peculiar observations could be the result of the magnetic topology of the AR. **17-24 August 2002** **Table**

Radiation Dose Nowcast for the Ground Level Enhancement on 10-11 September 2017

Ryuho **Kataoka**1,2, Tatsuhiko Sato3 , Shoko Miyake4 , Daikou Shiota5,6, and Yûki Kubo5
Space Weather, **2018**
http://sci-hub.tw/10.1029/2018SW001874
A ground level enhancement (GLE) event occurred on **10-11 September 2017**, associated with an X8.2 solar flare on the western limb of the Sun. We report the results of our manually conducted nowcast using WASAVIES (WArning System for AVIation Exposure to Solar energetic particles). The maximum radiation dose rate at a flight

altitude of 12 km was estimated to be approximately 3 μSv/h, which is less than half of the dose rate due to galactic cosmic rays. We also discuss a possible quasi-parallel shock-acceleration mechanism that may have led to the exceptionally soft proton energy spectrum as GLE events.

Radiation dose forecast of WASAVIES during ground-level enhancement

Ryuho **Kataoka**1,*, Tatsuhiko Sato2, Yûki Kubo3, Daikou Shiota4, Takao Kuwabara5, Seiji Yashiro6 andHiroshi Yasuda7
Space Weather,
Volume 12, Issue 6, pages 380–386, June **2014**

Solar energetic particles (SEPs) sometimes induce powerful air showers that significantly increase the radiation dose at flight altitudes. In order to provide information of such a space radiation hazard to aircrew, a forecast model is developed for WASAVIES (Warning System of Aviation Exposure to SEP), based on the focused transport equation of solar protons and Monte Carlo particle transport simulation of the air shower. WASAVIES gives a simple and fast way to predict the time profile of dose rate during ground-level enhancements.

Observational evidence for local particle acceleration associated with magnetically confined magnetic islands in the heliosphere – a review

Olga V. **Khabarova** 1 , Gary P. Zank 2,3, Olga E. Malandraki 4 , Gang Li 2, 3 , Jakobus A. le Roux 2,3, Gary M. Webb
Sun and Geosphere, **2017**; 12/1: 23 -30
http://newserver.stil.bas.bg/SUNGEO//00SGArhiv/SG_v12_No1_2017-pp-23-30.pdf

The occurrence of unusual energetic particle enhancements up to several MeV/nuc at leading edges of corotating interaction regions (CIRs), near the heliospheric current sheet and downstream of interplanetary shocks at 1AU has puzzled observers for a long time. Commonly accepted mechanisms of particle energization, such as a classical diffusive shock acceleration mechanism or magnetic reconnection at current sheets, are unable to explain these phenomena. We present a review of recently obtained observational results that attribute these atypical energetic particle events to local acceleration of particles in regions filled with small-scale magnetic islands confined by currents sheets of various origins. The observations are in very good accordance with the theory of stochastic particle energization in the supersonic solar wind via a sea of small-scale flux-ropes interacting dynamically (Zank et al., 2014, 2015; le Roux et al., 2015, 2016**). 07-09-1999, March 1st, 2006 , August 24-26, 2007**

Energetic Particles of keV–MeV Energies Observed near Reconnecting Current Sheets at 1 au

Olga V. **Khabarova**1 and Gary P. Zank
2017 ApJ 843 4
http://sci-hub.cc/10.3847/1538-4357/aa7686

We provide evidence for particle acceleration up to ~5 MeV at reconnecting current sheets in the solar wind based on both case studies and a statistical analysis of the energetic ion and electron flux data from the five Advanced Composition Explorer Electron, Proton, and Alpha Monitor (EPAM) detectors. The case study of a typical reconnection exhaust event reveals (i) a small-scale peak of the energetic ion flux observed in the vicinity of the reconnection exhaust and (ii) a long-timescale atypical energetic particle event (AEPE) encompassing the reconnection exhaust. AEPEs associated with reconnecting strong current sheets last for many hours, even days, as confirmed by statistical studies. The case study shows that time-intensity profiles of the ion flux may vary significantly from one EPAM detector to another partially because of the local topology of magnetic fields, but mainly because of the impact of upstream magnetospheric events; therefore, the occurrence of particle acceleration can be hidden. The finding of significant particle energization within a time interval of ±30 hr around reconnection exhausts is supported by a superposed epoch analysis of 126 reconnection exhaust events. We suggest that energetic particles initially accelerated via prolonged magnetic reconnection are trapped and reaccelerated in small- or medium-scale magnetic islands surrounding the reconnecting current sheet, as predicted by the transport theory of Zank et al. Other mechanisms of initial particle acceleration can contribute also. **2-4 Oct 2000**

SMALL-SCALE MAGNETIC ISLANDS IN THE SOLAR WIND AND THEIR ROLE IN PARTICLE ACCELERATION. II. PARTICLE ENERGIZATION INSIDE MAGNETICALLY CONFINED CAVITIES

Olga V. **Khabarova**, Gary P. Zank2,3, Gang Li2,3, Olga E. Malandraki4, Jakobus A. le Roux2,3, and Gary M. Webb2
2016 ApJ 827 122

We explore the role of heliospheric magnetic field configurations and conditions that favor the generation and confinement of small-scale magnetic islands associated with atypical energetic particle events (AEPEs) in the solar wind. Some AEPEs do not align with standard particle acceleration mechanisms, such as flare-related or simple diffusive shock acceleration processes related to interplanetary coronal mass ejections (ICMEs) and corotating interaction regions (CIRs). As we have shown recently, energetic particle flux enhancements may well originate locally and can be explained by particle acceleration in regions filled with small-scale magnetic islands with a typical width of ~0.01 au or less, which is often observed near the heliospheric current sheet (HCS). The particle energization is a consequence of magnetic reconnection-related processes in islands experiencing either merging or contraction, observed, for example, in HCS ripples. Here we provide more observations that support the idea and the theory of particle energization produced by small-scale-flux-rope dynamics (Zank et al. and Le Roux et al.). If the particles are pre-accelerated to keV energies via classical mechanisms, they may be additionally accelerated up to 1–1.5 MeV inside magnetically confined cavities of various origins. The magnetic cavities, formed by current sheets, may occur at the interface of different streams such as CIRs and ICMEs or ICMEs and coronal hole flows. They may also form during the HCS interaction with interplanetary shocks (ISs) or CIRs/ICMEs. Particle acceleration inside magnetic cavities may explain puzzling AEPEs occurring far beyond ISs, within ICMEs, before approaching CIRs as well as between CIRs.

Small-scale Magnetic Islands in the Solar Wind and Their Role in Particle Acceleration. I. Dynamics of Magnetic Islands Near the Heliospheric Current Sheet

O. **Khabarova**1, G. P. Zank2,3, G. Li2, J. A. le Roux2,3, G. M. Webb2, A. Dosch2, and O. E. Malandrak

2015 ApJ 808 181

Increases of ion fluxes in the keV–MeV range are sometimes observed near the heliospheric current sheet (HCS) during periods when other sources are absent. These resemble solar energetic particle events, but the events are weaker and apparently local. Conventional explanations based on either shock acceleration of charged particles or particle acceleration due to magnetic reconnection at interplanetary current sheets (CSs) are not persuasive. We suggest instead that recurrent magnetic reconnection occurs at the HCS and smaller CSs in the solar wind, a consequence of which is particle energization by the dynamically evolving secondary CSs and magnetic islands. The effectiveness of the trapping and acceleration process associated with magnetic islands depends in part on the topology of the HCS. We show that the HCS possesses ripples superimposed on the large-scale flat or wavy structure. We conjecture that the ripples can efficiently confine plasma and provide tokamak-like conditions that are favorable for the appearance of small-scale magnetic islands that merge and/or contract. Particles trapped in the vicinity of merging islands and experiencing multiple small-scale reconnection events are accelerated by the induced electric field and experience first-order Fermi acceleration in contracting magnetic islands according to the transport theory of Zank et al. We present multi-spacecraft observations of magnetic island merging and particle energization in the absence of other sources, providing support for theory and simulations that show particle energization by reconnection related processes of magnetic island merging and contraction.

Multispacecraft Observations of a Widespread Solar Energetic Particle Event on 2022 February 15–16

L. Y. **Khoo**1, B. Sánchez-Cano2, C. O. Lee3, L. Rodríguez-García4,5, A. Kouloumvakos6, E. Palmerio7, F. Carcaboso8, D. Lario9, N. Dresing10, C. M. S. Cohen11Show full author list

2024 ApJ 963 107

https://iopscience.iop.org/article/10.3847/1538-4357/ad167f/pdf

On **2022 February 15–16**, multiple spacecraft measured one of the most intense solar energetic particle (SEP) events observed so far in Solar Cycle 25. This study provides an overview of interesting observations made by multiple spacecraft during this event. Parker Solar Probe (PSP) and BepiColombo were close to each other at 0.34–0.37 au (a radial separation of ∼0.03 au) as they were impacted by the flank of the associated coronal mass ejection (CME). At about 100° in the retrograde direction and 1.5 au away from the Sun, the radiation detector on board the Curiosity surface rover observed the largest ground-level enhancement on Mars since surface measurements began. At intermediate distances (0.7–1.0 au), the presence of stream interaction regions (SIRs) during the SEP arrival time provides additional complexities regarding the analysis of the distinct contributions of CME-driven versus SIR-driven events in observations by spacecraft such as Solar Orbiter and STEREO-A, and by near-Earth spacecraft like ACE, SOHO, and WIND. The proximity of PSP and BepiColombo also enables us to directly compare their measurements and perform cross-calibration for the energetic particle instruments on board the two spacecraft. Our analysis indicates that energetic proton measurements from BepiColombo and PSP are in reasonable agreement with each other to within a factor of ∼1.35. Finally, this study introduces the various ongoing efforts that will collectively improve our understanding of this impactful, widespread SEP event.

Global Solar Magnetic Field and Cosmic Ray Ground Level Enhancement

G. N. **Kichigin**, M. V. Kravtsova, V. E. Sdobnov

Solar Physics September **2019**, 294:116

https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1516-5.pdf

sci-hub.se/10.1007/s11207-019-1516-5

We propose a mechanism for proton propagation from the Sun to Earth orbit in the electromagnetic field presented, in the simplest case, through the Parker model. Within this model, proton ingress on the Earth is shown possible in the case when the Earth is in the surroundings of the heliospheric current sheet neutral line (HCSNL), at the distance from the latter that is smaller than the Larmor radius of the protons drifting along the HCSNL. Based on that model, we analyzed the paths of the protons with energies characteristic of solar proton events. As a result of such an analysis, solar proton events on the Earth appear to be observed only in the case when energetic protons eject from an active region (AR) located in the northern (southern) hemisphere of the Sun, at the positive (negative) polarity of the solar global magnetic field in that AR. There is a minimal value for the proton energy below which solar proton events on the Earth are not observed. This energy value is proportional to the value for the angle of the latitude at which the flare AR is located.
Table 1 CR ground level enhancements over 1976 – 2017.

Solar Energetic Particle Events with Short and Long Onset Times

Kosuke **Kihara**, Ayumi Asai, Seiji Yashiro, Nariaki V. Nitta

ApJ **946** 21 **2023**

https://arxiv.org/pdf/2302.13541.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/acbea3/pdf

Gradual solar energetic particle (SEP) events, usually attributed to shock waves driven by coronal mass ejections (CMEs), show a wide variety of temporal behaviors. For example, TO, the >10 MeV proton onset time with respect to the launch of the CME, has a distribution of at least an order of magnitude, even when the source region is not far from the so-called well-connected longitudes. It is important to understand what controls TO, especially in the context of space weather prediction. Here we study two SEP events from the western hemisphere that are different in TO on the basis of >10 MeV proton data from the Geostationary Operations Environmental Satellite, despite similar in the CME speed and longitude of the source regions. We try to find the reasons for different TO, or proton release times, in how the CME-driven shock develops and the Alfvén Mach number of the shock wave reaches some threshold, by combining the CME height-time profiles with radio dynamic spectra. We also discuss how CME-CME interactions and active region properties may affect proton release times. **2014-04-18, 2017-07-14**

Statistical Analysis of the Relation between Coronal Mass Ejections and Solar Energetic Particles

Kosuke **Kihara**, Yuwei Huang, Nobuhiko Nishimura, Nariaki V. Nitta, Seiji Yashiro, Kiyoshi Ichimoto, Ayumi Asai

ApJ **900** 75 **2020**

https://arxiv.org/pdf/2007.08062.pdf **File**

https://doi.org/10.3847/1538-4357/aba621

To improve the forecasting capability of impactful solar energetic particle (SEP) events, the relation between coronal mass ejections (CMEs) and SEP events needs to be better understood. Here we present a statistical study of SEP occurrences and timescales with respect to the CME source locations and speeds, considering all 257 fast (vCME ≥ 900 km/s) and wide (angular width ≥ 60∘) CMEs that occurred between December 2006 and October 2017. We associate them with SEP events at energies above 10 MeV. Examination of the source region of each CME reveals that CMEs more often accompany a SEP event if they originate from the longitude of E20-W100 relative to the observer. However, a SEP event could still be absent if the CME is < 2000 km/s. For the associated CME-SEP pairs, we compute three timescales for each of the SEP events, following Kahler (2005, 2013); namely the timescale of the onset (TO), the rise time (TR), and the duration (TD). They are correlated with the longitude of the CME source region relative to the footpoint of the Parker spiral (ΔΦ) and vCME. The TO tends to be short for |ΔΦ| < 60∘ . This trend is weaker for TR and TD. The SEP timescales are only weakly correlated with vCME. Positive correlations of both TR and TD with vCME are seen in poorly connected (large |ΔΦ|) events. Additionally, TO appears to be negatively correlated with vCME for events with small |ΔΦ|. **3 Sep 2013**
Table 1. Properties of Fast and Wide CMEs and Associated SEP Events (2006-2017)
Table 2. Timescales of SEP Events

An Interpretation of a Peculiar Correlation between Proton Events and Hα-Flares in the Context of Unsteady Reconnection

Jik-Su **Kim**1, Chol-Jun Kim2,*, Chol-Min Choe2

Solar Phys. **2019** **File**

In a previous work, a specific correlation between proton events and related Hα-flares was discovered. According to that, in a Hα-flare importance diagram, Hα-flares accompanying the proton events were distributed on upper triangle of the diagram divided by the diagonal spanning SF and 3B signatures. Observational data published thereafter show the same specific correlation as in the previous work. The specific correlation has been interpreted by a competition between direct current electric field (DCEF) acceleration of ions and ion-anisotropic kinetic instability in the acceleration site through unsteady magnetic reconnection. On account of this mechanism, we can explain the observational facts that Hα-flare signatures 3N, 3F, 2F and 1F do not accompany proton events at all or almost do not and, on the contrary, the small and weak signature as SF accompanies a few proton events.

A technique for prediction of SPEs from solar radio flux by statistical analysis, ANN and GA.

Kim, K.N., Sin, S.A., Song, K.A., Kong, J.H.,
2018. Astrophys. Space Sci. 363 (8), 170.
https://doi.org/10.1007/s10509-018-3263-8
https://sci-hub.ru/10.1007/s10509-018-3263-8

Solar Radio Flux (SRF) is the significant index in easily evaluating everyday solar activities. From the statistical analysis of SRF at 2800 MHz, 1415 MHz and 610 MHz from 1976 to 1994, and only 111 Solar Proton Events (SPEs) occurring in the same period, we have given the statistical relation between them. In fact, there occurred a total of 131 SPEs in the same period, but we dealt with only 111 SPEs of them, because of lack of SRF data in SGD (2800 MHz, 1415 MHz and 610 MHz). We also discussed the possible parameters of SRF at 2800 MHz, 1415 MHz and 610 MHz for prediction of SPEs by statistical analysis, Artificial Neural Network (ANN) and Genetic Algorithm (GA) using MATLAB. In this study, we used some parameters: the daily total SRF, the overall rate of increase of SRF and SPEs.

Characteristics of Four SPE Groups with Different Origins and Acceleration Processes†

R.-S. **Kim**, K.-S. Cho, S.-C. Bong, A. D. Joshi, Y.-D. Park, J. Lee
JGR Volume 120, Issue 9 Pages 7083–7093 **2015**
http://onlinelibrary.wiley.com/doi/10.1002/2015JA021280/epdf

Solar proton events (SPEs) can be categorized into four groups based on their associations with flare or CME inferred from onset timings as well as acceleration patterns using multienergy observations. In this study, we have investigated whether there are any typical characteristics of associated events and acceleration sites in each group using 42 SPEs from 1997 to 2012. We find: (i) if the proton acceleration starts from a lower energy, a SPE has a higher chance to be a strong event (> 5000 pfu) even if its associated flare and/or CME are not so strong. The only difference between the SPEs associated with flare and CME is the location of the acceleration site. (ii) For the former (Group A), the sites are very low (~ 1 Rs) and close to the western limb, while the latter (Group C) have relatively higher (mean=6.05 Rs) and wider acceleration sites. (iii) When the proton acceleration starts from the higher energy (Group B), a SPE tends to be a relatively weak event (< 1000 pfu), although its associated CME is relatively stronger than previous groups. (iv) The SPEs categorized by the simultaneous acceleration in whole energy range within 10 minutes (Group D), tend to show the weakest proton flux (mean=327 pfu) in spite ofstrong associated eruptions. Based on those results, we suggest that the different characteristics of SPEs are mainly due to the different conditions of magnetic connectivity and particle density, which are changed with longitude and height as well as their origin. **Table 1 Characteristics of SPEs and Associated Solar Eruptive Events**
1998-05-02, 2000-07-22, 2002-04-17, 2001-04-02

A refined classification of SPEs based on the multi-energy channel observations†

R.-S. **Kim**1, K.-S. Cho1, J. Lee2, S.-C. Bong2 andY.-D. Park
JGR, **119,** 9419 **2014**
http://onlinelibrary.wiley.com/doi/10.1002/2014JA020358/pdf

We have investigated characteristics of solar proton events (SPEs) and their association with other types of solar eruption using **42 SPEs** observed with SOHO/ERNE detector from 1997 to 2012. A velocity dispersion analysis was performed to correctly estimate the onset times of proton flux increase at the solar vicinity. These SPE onset times were compared with those of associated flares, coronal mass ejections (CMEs) and interplanetary (IP) type II radio bursts. We found: (i) the proton flux of 13 SPEs (31%) increase during the flare X-ray intensity is increasing, and the rest 29 SPEs (69%) show onsets well coincident with the first appearance of CMEs in LASCO field-of-view. (ii) All flare-associated SPEs show the flux enhancements starting from the lower energy, while the CME-associated SPEs show the flux enhancements starting from either the higher or the lower energies. In the other events the flux enhancement occurs simultaneously at all energies within 10 minutes. (iii) For the former, large flux enhancements occur in a short time, while the latter tend to show relatively weak and slow flux enhancements. Our classification uses two criteria, SPE onset timing relative to flares and energy-dependent flux enhancement, unlike the conventional classification of SPEs based on whether the flux time profile is impulsive or gradual. Nevertheless our classification scheme refines the distinction between the flare-associated SPEs and the CME-associated SPEs in terms of the onset timing. Additional information on the proton acceleration as implied by the energy dependent patterns of flux enhancement is briefly discussed. **4 November 1997**
Table 1. Timing of SPEs and related solar eruptive phenomena

Comparative studies of hard X-ray spectral evolution in solar flares with high energy proton events observed at earth,

Kiplinger, A.

(**1995**), Astrophys. J., 453, 973.

http://articles.adsabs.harvard.edu/pdf/1995ApJ...453..973K

This paper presents the results of two extensive studies of hard X-ray spectral evolution in solar flares and their associations with energetic interplanetary proton events. The focus of this work is to establish the degree to which events that display progressively hardening hard X-ray spectra, at any time and over all observable timescales, are associated with high-energy interplanetary proton events. The first study examined a sample of 152 hard X-ray flares well observed with the HXRBS instrument on the Solar Maximum Mission (SMM). The study showed that 22 events revealed a progressive spectral hardening either over flux peaks (i.e., a soft-hard- harder spectral evolution) or during flux decays and that 18 of these 22 events (82%) had associated 10 MeV proton events or enhancements. Conversely, the absence of spectral hardening is associated with the absence of interplanetary protons with 124 of the 130 remaining flares (95.4%). Since the hard X-ray counting rate threshold of the first study was sufficiently high (5000 counts s-1) to exclude many flares (more than 36%) associated with the largest interplanetary proton events, a second study was conducted using 193 less intense HXRBS events (a one out of three sample) and their associations with only large proton events. This study also identifies events with progressive spectral hardening. It also employs selection criteria suggested by the results of the first study to "predict" which flares would or would not have associated large proton events. This prescription for "predicting" proton events did so correctly for four large (SESC qualified) proton events, missed none, and produced only one "false alarm" in which the criteria were met but only a small proton event was seen at earth. Thus, a correct "prediction" was made for all but one of the 193 events. The results of the first study are then combined with the weighted results of the one out of three study, using the same selection criteria, to project correctly predicted associations of 22 out of 23 SESC events, for a 96% success rate, while 700 out of 708 flares were projected to be correct rejections with no associated proton events. The data suggest that progressive hardening is a diagnostic of high-energy particle acceleration of electrons and of protons and that it is not a manifestation of the "big flare syndrome" which asserts that the largest flares are associated with many or most known phenomena. There also appears to be an approximate relationship between the timescales (FWHM) of progressively hardening X-ray peaks and the cube of the interplanetary peak proton fluxes. The strong associations of particular hard X-ray characteristics and interplanetary proton events are of interest both on physical grounds and because the techniques employed can be directly adapted into a practical means of predicting which events are most likely to be associated with large interplanetary proton events that pose threats to humans in space and to spacecraft. **7 Dec 1982, 13 May 1983, 16 Dec 1988**

Tables 1980-1989

GYROSURFING ACCELERATION OF IONS IN FRONT OF EARTH's QUASI-PARALLEL BOW SHOCK

Arpad **Kis**1,5, Oleksiy Agapitov2,6, Vladimir Krasnoselskikh2, Yuri V. Khotyaintsev3, Iannis Dandouras4, Istvan Lemperger1, and Viktor Wesztergom

2013 ApJ 771 4

It is well known that shocks in space plasmas can accelerate particles to high energies. However, many details of the shock acceleration mechanism are still unknown. A critical element of shock acceleration is the injection problem; i.e., the presence of the so called seed particle population that is needed for the acceleration to work efficiently. In our case study, we present for the first time observational evidence of gyroresonant surfing acceleration in front of Earth's quasi-parallel bow shock resulting in the appearance of the long-suspected seed particle population. For our analysis, we use simultaneous multi-spacecraft measurements provided by the Cluster spacecraft ion (CIS), magnetic (FGM), and electric field and wave instrument (EFW) during a time period of large inter-spacecraft separation distance. The spacecraft were moving toward the bow shock and were situated in the foreshock region. The results show that the gyroresonance surfing acceleration takes place as a consequence of interaction between circularly polarized monochromatic (or quasi-monochromatic) transversal electromagnetic plasma waves and short large amplitude magnetic structures (SLAMSs). The magnetic mirror force of the SLAMS provides the resonant conditions for the ions trapped by the waves and results in the acceleration of ions. Since wave packets with circular polarization and different kinds of magnetic structures are very commonly observed in front of Earth's quasi-parallel bow shock, the gyroresonant surfing acceleration proves to be an important particle injection mechanism. We also show that seed ions are accelerated directly from the solar wind ion population.

Relationships between the Spectra of near-Earth Proton Enhancements, Hard X-Ray Bursts, and CME Speeds

V.I. **Kiselev** _ N.S. Meshalkina _V.V. Grechnev

Solar Phys. **297**, Article number: 53 **2022** **File**

https://doi.org/10.1007/s11207-022-01986-7

Some studies propose the transfer of flare-accelerated protons in an erupting ux rope until its reconnection with an open structure releases the trapped protons. Coulomb collisions in the dense flux-rope body deplete the low-energy part of the proton spectrum. On the other hand, shock-acceleration progressively replenishes this spectral part. These processes form a double power-law proton spectrum that is usually observed in the Earth orbit. We analyze the correlations between the slopes of near-Earth proton spectra below and above the break energy, on the one hand, and photon indices of the corresponding hard X-ray (HXR) bursts and speeds of associated coronal mass ejections (CMEs), on the other hand. We use catalogs of proton events in 1991–2006, HXR spectra obtained by Yohkoh and the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI), and CME catalogs. Significant correlations have been found between the proton spectral slopes i) above the break energy and HXR spectral indices (0.86), and ii) below the break energy and CME speeds (-0:75). The results indicate a statistical predominance of flare-acceleration at higher proton energies and shock-acceleration at their lower energies. The highest-energy proton spectra reconstructed in ground-level events exhibit the second break with a steepest slope above it. Neither this slope nor the second-break energy correlates with any other parameter. This particularity needs understanding.

2000-11-26

THE SHOCK WAVE DEVELOPMENT IN A MAJOR SOLAR ERUPTIVE EVENT RESPONSIBLE FOR GLE63

Valentin **Kiselev**, Victor Grechnev, Arcadiy Uralov, Alexey Kochanov

Second VarSITI General Symposium (VarSITI-**2017**)

http://varsiti2017.iszf.irk.ru/presentations/VarSITI%20Abstracts.pdf

The 26 December 2001 solar eruptive event produced a strong particle flux and groundlevel enhancement of cosmic-ray intensity (GLE63). This solar event associated with a moderate flare and fast coronal mass ejection (CME) was not comprehensively studied because of insufficient observations. We analyze the shock-wave excitation in this event and its posterior evolution. We found that two blast-wave-like shocks appeared during the flare impulsive phase. The first strong wavelike disturbance was impulsively excited by the main eruption close to the CME onset time. The second one was produced by a jet-like eruption five minutes later. Each wave rapidly steepened into a shock due to a steep falloff of the fast-mode speed away from the eruption region. Signatures of type II radio bursts indicate two different shock fronts following each other. The two shock waves eventually merged around the radial direction into a single shock. It was traced up to 25 solar radii as a spherical halo ahead of the expanding CME body, and a calculated trajectory of the type II emission matches its total evolution from 80 MHz to 150 kHz. Properties found for the shock wave indicate its intermediate regime between the blast wave and bow shock in the LASCO field of view. This shock-wave history updates a widely accepted view on a CME-driven shock: the shock wave actually appears earlier, being able to accelerate particles to high energies during the flare rise.

The 26 December 2001 solar event responsible for Ground Level Enhancement 63

V. **Kiselev**1, V. Grechnev

The 26th IUGG General Assembly June 22 **-** July 2, **2015**, Prague

The 26 December 2001 solar eruptive event was moderate in its manifestations (M7.1, peak microwave flux of 4000 sfu at 9.4 GHz, CME with a speed of 1446 km/s), but produced a big proton event and GLE63. In order to find a possible reason for the atypically high proton productivity of this event, we have studied it from multi-wavelength imaging and non-imaging data, including dynamic radio spectra, and quantitatively reconciled all of the findings with each other. The data indicate an additional eruption, which probably occurred from the same active region about half an hour before the major eruption. The major eruption(s) produced one or two blast-wave-like shocks during the impulsive phase of the flare. The traces of the impulsively excited shock wave were clearly observed in white light up to 25 solar radii as a halo in front of the expanding CME structures. The shape of the halo perfectly corresponded to a conic section. The shock wave ahead of the CME at these distances was, most likely, in an intermediate regime between the blast wave and the bow shock. The results show that i) the shock wave appeared during the flare rise, being able to accelerate particles considerably earlier than it is usually assumed in the CME-driven bow shock hypothesis; ii) during the major event, a flare ribbon intruded into a region above the sunspot umbra that seems to be typical of big particle events; iii) an additional possible reason for the high proton outcome of this event could be the preceding extra eruption, which stretched closed magnetic structures above the developing CME, thus facilitating its lift-off, enabling its higher speed and a stronger shock ahead it, and facilitating escape of flare-accelerated particles.

Strong non-radial propagation of energetic electrons in solar corona
A. **Klassen**, N. Dresing, R. Gómez-Herrero, B. Heber, and A. Veronig
A&A 614, A61 **2018**
http://www.ieap.uni-kiel.de/et/people/klassen/32041_Klassen.pdf
https://www.aanda.org/articles/aa/pdf/2018/06/aa32041-17.pdf
Analyzing the sequence of solar energetic electron events measured at both STEREO-A (STA) and STEREO-B (STB) spacecraft during **17-21 July 2014**, when their orbital separation was 34?, we found evidence of a strong non-radial electron propagation in the solar corona below the solar wind source surface. The impulsive electron events were associated with recurrent flare and jet (hereafter flare/jet) activity at the border of an isolated coronal hole situated close to the solar equator. We have focused our study on the solar energetic particle (SEP) event on **17 July 2014**, during which both spacecraft detected a similar impulsive and anisotropic energetic electron event suggesting optimal connection of both spacecraft to the parent particle source, despite the large angular separation between the parent flare and the nominal magnetic footpoints on the source surface of STA and STB of 68? and 90?, respectively. Combining the remote-sensing extreme ultraviolet (EUV) observations, in-situ plasma, magnetic field, and energetic particle data we investigated and discuss here the origin and the propagation trajectory of energetic electrons in the solar corona. We find that the energetic electrons in the energy range of 55-195 keV together with the associated EUV jet were injected from the flare site toward the spacecraft?s magnetic footpoints and propagate along a strongly non-radial and inclined magnetic field below the source surface. From stereoscopic (EUV) observations we estimated the inclination angle of the jet trajectory and the respective magnetic field of 63? ? 11? relative to the radial direction. We show how the flare accelerated electrons reach very distant longitudes in the heliosphere, when the spacecraft are nominally not connected to the particle source. This example illustrates how ballistic backmapping can occasionally fail to characterize the magnetic connectivity during SEP events. This finding also provides an additional mechanism (one among others), which may explain the origin of widespread SEP events.
CESRA #1992 Oct **2018** http://cesra.net/?p=1992

Unexpected spatial intensity distributions and onset timing of solar electron events observed by closely spaced STEREO spacecraft
A. **Klassen**1, N. Dresing1, R. Gomez-Herrero2, B. Heber1, R. Muller-Mellin1
A&A 593, A31 **2016**
http://www.ieap.uni-kiel.de/et/people/klassen/Klassen_28734.pdf
We present multi-spacecraft observations of four solar electron events using measurements from the Solar Electron Proton Telescope (SEPT) and the Electron Proton Helium INstrument (EPHIN) on board the STEREO and SOHO spacecraft, respectively, occurring between 11 October 2013 and 1 August 2014, during the approaching superior conjunction period of the two STEREO spacecraft. At this time the longitudinal separation angle between STEREO-A (STA) and STEREO-B (STB) was less than 72_. The parent particle sources (flares) of the four investigated events were situated close to, in between, or to the west of the STEREO's magnetic footpoints. The STEREO measurements revealed a strong di_erence in electron peak intensities (factor _12) showing unexpected intensity distributions at 1 AU, although the two spacecraft had nominally nearly the same angular magnetic footpoint separation from the flaring active region (AR) or their magnetic footpoints were both situated eastwards from the parent particle source. Furthermore, the events detected by the two STEREO imply a strongly unexpected onset timing with respect to each other: the spacecraft magnetically best connected to the flare detected a later arrival of electrons than the other one. This leads us to suggest the concept of a rippled peak intensity distribution at 1 AU formed by narrow peaks (fingers) superposed on a quasi-uniform Gaussian distribution. Additionally, two of the four investigated solar energetic particle (SEP) events show a so-called circumsolar distribution and their characteristics make it plausible to suggest a two-component particle injection scenario forming an unusual, non-uniform intensity distribution at 1AU. **11 October 2013. 25 February 2014. 1 August 2014**
See RHESSI Science Nuggets #279 July **2016** **October 11, 2013**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Unexpected_intensity_distributions_of_solar_electrons_in_the_heliosphere

Intensity distribution and onset delays of nearly relativistic electron events observed by closely-spaced STEREO spacecraft
Andreas **Klassen**∗1 , Nina Dresing , Ra´ul G´omez-Herrero , Bernd Heber , and Reinhold Mueller-Mellin
CESRA **2016** p.60
http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v3.pdf
We present multi-spacecraft observations of four solar electron events using measurements from the Solar Electron Proton Telescope (SEPT) and the Electron Proton Helium INstrument (EPHIN) onboard the STEREO and SOHO spacecraft, respectively, occurring between 11 October 2013 and 1 August 2014, during the approaching superior conjunction period of the two STEREO spacecraft. At this time the longitudinal separation angle between STEREO-

A (STA) and STEREO-B (STB) was less than 72◦. The parent particle sources (flares) of the four investigated events were situated close to, in between, or to the west of the STEREO's magnetic footpoints. The STEREO measurements revealed a strong difference in electron peak intensities (factor 12) showing non-expected intensity distributions at 1 AU, although the two spacecraft had nominally nearly the same angular magnetic footpoint separation to the flaring active region (AR) or their magnetic footpoints were both situated eastwards from the parent particle source. Furthermore, the events detected at the two STEREO imply a strongly unexpected onset timing with respect to each other: i.e. the spacecraft, best connected to the flare, detected a later arrival of electrons than the farther separated one. These facts led us to suggest a concept of a rippled peak intensity distribution at 1 AU formed by narrow peaks (fingers) superposed on a quasi-uniform Gaussian distribution. Additionally, two of four investigated solar energetic particle (SEP) events show a so-called circumsolar distribution and their characteristics make it plausible to suggest a two-component particle injection scenario forming an unusual, non-uniform intensity distribution at 1 AU.

First simultaneous observations of a near-relativistic electron spike event by both STEREO spacecraft

A. **Klassen**, N. Dresing, R. G?mez-Herrero, B. Heber

A&A 580, A115 **2015**

http://www.ieap.uni-kiel.de/et/people/klassen/Klassen_25700.pdf

Solar electron spike events are a special subclass of near-relativistic electron events characterized by their short duration, symmetric time profile, and their strong anisotropic pitch angle distribution. All previous studied events were only observed by a single spacecraft. For the first time, we present measurements of this kind of an electron spike event that was observed simultaneously by both close- spaced STEREO spacecraft on **2 May 2014**. The longitudinal separation angle between STEREO-A (STA) and STEREO-B (STB) was 38◦ . The spikes at STA and STB are characterized by very short durations of ≤ 12 minutes at full-width at half maximum (FWHM) and almost identical and symmetric time profiles. They exhibit similar properties in durations, pitch angle distributions (PADs), energy spectra, and peak intensities. The spike parent source was situated close to the STA nominal magnetic footpoint and was separated by 48 ◦ from STB?s footpoint. The intensity distribution and the relative onset timing behaved opposite to what is expected: STB measured a higher intensity and an earlier onset than the nominally better connected STA. We suggest that the spike electrons undergo a substantial nonradial injection into interplanetary (IP) space from the parent source, a flaring active region (AR), and propagate in a strong nonradial diverging magnetic field. In addition we show that because of the spike properties it is evident that, irrespective of how the electrons were injected into the IP medium, the en route particle scattering conditions along the paths to STA and STB were very similar. Evidently both s/c detected different parts of the same beam whose angular extension was at least 38◦ at 1 AU, comparable to the longitudinal separation between STA and STB.

Solar origin of in-situ near-relativistic electron spikes observed with SEPT/STEREO

A. **Klassen**, R. G?mez-Herrero, B. Heber, Y. Kartavykh, W. Dr?ge, K.-L. Klein

E-print, April **2012**; A&A

During 2010 - 2011 the Solar Electron Proton Telescope (SEPT) onboard the twin STEREO spacecraft detected a number of typical impulsive electron events showing a prompt intensity onset followed by a long decay, as well as several near-relativistic so-called electron spike events. These spikes are characterized by a very short duration of below 10 - 20 min at FWHM, almost symmetric time profiles, velocity dispersion and strong anisotropy, revealing a very weak scattering during particle propagation from the Sun to STEREO. Spikes are detected at energies below 300 keV and appear simulateneously with type III radio bursts detected by SWAVES/STEREO and narrow EUV jets in active regions. Using particle, EUV and radio imaging observations we found that nearrelativistic electrons were accelerated simultaneously and at the same location as the electrons emitting the accompanying type III radio bursts and together with coronal EUV jets. Furthermore, the sources of type III radio bursts match very well the locations and the trajectories of the associated EUV jet. Applying a particle propagation model we demonstrate that the spike characteristics reflect both, properties of the accelerator and effects of interplanetary propagation.

26 February 2011, 19 March 2011

Electron Spikes, Type III Radio Bursts and EUV Jets on 22 February 2010

A. **Klassen**, R. Gómez-Herrero and B. Heber

Solar Physics, Volume 273, Number 2, 413-419, **2011**

http://www.ieap.uni-kiel.de/et/people/klassen/SOLA1454R1_Klassen_vers_III.pdf

The Solar Electron Proton Telescope on board the twin STEREO spacecraft measures electrons and ions in the energy range from 30 to above 400 keV with an energy resolution better than 10%. On **22 February 2010** during a short interval of 100 minutes, a sequence of impulsive energetic electron events in the range below 120 keV was observed with the STEREO-A/SEPT instrument. Each of the four events was associated with a type III radio burst and a narrow EUV jet. All the events show nearly symmetric “spike”-like time profiles with very short durations ≃ 5 min. The estimated electron injection time for each individual event shows a small time delay between the electron spike and the corresponding type III radio emission and a close coincidence with an EUV jet. These observations reveal the existence of spike-like electron events showing nearly “scatter-free” propagation from the Sun to STEREO-A. From the time coincidence we infer that the mildly relativistic electrons are accelerated at the same time and at the same location as the accompanying type III emitting electrons and coronal EUV jets. The characteristics of the spikes reflect the injection and acceleration profiles in the corona rather than interplanetary propagation effects.

The almost monoenergetic ion event on 19 October 2009: SEPT/STEREO observations

A. **Klassen**1, R. Gómez-Herrero1, R. Müller-Mellin1, B. Heber1, R. F. Wimmer-Schweingruber1, A. Opitz2 and J.-A. Sauvaud2

A&A 528, A84 (**2011**)

http://www.ieap.uni-kiel.de/et/people/klassen/14563.pdf

The Solar Electron and Proton Telescope (SEPT) on board the twin spacecraft STEREO A and B measures electrons and ions in the energy range from 60 to above 400 keV with an energy resolution of 10%. On 19 October 2009, when STEREO-B was already 1.03 AU away from the Earth, a strong and prolonged almost monoenergetic ion event has been observed with the SEPT instrument. The event lasted 27 min and its energy spectrum contained a strong narrow peak at 235 keV with a relative full width at half maximum of 0.35. The event occurred during a period of slow solar wind in front of a weak ion increase associated with a distant corotating interaction region (CIR). Previously similar events containing spectral peaks were detected in the vicinity of the Earth’s magnetosphere using observations on Interball-1 and on both STEREO A & B spacecraft.
We present evidence that the narrow spectral peak is caused by a quasi-monoenergetic ion beam and suggest that the particles were accelerated at a distant CIR or CIR shock. We discuss the possible mechanisms that could be responsible for accelerating these ions: the shock drift acceleration, the surfatron mechanism and the acceleration in a large-scale electrostatic field.

Solar energetic electrons related to the 28 October 2003 flare

A. **Klassen**,1 S. Krucker,2 H. Kunow,1 R. Mu¨ ller-Mellin,1 R. Wimmer-Schweingruber,1
G. Mann,3 and A. Posner4

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, A09S04, doi:10.1029/2004JA010910, **2005**

Timing and electron energy spectrum analysis suggest that there are three separate stages of electron injection into interplanetary space: (1) An injection of radio type III–producing electrons is observed first; (2) an impulsive injection with an almost symmetric time profile with a short duration (_18 min) is released _11 min later, followed by (3) a gradual, long (>1 hour) lasting injection, with an onset _25 min after the first type III burst. While the first escaping type III–producing electrons are more likely related to the reconnection processes during the impulsive flare phase, the association of the two delayed electron injections with solar events is not well understood.

Current understanding of SEP acceleration and propagation **Review**

B. **Klecker**

2013, J. Phys.: Conf. Ser. 409, 012015, **File**

The solar energetic particle (SEP) populations of electrons and ions are highly variable in space and time, in intensity, energy, and composition. Over the last ~20 years advanced instrumentation onboard many spacecraft (e.g. ACE, Coronas, GOES, Hinode, RHESSI, SAMPEX, SDO, SOHO, STEREO, TRACE, Ulysses, Yokoh, to name a few) extended our ability to explore the characteristics of solar energetic particles by in-situ measurements in interplanetary space and by observing their source characteristics near the Sun by remote-sensing observation of electromagnetic emission over a wide frequency range. These measurements provide crucial information for understanding the sources of the particle populations and the acceleration and propagation processes involved. We are now able to measure intensity-time profiles and anisotropies, energy spectra, elemental and isotopic abundances, and the ionic charge of particles over an extended energy range of 0.01 to several 100 MeV/nuc and for a large dynamic range of particle intensities. Furthermore, multi-spacecraft in-situ observations at different solar longitudes and latitudes provide new insight into the acceleration and propagation processes of SEPs near the Sun and in interplanetary space. In this paper we present an overview of SEP observations, their implications for SEP acceleration and propagation processes, and discuss open questions.

ENERGETIC PARTICLE OBSERVATIONS

Report of Working Group C

B. **KLECKER**[1,*], H. KUNOW[2], H. V. CANE[3], S. DALLA[4], B. HEBER[2], K. KECSKEMETY[5], K.-L. KLEIN[6], J. KOTA[7], H. KUCHAREK[8], D. LARIO[9], M. A. LEE[8], M. A. POPECKI[8], A. POSNER[10], J. RODRIGUEZ-PACHECO[11], T. SANDERSON[12], G. M. SIMNETT[13], and E. C. ROELOF

Space Science Reviews (**2006**) 123: 217–250

https://link.springer.com/content/pdf/10.1007/s11214-006-9018-9.pdf

The characteristics of solar energetic particles (SEP) as observed in interplanetary space provide fundamental information about the origin of these particles, and the acceleration and propagation processes at the Sun and in interplanetary space. Furthermore, energetic particles provide information on the development and structure of coronal mass ejections as they propagate from the solar corona into the interplanetary medium. In this paper we review the measurements of energetic particles in interplanetary space and discuss their implication for our understanding of the sources, and of acceleration and propagation processes.

SOLAR ENERGETIC PARTICLE CHARGE STATES: AN OVERVIEW **Review**

B. **KLECKER**[1,*], E. M¨ OBIUS[2] and M. A. POPECKI[2]

Space Science Reviews (**2006**) 124: 289–301

https://link.springer.com/content/pdf/10.1007/s11214-006-9111-0.pdf

The ionic charge distributions of solar energetic particles (SEP) as observed in interplanetary space provide fundamental information about the origin of these particles, and the acceleration and propagation processes at the Sun and in interplanetary space. In this paper we review the measurements of ionic charge states of energetic particles in interplanetary space and discuss their implication for our understanding of SEP sources, and acceleration and propagation processes.

The relativistic solar particle event on 28 October 2021: Evidence of particle acceleration within and escape from the solar corona⋆

Karl-Ludwig **Klein**1,2, Sophie Musset1,3, Nicole Vilmer1,2, Carine Briand1,2, Säm Krucker4,5, Andrea Francesco Battaglia4,6, Nina Dresing7, Christian Palmroos7 and Dale E. Gary8

A&A 663, A173 (**2022**)

https://www.aanda.org/articles/aa/pdf/2022/07/aa43903-22.pdf **File**

Aims. We analyse particle, radio, and X-ray observations during the first relativistic proton event of solar cycle 25 detected on Earth. The aim is to gain insight into the relationship between relativistic solar particles detected in space and the processes of acceleration and propagation in solar eruptive events.

Methods. To this end, we used ground-based neutron monitor measurements of relativistic nucleons and space-borne measurements of electrons with similar speed to determine the arrival times of the first particles at 1 AU and to infer their solar release times. We compared the release times with the time histories of non-thermal electrons in the solar atmosphere and their escape to interplanetary space, as traced by radio spectra and X-ray light curves and images.

Results. Non-thermal electrons in the corona are found to be accelerated in different regions. Some are confined in closed magnetic structures expanding during the course of the event. Three episodes of electron escape to the interplanetary space are revealed by groups of decametric-to-kilometric type III bursts. The first group appears on the low-frequency side of a type II burst produced by a coronal shock wave. The two latter groups are accompanied at higher frequencies by bursts with rapid drifts to both lower and higher frequencies (forward- or reverse-drifting bursts). They are produced by electron beams that propagate both sunward and anti-sunward. The first relativistic electrons and nucleons observed near Earth are released with the third group of type III bursts, more than ten minutes after the first signatures of non-thermal electrons and of the formation of the shock wave in the corona. Although the eruptive active region is near the central meridian, several tens of degrees east of the footpoint of the nominal Parker spiral to the Earth, the kilometric spectrum of the type III bursts and the in situ detection of Langmuir waves demonstrate a direct magnetic connection between the L1 Lagrange point and the field lines onto which the electron beams are released at the Sun.

Conclusions. We interpret the forward- and reverse-drifting radio bursts as evidence of reconnection between the closed expanding magnetic structures of an erupting flux rope and ambient open magnetic field lines. We discuss the origin of relativistic particles near the Earth across two scenarios: (1) acceleration at the CME-driven shock as it intercepts interplanetary magnetic field lines rooted in the western solar hemisphere and (2) an alternative where the relativistic particles are initially confined in the erupting magnetic fields and get access to the open field lines to the Earth through these reconnection events.

Radio astronomical tools for the study of solar energetic particles II.Time-extended acceleration at subrelativistic and relativistic energies **Review**

Karl-Ludwig **Klein1***

Front. Astron. Space Sci. Volume 7, id.93 **2020** **File**
https://doi.org/10.3389/fspas.2020.580445
https://www.frontiersin.org/articles/10.3389/fspas.2020.580445/full
Solar energetic particle (SEP) events are commonly separated in two categories: numerous 'impulsive' events of relatively short duration, and a few 'gradual' events, where SEP-intensities may stay enhanced over several days at energies up to several tens of MeV. In some gradual events the SEP spectrum extends to relativistic energies (> 1 GeV), over shorter durations. The two categories are strongly related to an idea developed in the 1960s based on radio observations: Type III bursts, which were addressed in a companion chapter, outline impulsive acceleration of electrons to subrelativistic energies, while the large and the relativistic SEP events were ascribed to a second acceleration process. At radio wavelengths, typical counterparts were bursts emitted by electrons accelerated at coronal shock waves (type II bursts) and by electron populations in large-scale closed coronal structures (type IV bursts). Both burst types
are related to coronal mass ejections (CMEs). Type II bursts from metric to kilometric wavelengths tend to accompany large SEP events, which is widely considered as a confirmation that CME-driven shocks accelerate the SEPs. But type II bursts, especially those related to SEP events, are most often accompanied by type IV bursts, where the electrons are rather accelerated in the wake of the CME. Individual event studies suggest that although the CME shock is the most plausible accelerator of SEPs up to some yet unknown limiting energy, the relativistic SEP events show time structure that rather points to coronal acceleration related to type IV bursts. This chapter addresses the question what type II bursts tell us about coronal shock waves and how type II and type IV radio bursts are related with relativistic proton signatures as seen by particle detectors on the Earth and by their gamma-ray emission in the solar atmosphere, focusing on two relativistic SEP events, on **2005 Jan 20** and **2017 Sep 10**. The importance of radio emissions as a complement to the upcoming SEP observations from close to the Sun is underlined. **1989 Sep 29**

Radio astronomical tools for the study of solar energetic particles I. Correlations and diagnostics of impulsive acceleration and particle propagation **Review**
Karl-Ludwig **Klein**
Front. Astron. Space Sci. Volume 7, id.105 **2020**
https://doi.org/10.3389/fspas.2020.580436
https://www.frontiersin.org/articles/10.3389/fspas.2020.580436/full **File**
Solar energetic particles (SEPs) are sporadically ejected from the Sun during flares and coronal mass ejections. They are of major astrophysical interest, because the proximity of the Sun allows for detailed multi-messenger studies. They affect space weather due to interactions with electronics, with the Earth's atmosphere, and with humans if they leave the protective shield of the magnetosphere of the Earth. Since early studies in the 1950s, starting with particle detectors on the ground, SEP events have been related to radio bursts.Two subjects are addressed in this chapter: attempts to establish quantitative correlations between SEPs and microwave bursts produced by gyro synchrotron radiation of mildly relativistic electrons, and the information derived from type III radio bursts on impulsive processes of particle acceleration and the coronal and interplanetary propagation. Type III radio bursts produced by electron beams on open magnetic field lines have a wide range of applications, including the identification of acceleration regions, the identification of confined particle acceleration with coronal signatures, but no SEPs, and the paths that the electrons, and energetic charged particles in general, take to travel from the low corona to the Heliosphere in case they escape. Simple scenarios of coronal particle acceleration are confirmed in relatively simple and short events. But the comparison with particle transport models shows that longer and delayed acceleration episodes exist especially in large SEP events. They will be discussed in a companion chapter. **2 Apr 1995, 7 Apr 1997, 6 Nov 1997, 1 May 2000, 26 Dec 2001, 5 Nov 2011**

OBSERVATION OF PARTICLE ACCELERATION IN THE SOLAR CORONA WITH NEUTRON MONITORS AND RADIO INSTRUMENTS
K.-L. **Klein**1
SF2A-2019: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. Eds.: P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot, **2019**, pp.271-274
http://sf2a.eu/proceedings/2019/2019sf2a.conf..0271K.pdf
In the attempt to identify regions and mechanisms of relativistic proton acceleration at the Sun, we compare the arrival of the first particles at Earth, measured by neutron monitors, with radio signatures of electron acceleration in the corona. The first proton arrival is often, but not always, delayed with respect to the early radio signatures at the Sun. But the release at the Sun always occurs at times when the radio emission is ongoing. This is in line with earlier studies of individual events, which made us conclude that relativistic protons are accelerated in flare-like processes related to magnetic reconnection or turbulence in the wake of a coronal mass ejection, rather than at the shocks driven by the ejected magnetic stuctures. **2006 Dec 13**

Table 1. Onset times and onset-time delays of GLEs.

Combined observations of neutron monitors and radio instruments to elucidate processes of particle acceleration in the corona

K.-L. **Klein**

NMDB Meeting, 5–7 March **2019**, Athens, Greece

http://cosray.phys.uoa.gr/images/Input_for_NMDB_Meeting/ABSTRACT_BOOK__F_compressed_.pdf

The origin of solar energetic particles (SEPs) detected in space is often traced back to transient processes related to flares and coronal mass ejections (CMEs). Based on in situ measurements, it has been considered by a large part of the scientific community that the acceleration of particles of any energy by coronal shock waves driven by fast CMEs is the key process, while flares are supposed to be the accelerators of numerous, but small SEP events with relatively low particle energies. While the idea is attractive and most plausible to explain the long-lasting SEP events observed at relatively low energies (MeV to tens of MeV), it is also extrapolated to the highest energies, including Ground-Level Enhancements observed by neutron monitors. This extrapolation has, however, no observational justification whatsoever. This talk will summarise the arguments put forward for the shock acceleration of GLEs and address the difficulties to obtain observational evidence. I will then discuss the relevance of radio observations, which show electron acceleration at greater altitudes and over longer durations than the widely used hard X-ray diagnostics. It will be argued that although the radio emissions come mostly from electrons of rather low energies (some keV to tens of keV), their timing bears relationships with the neutron monitor signatures, especially with the two-part structure revealed recently by Moraal, McCracken and coworkers. This suggests that ***time-extended acceleration in the post-CME coroa, related to magnetic reconnection or turbulence, is also a plausible accelerator of the most energetic nucleons that can be accelerated during solar eruptions.***

X-Ray, Radio and SEP Observations of Relativistic Gamma-Ray Events **Review**

Karl-Ludwig **Klein**, Kostas Tziotziou, Pietro Zucca, Eino Valtonen, Nicole Vilmer, Olga E. Malandraki, Clarisse Hamadache, Bernd Heber, and Jürgen Kiener

In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 8, **2018**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf

File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf

The rather frequent occurrence, and sometimes long duration, of - ray events at photon energies above 100 MeV challenges our understanding of particle acceleration processes at the Sun. The emission is ascribed to pion-decay photons due to protons with energies above 300 MeV. We study the X-ray and radio emissions and the solar energetic particles (SEPs) in space for a set of 25 Fermi -ray events. They are accompanied by strong SEP events, including, in most cases where the parent activity is well-connected, protons above 300 MeV. Signatures of energetic electron acceleration in the corona accompany the impulsive and early post-impulsive -ray emission. -ray emission lasting several hours accompanies in general the decay phase of long-lasting soft X-ray bursts and decametric-tokilometric type II bursts. We discuss the impact of these results on the origin of the -ray events. **1982 Jun 3, 11 June 1991, 7 March 2011, 23 Jan 2012, 7 March 2012, 16-17 May 2012, 3 June 2012, 11 Apr 2013, 25 Feb 2014, 1 Sept 2014**

Eruptive Activity Related to Solar Energetic Particle Events **Review**

Karl-Ludwig **Klein**

In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 2, p. 27-44, **2018**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf

File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf

Solar energetic particle events are associated with solar activity, especially flares and coronal mass ejections (CMEs). In this chapter a basic introduction is presented to the nature of flares and CMEs. Since both are manifestations of evolving magnetic fields in the solar corona, the chapter starts with a qualitative description of the magnetic structuring and electrodynamic coupling of the solar atmosphere. Flares and the radiative manifestations of energetic particles, i.e. bremsstrahlung, gyrosynchrotron and collective plasma emission of electrons, and nuclear gamma-ray emission are briefly presented. Observational evidence on the particle acceleration region in flares is given, as well as a very elementary qualitative overview of acceleration processes. Then CMEs, their origin and their association with shock waves are discussed, and related particle acceleration processes are briefly described.

Acceleration and propagation of Solar Energetic Particles **Review**

Karl-Ludwig **Klein**, Silvia Dalla

Space Science Reviews Volume 212, Issue 3–4, pp 1107–1136 **2017 File**
https://arxiv.org/pdf/1705.07274.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0382-4.pdf
Solar Energetic Particles (SEPs) are an important component of Space Weather, including radiation hazard to humans and electronic equipment, and the ionisation of the Earth's atmosphere. We review the key observations of SEPs, our current understanding of their acceleration and transport, and discuss how this knowledge is incorporated within Space Weather forecasting tools. Mechanisms for acceleration during solar flares and at shocks driven by Coronal Mass Ejections are discussed, as well as the timing relationships between signatures of solar eruptive events and the detection of SEPs in interplanetary space. Evidence on how the parameters of SEP events are related to those of the parent solar activity is reviewed and transport effects influencing SEP propagation to near-Earth locations are examined. Finally, the approaches to forecasting Space Weather SEP effects are discussed. We conclude that both flare and CME shock acceleration contribute to Space Weather relevant SEP populations and need to be considered within forecasting tools. **1980 June 08**, 2005 January 20

Radio emission and relativistic proton acceleration in the large solar particle event of 20 Jan 2005

Karl-Ludwig **Klein** and Sophie Masson
Highlights of Solar Radio Physics 1/**2015 File**
http://www.lesia.obspm.fr/cesra/highlights/highlight15-1.html
Enhanced fluxes of solar energetic particles (SEP) - so-called SEP events - result from processes of explosive energy conversion in the corona, notably flares and coronal mass ejections. The highest energies of solar energetic nucleons detected in space or through gamma-ray emission in the solar atmosphere are in the GeV range. Where and how the particles are accelerated is still controversial. The most debated candidate processes are related to magnetic reconnection and to the shock wave driven by a fast coronal mass ejection (CME).
We search for observational indications on the acceleration site of relativistic protons in SEP events, via a comparative analyses of their timing, observed by neutron monitors on the Earth, and electromagnetic emissions of the associated eruptive solar activity. This is usually a difficult task, because the time profiles of the SEPs at 1 AU have been strongly smeared-out by the propagation in the turbulent interplanetary magnetic field. Since the scattering cross section is smaller at relativistic than at lower energies, relativistic proton events, also called ground-level enhancements (GLEs), give the best chance to observe a temporal relationship. It is probably for this reason that two successive pulses could be distinguished in the proton time profile of the 20 Jan 2005 GLE. We studied the first pulse in Masson et al. (2009), and the second in a recent publication (Klein et al., 2014). Here we give a brief outline of the results.

The relativistic solar particle event of 2005 January 20: prompt and delayed particle acceleration

K.-L. **Klein**, S. Masson, C. Bouratzis, V. Grechnev, A. Hillaris, P. Preka-Papadema
A&A**,** Volume 572, id.A4, 8 pp. **2014**
http://arxiv.org/pdf/1403.2260v1.pdf ; **File**
The highest energies of solar energetic nucleons detected in space or through gamma-ray emission in the solar atmosphere are in the GeV range. Where and how the particles are accelerated is still controversial. We search for observational evidence on the acceleration region(s) by comparing the timing of relativistic protons detected at Earth and radiative signatures in the solar atmosphere. To this end a detailed comparison is undertaken of the double-peaked time profile of relativistic protons, derived from the worldwide network of neutron monitors during the large particle event of 2005 January 20, with UV imaging and radio petrography over a broad frequency band from the low corona to interplanetary space. We show that both relativistic proton releases to interplanetary space were accompanied by distinct episodes of energy release and electron acceleration in the corona traced by the radio emission and by brightenings of UV kernels in the low solar atmosphere. ***The timing of electromagnetic emissions and relativistic protons suggests that the first proton peak was related to the acceleration of gamma-ray emitting protons during the impulsive flare phase, as shown before. The second proton peak occurred together with signatures of magnetic restructuring in the corona after the CME passage. We attribute the acceleration to reconnection and possibly turbulence in large-scale coronal loops.*** While type II radio emission was observed in the high corona, there is no evidence of a temporal relationship with the relativistic proton acceleration.

Particle Acceleration and Propagation in Strong Flares without Major Solar Energetic Particle Events

K.-L. **Klein** · G. Trottet · S. Samwel · O. Malandraki
Solar Phys (**2011**) 269: 309–333; **File**

Solar energetic particles (SEPs) detected in space are statistically associated with flares and coronal mass ejections (CMEs). But it is not clear how these processes actually contribute to the acceleration and transport of the particles. The present work addresses the question why flares accompanied by intense soft X-ray bursts may not produce SEPs detected by observations with the GOES spacecraft. We consider all **X-class** X-ray bursts between 1996 and 2006 from the western solar hemisphere. 21 out of 69 have no signature in GOES proton intensities above 10 MeV, despite being significant accelerators of electrons, as shown by their radio emission at cm wavelengths. The majority (11/20) has no type III radio bursts from electron beams escaping towards interplanetary space during the impulsive flare phase. Together with other radio properties, this indicates that the electrons accelerated during the impulsive flare phase remain confined in the low corona. This occurs in flares with and without a CME. Although GOES saw no protons above 10 MeV at geosynchronous orbit, energetic particles were detected in some (4/11) confined events at Lagrangian point L1 aboard ACE or SoHO. These events have, besides the confined microwave emission, dm-m wave type II and type IV bursts indicating an independent accelerator in the corona. Three of them are accompanied by CMEs. **We conclude that the principal reason why major solar flares in the western hemisphere are not associated with SEPs is the confinement of particles accelerated in the impulsive phase. A coronal shock wave or the restructuring of the magnetically stressed corona, indicated by the type II and IV bursts, can explain the detection of SEPs when flare-accelerated particles do not reach open magnetic field lines. But the mere presence of these radio signatures, especially of a metric type II burst, is not a sufficient condition for a major SEP event.**
Tables.

Energetic Particle Acceleration and Propagation in Strong CME-Less Flares

K.-L. **Klein** · G. Trottet · A. Klassen

Solar Phys (**2010**) **263**: 185–208, DOI 10.1007/s11207-010-9540-5; **File**

Flares and coronal mass ejections (CMEs) contribute to the acceleration and propagation of solar energetic particles (SEP) detected in the interplanetary space, but the exact roles of these phenomena are yet to be understood. We examine two types of energetic particle tracers related with 15 CME-less flares that emit bright soft X-ray bursts (GOES X class): radio emission of flare-accelerated electrons and *in situ* measurements of energetic electrons and protons near 1 AU. The CME-less flares are found to be vigorous accelerators of microwave-emitting electrons, which remain confined in low coronal structures. This is shown by unusually steep low-frequency microwave spectra and by lack of radio emission from the middle and high corona, including dm –m wave type IV continua and metre-tohectometre type III bursts. The confinement of the particles accelerated in CME-less flares agrees with the magnetic field configuration of these events inferred by others. Two events produced isolated metric type II bursts revealing coronal shock waves. None of the seven flares in the western hemisphere was followed by enhanced particle fluxes in the GOES detectors, but one, which was accompanied by a type II burst, caused a weak SEP event detected at SoHO and ACE. Three of the CME-less flares were followed within some hours by SEP-associated flares from the same active region. These SEP-producing events were clearly distinct from the CME-less ones by their association with fast and broad CMEs, dm –m wave radio emission, and intense DH type III bursts. ***We conclude that radio emission at decimetre and longer waves is a reliable indication that flare-accelerated particles have access to the high corona and interplanetary space. The absence of such emission can be used as a signal that no SEP event is to be expected despite the occurrence of a strong soft X-ray burst.***

Open magnetic flux tubes in the corona and the transport of solar energetic particles

Karl-Ludwig **Klein**1, S¨am Krucker2, Guillaume Lointier1,3, and Alain Kerdraon1

File 2008, A&A, 486, 589-596 (**2008**)
http://www.aanda.org.sci-hub.cc/articles/aa/abs/2008/29/aa9228-07/aa9228-07.html

We investigate how magnetic fields guide energetic particles through the corona into interplanetary space and eventually to a spacecraft near the Earth. A set of seven simple particle events is studied, where energetic electrons (30-500 keV; *Wind* spacecraft) or protons (5-55 MeV; SoHO) were released together with low-energy electron beams producing metric-to-kilometric type III emission. Imaging of the coronal (metre-wave) part of this emission with the Nanc¸ay Radioheliograph is used to identify the open flux tubes that guide these electrons - and by inference all particles detected at 1 AU. Open coronal field lines are also computed using potential magnetic field extrapolations, constrained by a source surface and by SoHO/MDI measurements in the photosphere (code by Schrijver and DeRosa). We find that in all events the type III radio sources lie in open flux tubes in the potential magnetic field extrapolations. The open flux tubes are rooted in small parts of the parent active region, covering a heliocentric angle of a few degrees in the photosphere. *But they expand rapidly above the neighbouring closed* *magnetic structures and cover several tens of degrees in longitude on the source surface. Some of these open field lines are found to connect the parent active region to the footpoint of the nominal Parker spiral on the source surface, within the uncertainty of about ±10◦ inherent to the evaluation of its connection longitude.* This is so even when the parent active region is as far as 50◦ away. In two cases where the coronal flux tubes point to high heliolatitudes, the detection of Langmuir waves at the *Wind* spacecraft in the ecliptic plane suggests that the interplanetary field lines curve down to the ecliptic before reaching 1 AU. *We conclude that non-radial open flux tubes in the corona can transport particles over several tens of degrees in longitude even in simple impulsive particle events. In all events we studied, potential magnetic field models give an adequate description of these structures.*

HIGH-ENERGY PARTICLES AT AND FROM THE SUN
Karl-Ludwig **Klein**1
SF2A **2007** J. Bouvier, A. Chalabaev, C. Charbonnel (eds)
http://sf2a.eu/proceedings/2007/2007sf2a.conf..0007K.pdf
Non thermal particles up to relativistic energies contain a large fraction of the energy released during solar activity, especially flares and coronal mass ejections. The Sun gives us a unique opportunity to observe radiative signatures of these particles at time scales relevant to their acceleration, to measure in space those particles which escape from the Sun, and to image the environment where the particles are accelerated. Shock waves of coronal mass ejections and magnetic reconnection during flares are the most plausible origins of energetic particle populations. The paper outlines recent work with emphasis on the French Solar-Terrerstrial Physics community. **15 Apr 2001, 20 Feb 2002**

The High Energy Solar Corona: Waves, Eruptions, Particles **Book**
Karl-Ludwig **Klein**, Alexander L. MacKinnon (Eds.)
Lecture Notes in Physics (LNP), volume 725, **2007**
https://link.springer.com/book/10.1007%2F978-3-540-71570-2

Radio bursts and solar energetic particle events.
Klein, K.-L.:
2006, In: Gopalswamy, N., Mewaldt, R., Torsti, J. (eds.) Solar Eruptions and Energetic Particles, AGU Monograph 165, American Geophysical Union, Washington DC, 233 – 244.

The onset of solar energetic particle events: Prompt release of deka-MeV protons and associated coronal activity,
Klein, K.-L., and A. Posner
(**2005**), Astron. Astrophys., 438, 1029.
https://ui.adsabs.harvard.edu/link_gateway/2005A%26A...438.1029K/PUB_PDF
Between 1996 and 2002, the COSTEP particle instrument aboard the SoHO mission observed 18 solar energetic particle events where the release times of protons up to 54 MeV could be determined to within an uncertainty of about ten minutes, and where metre wave imaging observations with the Nançay Radioheliograph were available. In six of them the proton release starts, within the uncertainty of the method, simultaneously with the release of electron beams observed through their type III emission at decametric-to-kilometric wavelengths, during flares in Hα or EUV. These well-connected events are studied to identify the coronal processes that occur when the particle release starts at the Sun. Given that big events are not reliably measured by COSTEP due to its large geometric factor, they are rather weak with peak intensities (9× 10-4- 5 × 10-2) [(cm2 s sr MeV)-1] in the (8-25) MeV range. All are accompanied by fast (400-1300 km s-1) and narrow coronal mass ejections (CMEs). While half of the events is accompanied by significant microwave bursts, the other half shows little or no evidence of electron acceleration in the low corona and rather weak soft X-ray bursts. The association with weak flares may point to different acceleration sites of the interacting and the escaping particles. From the radio observations of the type III bursts and the associated metre wave emission, the escaping electrons, and by inference also the first escaping protons, are accelerated roughly between 0.1 R_⊙ and 0.5 R_⊙ above the photosphere, a height range shown to be well behind the front of the CMEs at the time of acceleration. The data show no evidence that the shock waves, which are presumably driven by at least the fastest of these CMEs, participate in the early acceleration of the escaping protons or affect the escape of the protons accelerated at lower height.

Coronal electron acceleration and relativistic proton production during the 14 July 2000 flare and CME
Klein, K. -L.; Trottet, G.; Lantos, P.; Delaboudinière, J. -P.
Astronomy and Astrophysics, v.373, p.1073-1082 (**2001**)

https://www.aanda.org/articles/aa/pdf/2001/27/aa1241.pdf
The large solar flare of **14 July 2000** 10 UT occurred in an active region near the central meridian. It was accompanied by the eruption of a filament and a rapid halo-type coronal mass ejection (CME). Large particle fluxes were detected up to relativistic energies at 1 AU. In this paper accelerated particles and plasma structures in the corona are traced using radio, X-ray, EUV and visible light observations, together with neutron monitor measurements of relativistic protons at 1 AU. Both the bulk of the radio emission at decimetric and longer waves and the escape of suprathermal electrons and relativistic protons from the Sun were delayed by 10-20 min with respect to the hard X-ray emission. Despite the delay and the association with a flare near the central meridian the neutron monitor time profile was impulsive. We show that the escape of the relativistic protons occurred in time coincident both with a coronal shock wave, which may be the bow shock of the CME, and with radio sources which trace electron acceleration and **magnetic field reconfiguration in the western hemisphere**. Three observations support the idea **that the relativistic protons were accelerated during this reconfiguration, at heights between 0.1 and 1 R_sun above the photosphere, and not in the flaring active region or at the bow shock of the CME**: (i) the rise of the neutron monitor count rates is simultaneous with the brightening of a new continuum radio source; (ii) the duration of the continuum emission is similar to the rise time of the neutron monitor count rates; (iii) the radio source is close to the Earth-connected interplanetary magnetic field line.

The origin of solar energetic particle events: Coronal acceleration versus shock wave acceleration.

Klein, K.-L., Trottet, G.:
2001, Space Sci. Rev. 95, 215 – 225.
https://link.springer.com/content/pdf/10.1023%2FA%3A1005236400689.pdf
We review evidence that led to the view that acceleration at shock waves driven by coronal mass ejections (CMEs) is responsible for large particle events detected at 1 AU. It appears that even if the CME bow shock acceleration is a possible model for the origin of rather low energy ions, it faces difficulties on account of the production of ions far above 1 MeV: (i) although shock waves have been demonstrated to accelerate ions to energies of some MeV nucl−1 in the interplanetary medium, their ability to achieve relativistic energies in the solar environment is unproven; (ii) SEP events producing particle enhancements at energies ≥100 MeV are also accompanied by flares; those accompanied only by fast CMEs have no proton signatures above 50 MeV. We emphasize detailed studies of individual high energy particle events which **provide strong evidence that time-extended particle acceleration which occurs in the corona after the impulsive flare contributes to particle fluxes in space**. It appears thus that the CME bow shock scenario has been overvalued and that **long lasting coronal energy release processes have to be taken into account** when searching for the origin of high energy SEP events.

Coronal electron acceleration and relativistic proton production during the 14 July 2000 flare and CME

Klein, K. -L.; Trottet, G.; Lantos, P.; Delaboudinière, J. -P.
Astronomy and Astrophysics, v.373, p.1073-1082 (**2001**)
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The large solar flare of **14 July 2000** 10 UT occurred in an active region near the central meridian. It was accompanied by the eruption of a filament and a rapid halo-type coronal mass ejection (CME). Large particle fluxes were detected up to relativistic energies at 1 AU. In this paper accelerated particles and plasma structures in the corona are traced using radio, X-ray, EUV and visible light observations, together with neutron monitor measurements of relativistic protons at 1 AU. Both the bulk of the radio emission at decimetric and longer waves and the escape of suprathermal electrons and relativistic protons from the Sun were delayed by 10-20 min with respect to the hard X-ray emission. Despite the delay and the association with a flare near the central meridian the neutron monitor time profile was impulsive. We show that the escape of the relativistic protons occurred in time coincident both with a coronal shock wave, which may be the bow shock of the CME, and with radio sources which trace electron acceleration and **magnetic field reconfiguration in the western hemisphere**. Three observations support the idea **that the relativistic protons were accelerated during this reconfiguration, at heights between 0.1 and 1 R_sun above the photosphere, and not in the flaring active region or at the bow shock of the CME**: (i) the rise of the neutron monitor count rates is simultaneous with the brightening of a new continuum radio source; (ii) the duration of the continuum emission is similar to the rise time of the neutron monitor count rates; (iii) the radio source is close to the Earth-connected interplanetary magnetic field line.

Flare-associated energetic particles in the corona and at 1 AU

Klein, K. -L. ; Chupp, E. L. Trottet, G. ; Magun, A. ; Dunphy, P. P. ; Rieger, E. ; Urpo, S.
Astronomy and Astrophysics, v.348, p.271-285 (**1999**)
https://articles.adsabs.harvard.edu/pdf/1999A%26A...348..271K
It is widely believed that the longest lasting and most energetic solar energetic particle events (SEPs) observed in interplanetary space result from acceleration by the bow shocks of coronal mass ejections (CMEs). Using gamma-

ray, X-ray and radio diagnostics of interacting particles and spaceborne and ground-based detection of >=20 MeV protons at 1 AU during two large events (**1989 September 29 and October 19**), we demonstrate that time-extended acceleration processes in the low and middle corona, far behind the CME, leave their imprints in the proton intensity time profiles in interplanetary space for one to several hours after the onset of the flare: (1) New increases of >=20 MeV proton fluxes at 1 AU can be traced back to episodes of coronal acceleration. (2) Increasing richness of relativistic protons observed at 1 AU in the course of the SEPs is associated with new coronal particle injection after the impulsive phase. (3) Particle injection sites enabling a rapid access to the well-connected magnetic field line, as required by the SEP time profile, exist in the middle corona even if the nominal Hα flare location is far away. These findings suggest that contrary to the prevalent view acceleration processes in the low and middle corona supply both interacting and at least part of the interplanetary particles. The association of the most proton-rich component of the SEPs with delayed low-frequency radio emission is consistent with ionization state studies of SEPs, in that both require acceleration in a tenuous plasma. We conclude that the complexity of the corona provides the ingredients for the acceleration of particles and their injection into a large range of heliocentric angles. The CME may play the role of a trigger or even contribute to the buildup of magnetic stresses in the corona, but its bow shock is not the main accelerator of the high-energy protons.

Global Positioning System Energetic Particle Data: The Next Space Weather Data Revolution

Delores J. **Knipp**, Barbara L. Giles

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Synthesis of Geomagnetically Induced Currents: Commentary and Research

Delores J. **Knipp**

Space Weather 13, 727-729, **2015**

http://onlinelibrary.wiley.com/doi/10.1002/2015SW001317/epdf

Space Weather Quarterly Volume 12, Issue 4, p. 4-6, **2015**

http://onlinelibrary.wiley.com/doi/10.1002/SWQv12i004/epdf

Geomagnetically induced currents (GICs) have been the bane of technology-dependent societies
The highest concern for GICs is presently associated with regional high-voltage power grids
This collection brings together a broad group of papers highlighting the societal relevance of GICs

Source Regions of the Interplanetary Magnetic Field and Variability in Heavy-ion Elemental Composition in Gradual Solar Energetic Particle Events

Yuan-Kuen **Ko**1, Allan J. Tylka2, Chee K. Ng3, Yi-Ming Wang1, and William F. Dietrich

2013 ApJ 776 92

Gradual solar energetic particle (SEP) events are those in which ions are accelerated to their observed energies by interactions with a shock driven by a fast coronal mass ejection (CME). Previous studies have shown that much of the observed event-to-event variability can be understood in terms of shock speed and evolution in the shock-normal angle. However, an equally important factor, particularly for the elemental composition, is the origin of the suprathermal seed particles upon which the shock acts. To tackle this issue, we (1) use observed solar-wind speed, magnetograms, and the potential-field source-surface model to map the Sun-L1 interplanetary magnetic field (IMF) line back to its source region on the Sun at the time of the SEP observations and (2) then look for a correlation between SEP composition (as measured by Wind and Advanced Composition Explorer at ~2-30 MeV nucleon–1) and characteristics of the identified IMF source regions. The study is based on 24 SEP events, identified as a statistically significant increase in ~20 MeV protons and occurring in 1998 and 2003-2006, when the rate of newly emergent solar magnetic flux and CMEs was lower than in solar-maximum years, and the field-line tracing is therefore more likely to be successful. We find that the gradual SEP Fe/O is correlated with the field strength at the IMF source, with the largest enhancements occurring when the footpoint field is strong due to the nearby presence of an active region (AR). In these cases, other elemental ratios show a strong charge-to-mass (q/M) ordering (at least on average), similar to that found in impulsive events. Such results lead us to suggest that magnetic reconnection in footpoint regions near ARs bias the heavy-ion composition of suprathermal seed ions by processes qualitatively similar to those that produce larger heavy-ion enhancements in impulsive SEP events. To address potential technical concerns about our analysis, we also discuss efforts to exclude impulsive SEP events from our event sample.

A Comparative Study of Ground-level Enhancement Events of Solar Energetic Particles

Leon **Kocharov**1, Alexander Mishev1,2, Esa Riihonen3, Rami Vainio3, and Ilya Usoskin1,2

2023 ApJ 958 122

https://iopscience.iop.org/article/10.3847/1538-4357/acfee8/pdf **File**

Major solar eruptions can accelerate protons up to relativistic energies. Solar relativistic ions arriving at 1 au may cause a solar particle event detectable by the worldwide network of neutron monitors (NMs), a ground-level enhancement (GLE) event. Using the newly computed NM yield function, we have fitted the **15 historic GLEs**. Moments of the fitted proton distributions are used for the analysis. Profiles of the proton net flux are very diverse, while some profiles are similar. For this study, we select two events with similar time profiles, GLE 60 (**2001 April 15**) and GLE 65 (**2003 October 28**), and ask what makes these GLEs similar. We compare the GLEs with their progenitor solar flares and coronal mass ejections (CMEs). We find a close relationship between the rise and peak of the GLE, on the one hand, and the solar flare and the metric radio emissions from extended coronal sources at the base of the CME, on the other hand. The GLE decay time, the rate of the proton spectrum evolution, and the CME speed are proportional to the duration of the soft X-ray flare. We compare the two GLEs with GLE 59 (**2000 July 14**) analyzed by Klein et al. and with the deka-MeV nucleon−1 proton and helium data from the ERNE instrument on the Solar and Heliospheric Observatory spacecraft. ***The comparison indicates that a single solar eruption can produce more than one component of solar energetic particles, differently contributing at different energies and locations.***

Multiple Sources of Solar High-energy Protons

Leon **Kocharov**1,2, Nicola Omodei3, Alexander Mishev1,2, Melissa Pesce-Rollins4, Francesco Longo5,6, Sijie Yu7, Dale E. Gary7, Rami Vainio8, and Ilya Usoskin1,2

2021 ApJ 915 12

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https://doi.org/10.3847/1538-4357/abff57

During the 24th solar cycle, the Fermi Large Area Telescope (LAT) has observed a total of 27 solar flares possessing delayed γ-ray emission, including the exceptionally well-observed flare and coronal mass ejection (CME) on 2017 September 10. Based on the Fermi/LAT data, we plot, for the first time, maps of possible sources of the delayed >100 MeV γ-ray emission of the 2017 September 10 event. The long-lasting γ-ray emission is localized under the CME core. The γ-ray spectrum exhibits intermittent changes in time, implying that more than one source of high-energy protons was formed during the flare–CME eruption. We find a good statistical correlation between the γ-ray fluences of the Fermi/LAT-observed delayed events and the products of corresponding CME speed and the square root of the soft X-ray flare magnitude. Data support the idea that both flares and CMEs jointly contribute to the production of subrelativistic and relativistic protons near the Sun.

Interplanetary Protons versus Interacting Protons in the 2017 September 10 Solar Eruptive Event

Leon **Kocharov**1, Melissa Pesce-Rollins2, Timo Laitinen3, Alexander Mishev1,4, Patrick Kühl5, Andreas Klassen5, Meng Jin6,7, Nicola Omodei8, Francesco Longo9,10, David F. Webb11

2020 ApJ 890 13 **File**

sci-hub.si/10.3847/1538-4357/ab684e

https://iopscience.iop.org/article/10.3847/1538-4357/ab684e/pdf

We analyze the relativistic proton emission from the Sun during the eruptive event on 2017 September 10, which caused a ground-level enhancement (GLE 72) registered by the worldwide network of neutron monitors. Using the neutron monitor data and interplanetary transport modeling both along and across interplanetary magnetic field (IMF) lines, we deduce parameters of the proton injection into the interplanetary medium. The inferred injection profile of the interplanetary protons is compared with the profile of the >100 MeV γ-ray emission observed by the Fermi Large Area Telescope, attributed to pion production from the interaction of >300 MeV protons at the Sun. GLE 72 started with a prompt component that arrived along the IMF lines. This was followed by a more prolonged enhancement caused by protons arriving at the Earth across the IMF lines from the southwest. The interplanetary proton event is modeled using two sources—one source at the root of the Earth-connected IMF line and another source situated near the solar western limb. The maximum phase of the second injection of interplanetary protons coincides with the maximum phase of the prolonged >100 MeV γ-ray emission that originated from a small area at the solar western limb, below the current sheet trailing the associated coronal mass ejection (CME). A possible common source of interacting protons and interplanetary protons is discussed in terms of proton acceleration at the CME bow shock versus coronal (re-)acceleration in the wake of the CME.

Spatial Organization of Seven Extreme Solar Energetic Particle Events

Leon **Kocharov**1, Silja Pohjolainen2, Mike J. Reiner3,4, Alexander Mishev5, Haimin Wang6,7, Ilya Usoskin1,5, and Rami Vainio8
2018 ApJL 862 L20
http://sci-hub.tw/http://iopscience.iop.org/article/10.3847/2041-8213/aad18d/meta
https://iopscience.iop.org/article/10.3847/2041-8213/aad18d/pdf
Emission of relativistic protons and helium responsible for extreme solar particle events (ground level enhancements (GLEs)) is often structured. We investigate its organization depending on the eruption stage characterized by the heliocentric height of associated coronal mass ejections (CMEs). Seven GLEs are considered: events on **1997 November 6, 1998 May 2, 2000 July 14, 2001 December 26, 2003 November 2, 2006 December 13, and 2012 May 17**, which are half of the SOlar and Heliospheric Observatory (SOHO)-era GLEs, excluding very weak events. Count-rate profiles of the GLEs plotted as a function of the CME height reveal two types (or two components) of the high-energy particle emission. The first component rises in a step-like manner during the CME transit from 2 R ⊙ to 3 R ⊙, when the CME exits from predominantly closed coronal magnetic structures, irrespective of the CME speed (type H). This component is of coronal origin. The second component of the GLE-producing particles starts to rise when CME is at about 4 R ⊙, achieves its maximum at 6–10 R ⊙, and declines shortly after that (type J). The type J particle injection into the interplanetary space coincides with the decametric–hectometric radio burst complex that includes enhanced emission of type II and concurrent low-frequency type III bursts, indicative of the CME interaction with a streamer-like structure at a few solar radii from the Sun. Those could be delayed particles from the flare region. A possible additional contribution of the CME-bow-shock acceleration in unstructured solar wind is not large in the two considered types of events.

Investigating the Origins of Two Extreme Solar Particle Events: Proton Source Profile and Associated Electromagnetic Emissions

Leon **Kocharov**1, Silja Pohjolainen2, Alexander Mishev3, Mike J. Reiner4, Jeongwoo Lee5,6, Timo Laitinen7, Leonid V. Didkovsky8, Victor J. Pizzo9, Roksoon Kim10, Andreas Klassen11 …
2017 ApJ 839 79
http://iopscience.iop.org.sci-hub.cc/0004-637X/839/2/79/
https://iopscience.iop.org/article/10.3847/1538-4357/aa6a13/pdf
We analyze the high-energy particle emission from the Sun in two extreme solar particle events in which protons are accelerated to relativistic energies and can cause a significant signal even in the ground-based particle detectors. Analysis of a relativistic proton event is based on modeling of the particle transport and interaction, from a near-Sun source through the solar wind and the Earth's magnetosphere and atmosphere to a detector on the ground. This allows us to deduce the time profile of the proton source at the Sun and compare it with observed electromagnetic emissions. The **1998 May 2** event is associated with a flare and a coronal mass ejection (CME), which were well observed by the Nançay Radioheliograph, thus the images of the radio sources are available. For the **2003 November 2** event, the low corona images of the CME liftoff obtained at the Mauna Loa Solar Observatory are available. Those complementary data sets are analyzed jointly with the broadband dynamic radio spectra, EUV images, and other data available for both events. We find a common scenario for both eruptions, including the flare's dual impulsive phase, the CME-launch-associated decimetric-continuum burst, and the late, low-frequency type III radio bursts at the time of the relativistic proton injection into the interplanetary medium. The analysis supports the idea that the two considered events start with emission of relativistic protons previously accelerated during the flare and CME launch, then trapped in large-scale magnetic loops and later released by the expanding CME.

COMPARATIVE MORPHOLOGY OF SOLAR RELATIVISTIC PARTICLE EVENTS

Leon **Kocharov**1, Andreas Klassen2, Eino Valtonen3, Ilya Usoskin1,4, and James M. Ryan
2015 ApJ 811 L9
Time profiles of the 0.25–10 MeV electrons and the ~(0.1–1) GeV nucleon−1 protons and helium associated with two solar coronal mass ejections (CMEs) are analyzed with a newly formulated method based on modeling of the particle transport in the interplanetary medium. With the modeling, we fit the observed angular distribution of solar particles and infer, for a particular particle instrument and magnetic field orientation, the time delay of the particle registration at 1 AU in respect to the solar source. Then, after the time offset removal, intensity re-normalization and background equalization, the time–intensity profiles of high-energy protons, helium and electrons in different energy channels are superposed and compared. The comparison reveals episodes of remarkable coincidence of different profiles, as well as episodes of essentially different behavior. It implies at least three sources of solar high-energy particles operating in a single event. The first, short-duration source emits electrons next to the flare's impulsive phase and CME liftoff. The second source gradually rises and continues for more than an hour, emitting electrons and lower energy protons, which is consistent with shock acceleration on open magnetic field lines extending to solar wind. An another, third source is the main source of relativistic ions in space. It is retarded in respect to the flare's impulsive phase and may be associated with a structure encountered by the shock within a few solar radii from the Sun.

Solar Interacting Protons Versus Interplanetary Protons in the Core Plus Halo Model of Diffusive Shock Acceleration and Stochastic Re-acceleration

L. **Kocharov**1, T. Laitinen2, R. Vainio3, A. Afanasiev3, K. Mursula4, and J. M. Ryan

2015 ApJ 806 80

https://iopscience.iop.org/article/10.1088/0004-637X/806/1/80/pdf

With the first observations of solar γ-rays from the decay of pions, the relationship of protons producing ground level enhancements (GLEs) on the Earth to those of similar energies producing the γ-rays on the Sun has been debated. These two populations may be either independent and simply coincident in large flares, or they may be, in fact, the same population stemming from a single accelerating agent and jointly distributed at the Sun and also in space. Assuming the latter, we model a scenario in which particles are accelerated near the Sun in a shock wave with a fraction transported back to the solar surface to radiate, while the remainder is detected at Earth in the form of a GLE. Interplanetary ions versus ions interacting at the Sun are studied for a spherical shock wave propagating in a radial magnetic field through a highly turbulent radial ray (the acceleration core) and surrounding weakly turbulent sector in which the accelerated particles can propagate toward or away from the Sun. The model presented here accounts for both the first-order Fermi acceleration at the shock front and the second-order, stochastic re-acceleration by the turbulence enhanced behind the shock. We find that the re-acceleration is important in generating the γ-radiation and we also find that up to 10% of the particle population can find its way to the Sun as compared to particles escaping to the interplanetary space.

Transmission and Emission of Solar Energetic Particles in Semi-transparent Shocks

Leon **Kocharov**1, Timo Laitinen2, Ilya Usoskin1,3, and Rami Vainio

2014 ApJ 787 L21

While major solar energetic particle (SEP) events are associated with coronal mass ejection (CME)-driven shocks in solar wind, accurate SEP measurements reveal that more than one component of energetic ions exist in the beginning of the events. Solar electromagnetic emissions, including nuclear gamma-rays, suggest that high-energy ions could also be accelerated by coronal shocks, and some of those particles could contribute to SEPs in interplanetary space. However, the CME-driven shock in solar wind is thought to shield any particle source beneath the shock because of the strong scattering required for the diffusive shock acceleration. In this Letter, we consider a shock model that allows energetic particles from the possible behind-shock source to appear in front of the shock simultaneously with SEPs accelerated by the shock itself. We model the energetic particle transport in directions parallel and perpendicular to the magnetic field in a spherical shock expanding through the highly turbulent magnetic sector with an embedded quiet magnetic tube, which makes the shock semi-transparent for energetic particles. The model energy spectra and time profiles of energetic ions escaping far upstream of the shock are similar to the profiles observed during the first hour of some gradual SEP events.

The Effect of Turbulence Intermittence on the Emission of Solar Energetic Particles by Coronal and Interplanetary Shocks

Leon **Kocharov**1, Timo Laitinen2, and Rami Vainio

2013 ApJ 778 L5

Major solar energetic particle events are associated with shock waves in solar corona and solar wind. Fast scattering of charged particles by plasma turbulence near the shock wave increases the efficiency of the particle acceleration in the shock, but prevents particles from escaping ahead of the shock. However, the turbulence energy levels in neighboring magnetic tubes of solar wind may differ from each other by more than one order of magnitude. We present the first theoretical study of accelerated particle emission from an oblique shock wave propagating through an intermittent turbulence background that consists of both highly turbulent magnetic tubes, where particles are accelerated, and quiet tubes, via which the accelerated particles can escape to the non-shocked solar wind. The modeling results imply that the presence of the fast transport channels penetrating the shock and cross-field transport of accelerated particles to those channels may play a key role in high-energy particle emission from distant shocks and can explain the prompt onset of major solar energetic particle events observed near the Earth's orbit.

NON-STANDARD ENERGY SPECTRA OF SHOCK-ACCELERATED SOLAR PARTICLES

Leon **Kocharov**1, Rami Vainio1, Jens Pomoell1, Eino Valtonen2, Andreas Klassen3, and C. Alex Young

2012 ApJ 753 87

We consider a numerical model for the shock acceleration of energetic ions in the magnetic environment of the solar corona. The model is motivated by observations of the deka-to-hecto-MeV proton energy spectra, ion and electron timing, and abundances in the beginning of major solar energetic particle (SEP) events, prior to the event's main phase associated with coronal mass ejection (CME) driven shock in the solar wind. Inasmuch as the obliquity of the CME-liftoff-associated shocks in solar corona and hence the seed-particle supply for the shock acceleration are essentially time dependent, a steady state energy spectrum of accelerated protons near the shock could not be attained. Energy spectrum of the SEP emission depends on the spatial and energy distribution of seed particles for the coronal shock acceleration, on the shock wave history, and on the location and scenario of the energetic particle escape into the interplanetary medium. We use a numerical model of the shock acceleration on a semicircular magnetic field line to learn a significance of different effects. If the shock geometry in a particular magnetic tube changes from nearly parallel to perpendicular, the resulting SEP spectrum in most distant sections of the tube, e.g., at the top of a transequatorial loop, resembles a wide beam, which is very different from the standard power-law spectrum that would be expected in a steady state. Possible escape of the shock-accelerated particles from more than one coronal location, stochastic re-acceleration, and the magnetic tube expansion can make the SEP spectra even more complicated.

AN ANALYTICAL MODEL FOR THE CORONAL COMPONENT OF MAJOR SOLAR ENERGETIC PARTICLE EVENTS

Leon **Kocharov**1,2, Kyung-Suk Cho3 and Eino Valtonen

2011 ApJ 735 4

We formulate an analytical model of the coronal-phase acceleration observed in the beginning of major solar energetic particle (SEP) events, before the main-phase acceleration associated with coronal mass ejections (CMEs) in solar wind. The model is driven and constrained by the broadband observations of SEPs and CMEs, in particular SEP data from the particle telescope of the Energetic and Relativistic Nuclei and Electron (ERNE) experiment on the Solar and Heliospheric Observatory (SOHO) spacecraft, solar radio spectrograms, and low-corona observations of CMEs. The model is also verified against observations of solar high-energy neutrons and neutron-decay protons. The model suggests SEP acceleration above ~ 50 MeV nucleon–1 by coronal shock and the shock-amplified turbulence in closed magnetic structures, and particle release at magnetic reconnection between the closed structure of expanding CME and pre-existing open magnetic flux tubes. The analytical model connects parameters of coronal shocks and structures and the SEP parameters in space, which facilitates analysis of multiwavelength data and will assist in further development of coronal acceleration models.

OBSERVED CORE OF A GRADUAL SOLAR ENERGETIC PARTICLE EVENT

L. **Kocharov**1, M. J. Reiner2, A. Klassen3, B. J. Thompson2, and E. Valtonen1

Astrophysical Journal, 725:2262–2269, **2010, File**

Using space-borne particle and EUV detection and radio spectrograms from both ground-based and space-borne instruments, we study the first phase of the major solar energetic particle (SEP) event associated with the western solar flare and fast and wide coronal mass ejection (CME) on **2000 April 4.** The SEP event being observed at the magnetic connection to the eruption’s center starts with deka–MeV nucl-1 helium- and relativistic electron-rich production from coronal sources identified with the electromagnetic diagnostics and the SEP event modeling. The broadband observations and modeling of the initial phase of the “well-connected” major SEP event support the idea that acceleration of SEPs starts in the helium-rich plasma of the eruption’s core in association with coronal shocks and magnetic reconnections caused by the CME liftoff, and that the coronal component dominates during the first hour of the SEP event considered, not yet being shielded by the CME bow shock in the solar wind. The first phase of the SEP event is followed by a second phase of SEP production associated with a decelerating CME-driven shock wave in the solar wind, which accelerates ions from a distinct, helium-poor seed particle population that may originate from the CME interaction with a coronal streamer.

GRADUAL SOLAR ENERGETIC PARTICLE EVENT ASSOCIATED WITH A DECELERATING SHOCK WAVE

L. **Kocharov**1, T. Laitinen1, A. Al-Sawad1, O. Saloniemi1, E. Valtonen1, and M. J. Reiner

Astrophysical Journal, 700:L51–L55, **2009** July

On 2000 April 4–6 the Energetic and Relativistic Nuclei and Electron particle telescope on the *Solar and Heliospheric Observatory* spacecraft observed a major solar energetic particle (SEP) event associated with two coronal mass ejections (CMEs) separated by approximately 8 hr. The first CME was accompanied by a low-frequency type II radio burst observed by the WAVES receivers on the *Wind* spacecraft. Analysis of the high-precision measurements of the ~20 MeV proton flux anisotropy, model fitting of the type II dynamic spectrum, and SEP transport modeling support the idea that the shock wave of the first CME was an efficient accelerator for ~20 MeV protons during only the first 6 hr after the launch. This shock gradually slowed down, weakened, and became transparent for the protons produced by the second eruption behind the previous CME. The main production of SEPs due to the two successive eruptions continued together for 12 hr. The near-Earth SEP event was additionally amplified by the SEP mirroring in the interplanetary magnetic field draping at the edge of an old CME beyond the Earth's orbit, which made the SEP intensity–time profiles more prolonged than would be expected based on the assumption of SEP transport in the standard solar wind.

A unified model of solar energetic particle transport in structured solar wind

Kocharov, L.; Pizzo, V. J.; Odstrcil, D.; Zwickl, R. D.

J. Geophys. Res., Vol. 114, No. A5, A05102, **2009**

http://dx.doi.org/10.1029/2008JA013837

Solar energetic particle (SEP) fluxes, after their propagation from the particles' source to the Earth's orbit, depend on the state of solar wind, which is known to be highly variable in both time and space. Commonly used SEP transport models are based on the assumption of the standard interplanetary magnetic field, which would be the case for a uniform, steady state expansion of solar wind. Modeling of SEP transport in the standard solar wind can be facilitated by the use of a corotating reference frame, wherein the solar wind speed is parallel to interplanetary magnetic field at each point and the magnetic field is static. However, this approach is not possible in the realistic solar wind. This necessitates development of a more general SEP model applicable to particle transport in arbitrarily structured solar wind and in interplanetary coronal mass ejections, magnetic clouds, and shocks. In the framework of focused transport theory, we formulate a practical model of SEP transport in an evolving, structured solar wind. This unified model accommodates the results of three-dimensional MHD modeling of solar wind based on observations of the sun, solar wind, and SEPs in a particular event. A relation between the generalized focused transport model and the diffusion-convection equation of cosmic ray transport is discussed.

A NEW APPROACH TO INTERPLANETARY TRANSPORT OF SOLAR ENERGETIC PARTICLES IN IMPULSIVE EVENTS

L. **Kocharov**,1 V. J. Pizzo,1 R. D. Zwickl,1 and E. Valtonen2

The Astrophysical Journal, 680: L69–L72, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/589829

Impulsive, ^{3}He-rich events originate close to the interface between slow solar wind overlying active regions and a faster solar wind coming from small coronal holes. This causes large-scale magnetic compressions to be an interplanetary environment for solar energetic particle (SEP) transport in impulsive events, which is typically ignored by SEP modelers. We have modeled SEP transport in a simplified corotating solar wind structure to estimate the possible effect of the rising wind speed on particle anisotropy and spectra at 1 AU. Along with traditional modeling of SEP transport in the static magnetic field and the field-aligned solar wind flow of the corotating frame of reference, we have formulated and tested a new model that is the first model of focused transport applicable to a general case of SEP propagation in realistic, dynamic, and structured solar wind. Numerical modeling shows that a fast increase of the wind speed by only 200 km s can strongly affect the SEP flux $_{-1}$ anisotropy at 1 AU. Accurate analysis of impulsive SEP events can be done with the use of solar wind data, SEP flux anisotropy measurements, and the new approach that accounts for the solar wind structures associated with the sources of impulsive events and uses the general solution of the focused transport problem applicable to SEPs in realistic solar wind.

High-Energy Protons Associated with Liftoff of a Coronal Mass Ejection

Kocharov, L.; Saloniemi, O.; Torsti, J.; Riihonen, E.; Lehti, J.; Klein, K.-L.; Didkovsky, L.; Judge, D. L.; Jones, A. R.; Pyle, R.

Astrophysical Journal, Volume 659, Issue 1, pp. 780-787. **2007**

https://iopscience.iop.org/article/10.1086/512357/pdf

Large solar energetic particle (SEP) events occur in association with fast coronal mass ejections (CMEs) and flares. We have studied in detail the rise phase of the SEP event of **1998 May 2** observed with the particle telescope ERNE aboard the Solar and Heliospheric Observatory (SOHO) spacecraft and ground-based neutron monitors. Using the ERNE data and numerical modeling of the SEP transport, we present improved evaluations of the solar release profile of deka-MeV protons. The SOHO EIT images are used to study the CME liftoff processes and possible sources of deka-MeV and hecto-MeV proton streams. In a first stage of the deka-MeV proton production, which starts not later than 4 minutes after the radio flash and the Moreton wave start, particles get accelerated from a few MeV through 20 MeV in ~15 minutes. Both ERNE and neutron monitor data are used to study the release of solar protons in the hecto-MeV range. The proton acceleration to above 400 MeV was completed not later than 15-20 minutes after the onset of the eruption. However, injection profiles of deka-MeV protons and hecto-MeV protons were different. *Differences in the release scenarios, energy spectra, and composition of deka-MeV protons versus hecto-MeV protons suggest* ***two different acceleration regions involved****, perhaps situated on initially open lines and initially closed lines of the coronal magnetic field. The first SEP productions were followed by a prolonged period of proton reacceleration, which continued in the ~10-100 MeV range for many hours and during which a common energy spectrum was formed.*

Modeling the Shock Aftermath Source of Energetic Particles in the Solar Corona

Kocharov, L., Lytova, M., Vainio, R., Laitinen, T., Torsti, J.

2005 ApJ 620 1052

https://iopscience.iop.org/article/10.1086/427162/pdf

Recent observations on board the Solar and Heliospheric Observatory (SOHO) indicate that acceleration of solar energetic particles (SEPs) at intermediate scales in the solar corona, between flare acceleration and interplanetary CME-driven shock acceleration, significantly contributes to the production of >10 MeV protons. Coronal shocks seem to be the most plausible candidate for the post-impulsive phase acceleration, which emits ~1-100 MeV protons into the interplanetary medium for about 1 hr after the flare. We have employed a Monte Carlo technique to model the diffusive shock acceleration of protons in a turbulent layer at the base of the solar wind. We find that a power-law spectrum of energetic protons can be emitted from the trailing turbulent layer left behind the shock into the solar wind for a few tens of minutes after the CME liftoff. In contrast to an earlier expectation, the propagation direction of the shock wave is found not to be crucial. Both outward-propagating and refracting shocks can load the corona with energetic protons. Those protons escape into the interplanetary medium well after the passage of the shock. We have studied successive transformations of the particle spectra during shock acceleration, coronal transport, and possible reacceleration, for different populations of seed particles. The simulated production time profiles and energy spectra are found to be consistent with observations of the **1996 July 9** event by the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on board SOHO. The new model can be easily combined with our previous interplanetary transport models, forming a basis on which to interpret SEP observations made at 1 AU.

Hybrid Solar Energetic Particle Events Observed on Board Soho

L. **Kocharov** & J. Torsti

Solar Physics volume 207, pages149–157(**2002**)

https://link.springer.com/content/pdf/10.1023/A:1015540311183.pdf

We summarize ERNE/SOHO observations of solar energetic particle events associated with impulsive soft X-ray flares and LASCO coronal mass ejections (CMEs). The new observational data support an idea that the >10 MeV proton acceleration may be initiated at different coronal sources, operating in the flaring active region and on the global coronal scale, in concert with CME development. However, the particle acceleration continues beyond the coronal scales and may culminate at the interplanetary CME well after the flare. We emphasize the importance of CME liftoff/aftermath processes in the solar corona and the possible role of seed particle re-acceleration, which may explain the existence of hybrid solar energetic particle events.

Measurement of Solar Neutrons on 05 March 2012, Using a Fiber-Type Neutron Monitor Onboard the Attached Payload to the ISS

K. **Koga**, Y. Muraki, S. Masuda, S. Shibata, H. Matsumoto, H. Kawano

Solar Physics   August **2017**, 292:115

The solar neutron detector Space Environment Data Acquisition Equipment – Attached Payload (SEDA-FIB) onboard the International Space Station (ISS) detected several events from the solar direction associated with three large solar flares observed on 05 (X1.1), 07 (X5.4), and 09 (M6.3) March 2012. In this study, we focus on the interesting event of 05 March, present the temporal profiles of the neutrons, and discuss the physics that may be related to a possible acceleration scenario for ions above the solar surface. We compare our data with images of the flares obtained by the ultraviolet telescope Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO).

Table Neutron Measurement on ISS (2010-2015)

Multiproxy Reconstructions of Integral Energy Spectra for Extreme Solar Particle Events of 7176 BCE, 660 BCE, 775 CE, and 994 CE

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022JA031186
Extreme solar particle events (ESPEs) are rare and the most potent known processes of solar eruptive activity. During ESPEs, a vast amount of cosmogenic isotopes (CIs) 10Be, 36Cl, and 14C can be produced in the Earth's atmosphere and deposited in natural stratified archives. Accordingly, CI measurements in these archives allow us to evaluate particle fluxes during ESPEs. In this work, we present a new method of ESPE fluence (integral flux) reconstruction based on state-of-the-art modeling advances, allowing to fit together different CI data within one model. We represent the ESPE fluence as an ensemble of scaled fluence reconstructions for ground-level enhancement (GLE) events registered by the neutron monitor network since 1956 coupled with satellite and ionospheric measurements data. Reconstructed ESPE fluences appear softer in its spectral shape than earlier estimates, leading to significantly higher estimates of the low-energy (E < 100 MeV) fluence. This makes ESPEs even more dangerous for modern technological systems than previously believed. Reconstructed ESPE fluences are fitted with a modified Band function, which eases the use of obtained results in different applications.

Effective Energy of Cosmogenic Isotope (10Be, 14C and 36Cl) Production by Solar Energetic Particles and Galactic Cosmic Rays

Sergey **Koldobskiy**,Ilya Usoskin,Gennady A. Kovaltsov

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021JA029919
https://doi.org/10.1029/2021JA029919
Cosmogenic isotopes 14C, 10Be and 36Cl measured in datable natural archives provide the only known quantitative proxy for cosmic-ray (CR) and solar-activity variability before the era of direct measurements. Studies of relations between the measured isotope concentrations and CR variability require complicated modeling including the isotope production and transport in the terrestrial system. Here we propose a rough “effective energy” method to make quick estimates of the CR variability directly from the cosmogenic data using an approximate linear scaling between the measured isotope concentrations and the energy-integrated flux of CR above the effective energy. The method is based on the thoroughly computed effective yield function presented here. A simple way to account for the variable geomagnetic field is also provided. The method was developed for both solar energetic particles (SEPs) and galactic cosmic ray (GCR) variability and is shown to provide a robust result within 20% and 1% accuracy, respectively, without an assumption of the specific spectral shape. Applications of the effective-energy method to the known extreme SEP events and the secular GCR variability are discussed. The new method provides a simple and quick tool to assess the CR variability in the past. On the other hand, it does not supersede the full detailed modeling required for precise results.

New reconstruction of event-integrated spectra (spectral fluences) for major solar energetic particle events

Sergey A. **Koldobskiy**, Osku Raukunen, Rami Vainio, Gennady A. Kovaltsov, Ilya G. Usoskin

A&A 647, A132 **2021**
https://arxiv.org/pdf/2101.10234.pdf
https://doi.org/10.1051/0004-6361/202040058
https://www.aanda.org/articles/aa/pdf/2021/03/aa40058-20.pdf
Fluences of solar energetic particles (SEPs) are not easy to evaluate, especially for high-energy events (i.e. ground-level enhancements, GLEs). Earlier estimates of event-integrated SEP fluences for GLEs were based on partly outdated assumptions and data, and they required revisions. Here, we present the results of a full revision of the spectral fluences for most major SEP events (GLEs) for the period from 1956 -- 2017 using updated low-energy flux estimates along with greatly revisited high-energy flux data and applying the newly invented reconstruction method including an improved neutron-monitor yield function. Low- and high-energy parts of the SEP fluence were estimated using a revised space-borne/ionospheric data and ground-based neutron monitors, respectively. The measured data were fitted by the modified Band function spectral shape. The best-fit parameters and their uncertainties were assessed using a direct Monte Carlo method. As a result, a full reconstruction of the event-integrated spectral fluences was performed in the energy range above 30 MeV, parametrised, and tabulated for easy use along with estimates of the 68% confidence intervals. This forms a solid basis for more precise studies of the physics of solar eruptive events and the transport of energetic particles in the interplanetary medium, as well as the related applications. **19-Oct-1989**

Table 1. Event-integrated omnidirectional integral fluences F(> E) (in units of 105 cm−2) obtained here for GLEs # 40 – 72

Table 2. List of the analysed GLE events and best-fit parameters 1956-2017

New Method of Assessment of the Integral Fluence of Solar Energetic (> 1 GV Rigidity) Particles from Neutron Monitor Data

Sergey A. **Koldobskiy**, Gennady A. Kovaltsov, Alexander L. Mishev, lya G. Usoskin
Solar Physics July **2019**, 294:94
sci-hub.se/10.1007/s11207-019-1485-8
A new method to reconstruct the high-rigidity part (≥ 1 GV) of the spectral fluence of solar energetic particles (SEP) for GLE events, based on the world-wide neutron monitor (NM) network data, is presented. The method is based on the effective rigidity ReffReff and scaling factor KeffKeff. In contrast to many other methods based on derivation of the best-fit parameters of a prescribed spectral shape, it provides a true non-parametric (viz. free of a prioriassumptions on the exact spectrum) estimate of fluence. We reconstructed the SEP fluences for two recent GLE events, #69 (**20 Jan. 2005**) and #71 (**17 May 2012**), using four NM yield functions: (CD00 – Clem and Dorman in Space Sci. Rev.93, 335, 2000), (CM12 – Caballero-Lopez and Moraal in J. Geophys. Res.117, A12103, 2012), (Mi13 – Mishev, Usoskin, and Kovaltsov in J. Geophys. Res.118, 2783, 2013), and (Ma16 – Mangeard et al. in J. Geophys. Res.121, 7435, 2016b). The results were compared with full reconstructions and direct measurements by the PAMELA instrument. While reconstructions based on Mi13 and CM12 yield functions are consistent with the measurements, those based on CD00 and Ma16 ones underestimate the fluence by a factor of 2 – 3. It is also shown that the often used power-law approximation of the high-energy tail of SEP spectrum does not properly describe the GLE spectrum in the NM-energy range. Therefore, the earlier estimates of GLE integral fluences need to be revised.

Effective Rigidity of a Polar Neutron Monitor for Recording Ground-Level Enhancements

Sergey A. **Koldobskiy**, Gennady A. Kovaltsov, Ilya G. Usoskin
Solar Physics July **2018**, 293:110
http://sci-hub.tw/10.1007/s11207-018-1326-1
The “effective” rigidity of a neutron monitor for a ground-level enhancement (GLE) event is defined so that the event-integrated fluence of solar energetic protons with rigidity above it is directly proportional to the integral intensity of the GLE as recorded by a polar neutron monitor, within a wide range of solar energetic-proton spectra. This provides a direct way to assess the integral fluence of a GLE event based solely on neutron-monitor data. The effective rigidity/energy was found to be 1.13 – 1.42 GV (550 – 800 MeV). A small model-dependent, systematic uncertainty in the value of the effective rigidity is caused by uncertainties in the low-energy range of the neutron-monitor yield function, which requires more detailed computations of the latter.

Multi-spacecraft observations of near-relativistic electron events at different radial distances

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A&A 675, A155 (**2023**)
https://doi.org/10.1051/0004-6361/202345955
https://www.aanda.org/articles/aa/pdf/2023/07/aa45955-23.pdf
Aims. We study the radial evolution of near-relativistic **solar energetic electron (SEE)** events observed by at least two spacecraft at different heliocentric distances and with small separation angles between their magnetic footpoints at the Sun.
Methods. We identified SEE events for which Solar Orbiter and either Wind or STEREO-A had a small longitudinal separation (< 15°) between their nominal magnetic footpoints. For the approximation of the footpoint separation, we followed a ballistic back-mapping approach using in situ solar wind speed measurements. For all the SEE events that satisfied our selection criteria, we determined the onset times, rise times, peak fluxes, and peak values of the first-order anisotropy for electrons in the energy range from ∼50 − 85 keV. We compared the event parameters observed at different spacecraft and derived exponential indices αp for each parameter p, assuming an Rα-dependence on the heliocentric distance R.
Results. In our sample of SEE events, we find strong event-to-event variations in the radial dependence of all derived parameters. For the majority of events, the peak flux decreases with increasing radial distance. For the first-order anisotropy and the rise time no clear radial dependence was found. The derived onset delays observed between two spacecraft were found to be too long to be explained by ideal Parker spirals in multiple events.
Conclusions. The rudimentary methods presented in this study lead to event parameters with large uncertainties. The absence of a clear radial dependence on the first-order anisotropy and the rise time as well as the ambiguous onset timing of the SEE events found in this study could be the result of general limitations in the methods we used. Further studies, including analyses of the directional fluxes and transport simulations that take the individual instrument responses into account, would allow a better interpretation of the radial evolution of SEE events. **2022 March 18**
Tables. All selected SEE events with a small longitudinal separation between the magnetic footpoints of Solar Orbiter and STEREO-A. Wind. 2021-2022

The first widespread solar energetic particle event observed by Solar Orbiter on 2020 November 29

A. **Kollhoff**1, A. Kouloumvakos2, D. Lario3, N. Dresing4, R. Gómez-Herrero5, L. Rodríguez-García5, O. E. Malandraki6, I. G. Richardson3,7, A. Posner8, K.-L. Klein9, et al. +++

A&A 656, A20 (**2021**)
https://doi.org/10.1051/0004-6361/202140937
https://www.aanda.org/articles/aa/pdf/2021/12/aa40937-21.pdf

Context. On **2020 November 29**, the first widespread solar energetic particle (SEP) event of solar cycle 25 was observed at four widely separated locations in the inner (≲1 AU) heliosphere. Relativistic electrons as well as protons with energies > 50 MeV were observed by Solar Orbiter (SolO), Parker Solar Probe, the Solar Terrestrial Relations Observatory (STEREO)-A and multiple near-Earth spacecraft. The SEP event was associated with an M4.4 class X-ray flare and accompanied by a coronal mass ejection and an extreme ultraviolet (EUV) wave as well as a type II radio burst and multiple type III radio bursts.

Aims. We present multi-spacecraft particle observations and place them in context with source observations from remote sensing instruments and discuss how such observations may further our understanding of particle acceleration and transport in this widespread event.

Methods. Velocity dispersion analysis (VDA) and time shift analysis (TSA) were used to infer the particle release times at the Sun. Solar wind plasma and magnetic field measurements were examined to identify structures that influence the properties of the energetic particles such as their intensity. Pitch angle distributions and first-order anisotropies were analyzed in order to characterize the particle propagation in the interplanetary medium.

Results. We find that during the 2020 November 29 SEP event, particles spread over more than 230° in longitude close to 1 AU. The particle onset delays observed at the different spacecraft are larger as the flare–footpoint angle increases and are consistent with those from previous STEREO observations. Comparing the timing when the EUV wave intersects the estimated magnetic footpoints of each spacecraft with particle release times from TSA and VDA, we conclude that a simple scenario where the particle release is only determined by the EUV wave propagation is unlikely for this event. Observations of anisotropic particle distributions at SolO, Wind, and STEREO-A do not rule out that particles are injected over a wide longitudinal range close to the Sun. However, the low values of the first-order anisotropy observed by near-Earth spacecraft suggest that diffusive propagation processes are likely involved.

The Acceleration of Energetic Particles at Coronal Shocks and Emergence of a Double Power Law Feature in Particle Energy Spectra

Xiangliang **Kong**, Fan Guo, Yao Chen, Joe Giacalone

2019 *ApJ* **883** 49
https://arxiv.org/pdf/1907.13321.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ab3848/pdf

We present numerical modelling of particle acceleration at coronal shocks propagating through a streamer-like magnetic field by solving the Parker transport equation with spatial diffusion both along and across the magnetic field. We show that the location on the shock where the high-energy particle intensity is the largest, depends on the energy of the particles and on time. The acceleration of particles to more than 100 MeV mainly occurs in the shock-streamer interaction region, due to perpendicular shock geometry and the trapping effect of closed magnetic fields. A comparison of the particle spectra to that in a radial magnetic field shows that the intensity at 100 MeV (200 MeV) is enhanced by more than one order (two orders) of magnitude. This indicates that the streamer-like magnetic field can be an important factor in producing large solar energetic particle events. We also show that the energy spectrum integrated over the simulation domain consists of two different power laws. Further analysis suggests that it may be a mixture of two distinct populations accelerated in the streamer and open field regions, where the acceleration rate differs substantially. Our calculations also show that the particle spectra are affected considerably by a number of parameters, such as the streamer tilt angle, particle spatial diffusion coefficient, and shock compression ratio. While the low-energy spectra agree well with standard diffusive shock acceleration theory, the break energy ranges from ∼1 MeV to ∼90 MeV and the high-energy spectra can extend to ∼1 GeV with a slope of ∼2-3. **2012 May 17, 2017 September 10**

The acceleration of high-energy protons at coronal shocks: the effect of large-scale streamer-like magnetic field structures

Xiangliang **Kong**, Fan Guo, Joe Giacalone, Hui Li, Yao Chen

ApJ **851** 38 **2017**
https://arxiv.org/pdf/1710.11472.pdf

Recent observations have shown that coronal shocks driven by coronal mass ejections can develop and accelerate particles within several solar radii in large solar energetic particle (SEP) events. Motivated by this, we present an SEP acceleration study including the process that a fast shock propagates through a streamer-like magnetic field with both closed and open field lines in the low corona region. The acceleration of protons is modeled by numerically solving the Parker transport equation with spatial diffusion both along and across the magnetic field. We show that particles can be sufficiently accelerated to up to several hundred MeV within 2-3 solar radii. When the shock propagates through a streamer-like magnetic field, particles are more efficiently accelerated compared to the case with a simple radial magnetic field, mainly due to perpendicular shock geometry and the natural trapping effect of closed magnetic fields. Our results suggest that the coronal magnetic field configuration is an important factor for producing large SEP events. We further show that the coronal magnetic field configuration strongly influences the distribution of energetic particles, leading to different locations of source regions along the shock front where most of high energy particles are concentrated. This work may have strong implications to SEP observations. The upcoming Parker Solar Probe will provide in situ observations for the distribution of energetic particles in the coronal shock region, and test the results of the study.

Numerical simulations of particle acceleration at interplanetary quasi-perpendicular shocks

F.-J. **Kong**, G. Qin, L.-H. Zhang

2017 *ApJ* **845** 43

https://arxiv.org/pdf/1704.02975.pdf

Using test particle simulations we study the particle acceleration at highly perpendicular ($\theta_{Bn}\geq 75^\circ$) shocks under conditions of modeling magnetic turbulence. We adopt a backward-in-time method to solve the Lorentz equation using the observed shock parameters for quasi-perpendicular interplanetary shocks, and compare the simulation results with the ACE/EPAM observations to obtain the injection energy and timescale of particle acceleration. With our modeling and the observations we find that a large upstream speed is responsible for efficient particle acceleration. Our results also show that the quasi-perpendicular shocks are capable of accelerating thermal particles to high energies of the order of MeV for both kappa and Maxwellian upstream distribution, which may originate from the fact that in our model the local background magnetic field has component parallel to the shock normal.

Onsets and spectra of impulsive solar energetic electron events observed near the Earth

Eduard P. **Kontar** and Hamish A. S. Reid

E-print, March **2009**; ApJL, **695,** L140-L144 doi: 10.1088/0004-637X/695/2/L140

https://www.academia.edu/38529141/Onsets_and_spectra_of_impulsive_solar_energetic_electron_events_observed_near_the_Earth?email_work_card=view-paper

Impulsive solar energetic electrons are often observed in the interplanetary space near the Earth and have an attractive diagnostic potential for poorly understood solar flare acceleration processes. We investigate the transport of solar flare energetic electrons in the heliospheric plasma to understand the role of transport to the observed onset and spectral properties of the impulsive solar electron events. The propagation of energetic electrons in solar wind plasma is simulated from the acceleration region at the Sun to the Earth, taking into account self-consistent generation and absorption of electrostatic electron plasma (Langmuir) waves, effects of non-uniform plasma, collisions and Landau damping. The simulations suggest that the beam-driven plasma turbulence and the effects of solar wind density inhomogeneity play a crucial role and lead to the appearance of a) spectral break for a single power-law injected electron spectrum, with the spectrum flatter below the break, b) apparent early onset of low-energy electron injection, c) the apparent late maximum of low-energy electron injection. We show that the observed onsets, spectral flattening at low energies, and formation of a break energy at tens of keV is the direct manifestation of wave-particle interactions in non-uniform plasma of a single accelerated electron population with an initial power-law spectrum.

Building a new space weather facility at the National Observatory of Athens

Kontogiannis, Ioannis; Belehaki, Anna; Tsiropoula, Georgia; Tsagouri, Ioanna; Anastasiadis, Anastasios; Papaioannou, Athanasios

Advances in Space Research, Volume 57, Issue 1, p. 418-430. **2016**

http://sci-hub.cc/10.1016/j.asr.2015.10.028

The PROTEAS project has been initiated at the Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS) of the National Observatory of Athens (NOA). One of its main objectives is to provide observations, processed data and space weather nowcasting and forecasting products, designed to support the space weather research community and operators of commercial and industrial systems. The space weather products to be released by this facility, will be the result of the exploitation of ground-based, as well as space-borne observations and of model results and tools already available or under development by IAASARS researchers. The objective will be achieved through: (a) the operation of a small full-disk solar telescope to conduct regular observations of the Sun in the H-alpha line; (b) the construction of a database with near real-time solar observations which will be available to the community through a web-based facility (HELIOSERVER); (c) the development of a tool for forecasting Solar Energetic Particle (SEP) events in relation to observed solar eruptive events; (d) the upgrade of the Athens Digisonde with digital transceivers and the capability of operating in bi-static link mode and (e) the sustainable operation of the European Digital Upper Atmosphere Server (DIAS) upgraded with additional data sets integrated in an interface with the HELIOSERVER and with improved models for the real-time quantification of the effects of solar eruptive events in the ionosphere.

Cosmic-Ray Transport in Heliospheric Magnetic Structures. II. Modeling Particle Transport through Corotating Interaction Regions

Andreas **Kopp**1,2,6, Tobias Wiengarten3, Horst Fichtner3, Frederic Effenberger4, Patrick Kühl5, Bernd Heber5, Jan-Louis Raath2, and Marius S. Potgieter

2017 ApJ 837 37

The transport of cosmic rays (CRs) in the heliosphere is determined by the properties of the solar wind plasma. The heliospheric plasma environment has been probed by spacecraft for decades and provides a unique opportunity for testing transport theories. Of particular interest for the three-dimensional (3D) heliospheric CR transport are structures such as corotating interaction regions (CIRs), which, due to the enhancement of the magnetic field strength and magnetic fluctuations within and due to the associated shocks as well as stream interfaces, do influence the CR diffusion and drift. In a three-fold series of papers, we investigate these effects by modeling inner-heliospheric solar wind conditions with the numerical magnetohydrodynamic (MHD) framework Cronos (Wiengarten et al., referred as Paper I), and the results serve as input to a transport code employing a stochastic differential equation approach (this paper). While, in Paper I, we presented results from 3D simulations with Cronos, the MHD output is now taken as an input to the CR transport modeling. We discuss the diffusion and drift behavior of Galactic cosmic rays using the example of different theories, and study the effects of CIRs on these transport processes. In particular, we point out the wide range of possible particle fluxes at a given point in space resulting from these different theories. The restriction of this variety by fitting the numerical results to spacecraft data will be the subject of the third paper of this series.

PARTICLE ACCELERATION AT NEAR-PERPENDICULAR SHOCKS: THE ROLE OF FIELD-LINE TOPOLOGY

J ´ozsef **K´ota**

Astrophysical Journal, 723:393–397, **2010**

Particle acceleration at two-dimensional (2D) shocks can significantly differ from our expectations based on onedimensional
shocks. We discuss several features of 2D shocks. First, we present a simple example of diffusive acceleration to demonstrate that (1) “hot spots” and cold regions can be expected along the shock face, as the field-line configuration changes along the shock face, (2) the flux of accelerated particles (even the average flux) can be expected to increase beyond the shock, and (3) 2D structures may lead to a softening of the spectrum. We also address quasi-perpendicular shocks and discuss what happens when a field line is hit by a curved shock or is detaching from a shock. This mechanism is of interest on both large and small scales. We consider pure field-aligned transport and address both the diffusive (large scale) and scatter-free (small scale) cases, looking from the perspective of one field line. We find that quasi-trapping of particles in front of the shock can lead to rapid and effective acceleration via multiple mirroring on the ever faster moving shock. This mechanism may be of importance at various astrophysical, heliospheric, and coronal mass ejection driven shocks.

The multi-spacecraft high-energy solar particle event of 28 October 2021

A. **Kouloumvakos**, A. Papaioannou, C. O. G. Waterfall, S. Dalla, R. Vainio, G. M. Mason, B. Heber, P. Kühl, R. C. Allen, C.M.S. Cohen, G. Ho, A. Anastasiadis, A. P. Rouillard, J. Rodríguez-Pacheco, J. Guo, X. Li, M. Hörlöck, R. F. Wimmer-Schweingruber

A&A **2024**

https://arxiv.org/pdf/2401.05991.pdf

Aims. We studied the first multi-spacecraft high-energy solar energetic particle (SEP) event of solar cycle 25, which triggered a ground level enhancement (GLE) on 28 October 2021, using data from multiple observers that were widely distributed throughout the heliosphere.

Methods. We performed detail modelling of the shock wave and investigated the magnetic connectivity of each observer to the solar surface and examined the shock magnetic connection. We performed 3D SEP propagation simulations to investigate the role of particle transport in the distribution of SEPs to distant magnetically connected observers.

Results. Observations and modelling show that a strong shock wave formed promptly in the low corona. At the SEP

release time windows, we find a connection with the shock for all the observers. PSP, STA, and Solar Orbiter were connected to strong shock regions with high Mach numbers, whereas the Earth and other observers were connected to lower Mach numbers. The SEP spectral properties near Earth demonstrate two power laws, with a harder (softer) spectrum in the low-energy (high-energy) range. Composition observations from SIS (and near-Earth instruments) show no serious enhancement of flare-accelerated material.
Conclusions. A possible scenario consistent with the observations and our analysis indicates that high-energy SEPs at PSP, STA, and Solar Orbiter were dominated by particle acceleration and injection by the shock, whereas high-energy SEPs that reached near-Earth space were associated with a weaker shock; it is likely that efficient transport of particles from a wide injection source contributed to the observed high-energy SEPs. Our study cannot exclude a contribution from a flare-related process; however, composition observations show no evidence of an impulsive composition of suprathermals during the event, suggestive of a non-dominant flare-related process.

Extended 3He-rich Time Periods Observed by Solar Orbiter: Magnetic Connectivity and Sources

A. **Kouloumvakos**1, G. M. Mason1, G. C. Ho1, R. C. Allen1,
2023 ApJ 956 123
https://iopscience.iop.org/article/10.3847/1538-4357/acf44e/pdf
Observations of Solar Energetic Particles (SEPs) using the Suprathermal Ion Spectrograph (SIS), which is part of the Energetic Particle Detector suite on the Solar Orbiter mission, present an unprecedented opportunity to investigate the composition and evolution of SEPs in close proximity to the Sun. By analyzing data from the SIS instrument, we have compiled a catalog of extended time periods during the first five orbits of the spacecraft around the Sun, which exhibit a significant abundance of 3He. We have identified 33 periods lasting over one day that show a high abundance of 3He. For each period, we examined the SEP characteristics, the magnetic connectivity of the spacecraft, and the magnetically connected regions. Our findings show that these time periods typically span seven days and consist of multiple injections of 3He, and that the peak in 3He flux is observed two days after the time periods begin. The time periods usually start (end) when the spacecraft's magnetic connection changes to (from) an active region (AR). In most cases, we observed a stable magnetic connection between the spacecraft and one or more ARs, with an average connection time of 4.1 ± 1.8 days. **2021 July 23., 2022 January 13, 2022 February 05, 2022 July 19**
Table 1 List of the Extended 3 He-rich Time Periods 2020-2022

The effect of shock wave properties on the release timings of solar energetic particles

A. Kouloumvakos, R. Vainio, J. Gieseler and D. J. Price
A&A 669, A58 **2023**
https://doi.org/10.1051/0004-6361/202244363
https://www.aanda.org/articles/aa/pdf/2023/01/aa44363-22.pdf
Context. Fast and wide coronal mass ejections (CMEs) and CME-driven shock waves are capable of accelerating solar energetic particles (SEPs) and releasing them in very distant locations in the solar corona and near-Sun interplanetary space. SEP events have a variety of characteristics in their release times and particle anisotropies. In some events, specifics of the SEP release times are thought to be difficult to reconcile with the scenario that a propagating shock wave is responsible for the SEP release.
Aims. Despite the apparent difficulties posed by the shock scenario, many studies have not considered the properties of the propagating shock waves when making a connection with SEP release. This could probably resolve some of the issues and would help us to delve into and understand more important issues such as the effect of the shock acceleration efficiency on the observed characteristics of the SEP timings and the role of particle transport. This study aims to approach these issues from the shock wave perspective and elucidate some of these aspects.
Methods. We constructed a simple 2D geometrical model to describe the propagation and longitudinal extension of a disturbance. We used this model to examine the longitudinal extension of the wave front from the eruption site as a function of time, to calculate the connection times as a function of the longitudinal separation angle, and to determine the shock parameters at any connection point. We examined how the kinematic and geometric properties of the disturbance could affect the timings of the SEP releases at different heliolongitudes.
Results. We show that the extension of a wave close to the solar surface may not always indicate when a magnetic connection is established for the first time. The first connection times depend on both the kinematics and geometry of the propagating wave. A shock-related SEP release process can produce a large event-to-event variation in the relationship between the connection and release times and the separation angle to the eruption site. The evolution of the shock geometry and shock strength at the field lines connected to an observer are important parameters for the observed characteristic of the release times.
Хорошее Introduction

The first widespread solar energetic particle event of solar cycle 25 on 2020 November 29 Shock wave properties and the wide distribution of solar energetic particles⋆

A. **Kouloumvakos**1, R. Y. Kwon2,3, L. Rodríguez-García4, D. Lario5, N. Dresing6, E. K. J. Kilpua7, R. Vainio6, T. Török8, I. Plotnikov1, A. P. Rouillard1, C. Downs8, J. A. Linker8, O. E. Malandraki9, R. F. Pinto1,10, P. Riley8 and R. C. Allen11
A&A 660, A84 (**2022**)
https://doi.org/10.1051/0004-6361/202142515
https://www.aanda.org/articles/aa/pdf/2022/04/aa42515-21.pdf
Context. On **2020 November 29**, an eruptive event occurred in an active region located behind the eastern solar limb as seen from Earth. The event consisted of an M4.4 class flare, a coronal mass ejection, an extreme ultraviolet (EUV) wave, and a white-light (WL) shock wave. The eruption gave rise to the first widespread solar energetic particle (SEP) event of solar cycle 25, which was observed at four widely separated heliospheric locations (~230°).
Aims. Our aim is to better understand the source of this widespread SEP event, examine the role of the coronal shock wave in the wide distribution of SEPs, and investigate the shock wave properties at the field lines magnetically connected to the spacecraft.
Methods. Using EUV and WL data, we reconstructed the global three-dimensional structure of the shock in the corona and computed its kinematics. We determined the magnetic field configurations in the corona and interplanetary space, inferred the magnetic connectivity of the spacecraft with the shock surface, and derived the evolution of the shock parameters at the connecting field lines.
Results. Remote sensing observations show formation of the coronal shock wave occurring early during the eruption, and its rapid propagation to distant locations. The results of the shock wave modelling show multiple regions where a strong shock has formed and efficient particle acceleration is expected to take place. The pressure/shock wave is magnetically connected to all spacecraft locations before or during the estimated SEP release times. The release of the observed near-relativistic electrons occurs predominantly close to the time when the pressure/shock wave connects to the magnetic field lines or when the shock wave becomes supercritical, whereas the proton release is significantly delayed with respect to the time when the shock wave becomes supercritical, with the only exception being the proton release at the Parker Solar Probe.
Conclusions. Our results suggest that the shock wave plays an important role in the spread of SEPs. Supercritical shock regions are connected to most of the spacecraft. The particle increase at Earth, which is barely connected to the wave, also suggests that the cross-field transport cannot be ignored. The release of energetic electrons seems to occur close to the time when the shock wave connects to, or becomes supercritical at, the field lines connecting to the spacecraft. Energetic protons are released with a time-delay relative to the time when the pressure/shock wave connects to the spacecraft locations. We attribute this delay to the time that it takes for the shock wave to accelerate protons efficiently.

The Solar Origin of Particle Events Measured by Parker Solar Probe

Athanasios **Kouloumvakos**1, Angelos Vourlidas2, Alexis P. Rouillard1, Edmond C. Roelof2, Rick Leske3, Rui Pinto1, and Nicolas Poirier1
2020 ApJ 899 107
https://doi.org/10.3847/1538-4357/aba5a1
During the second solar encounter phase of Parker Solar Probe (PSP), two small solar energetic particle (SEP) events were observed by the Integrated Science Investigation of the Sun, on **2019 April 2 and 4**. At the time, PSP was approaching its second perihelion at a distance of ~24.8 million kilometers from the solar center, it was in near-radial alignment with STEREO-A and in quadrature with Earth. During the two SEP events multiple narrow ejections and a streamer-blowout coronal mass ejection (SBO-CME) originated from a solar region situated eastward of PSP. We analyze remote-sensing observations of the solar corona, and model the different eruptions and how PSP was connected magnetically to the solar atmosphere to determine the possible origin of the two SEP events. We find that the SEP event on April 2 was associated with the two homologous ejections from active region 12738 that included two surges and EUV waves occurring in quick succession. The EUV waves appear to merge and were fast enough to form a shock in the low corona. We show that the April 4 SEP event originates in the SBO-CME. Our modeling work suggests that formation of a weak shock is likely for this CME.

Evidence for a Coronal Shock Wave Origin for Relativistic Protons Producing Solar Gamma-Rays and Observed by Neutron Monitors at Earth

Athanasios **Kouloumvakos**, Alexis P. Rouillard, Gerald H. Share, Illya Plotnikov, Ronald Murphy, Athanasios Papaioannou, Yihong Wu
ApJ **893** 76 **2020** **File**
https://arxiv.org/pdf/2004.00355.pdf
sci-hub.si/10.3847/1538-4357/ab8227
We study the solar eruptive event on **2017 September 10** that produced long-lasting >100 MeV γ-ray emission and a ground level enhancement (GLE72). The origin of the high-energy ions producing late-phase gamma-ray emission (LPGRE) is still an open question, but a possible explanation is proton acceleration at coronal shocks produced by coronal mass ejections. We examine a common shock acceleration origin for both the LPGRE and GLE72. The γ-

ray emission observed by the Fermi-Large Area Telescope exhibits a weak impulsive phase, consistent with that observed in hard X-and γ-ray line flare emissions, and what appear to be two distinct stages of LPGRE. From a detailed modeling of the shock wave, we derive the 3D distribution and temporal evolution of the shock parameters, and we examine the shock wave magnetic connection with the visible solar disk. The evolution of shock parameters on field lines returning to the visible disk, mirrors the two stages of LPGRE. We find good agreement between the time history of >100 MeV γ-rays and one produced by a basic shock acceleration model. The time history of shock parameters magnetically mapped to Earth agrees with the rates observed by the Fort Smith neutron monitor during the first hour of the GLE72 if we include a 30% contribution of flare-accelerated protons during the first 10 minutes, having a release time following the time history of nuclear γ-rays. Our analysis provides compelling evidence for a common shock origin for protons producing the LPGRE and most of the particles observed in GLE72.
RHESSI Nuggets #375 April **2020**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Evidence_for_a_Coronal_Shock_Wave_Origin_for_Relativistic_Protons_Producing_Solar_Gamma-Rays_and_Observed_by_Neutron_Monitors_at_Earth

Connecting the Properties of Coronal Shock Waves with those of Solar Energetic Particles

Kouloumvakos A., A. P. Rouillard, Y. Wu, R. Vainio, A. Vourlidas, I. Plotnikov, A. Afanasiev, H. Önel
2019 ApJ 876 80
sci-hub.si/10.3847/1538-4357/ab15d7
https://iopscience.iop.org/article/10.3847/1538-4357/ab15d7/pdf
We develop and exploit a new catalog of coronal pressure waves modeled in 3D to study the potential role of these waves in accelerating solar energetic particles (SEPs) measured in situ. Our sample comprises modeled shocks and SEP events detected during solar cycle 24 observed over a broad range of longitudes. From the 3D reconstruction of shock waves using coronagraphic observations we derived the 3D velocity along the entire front as a function of time. Combining new reconstruction techniques with global models of the solar corona, we derive the 3D distribution of basic shock parameters such as Mach numbers, compression ratios, and shock geometry. We then model in a time-dependent manner how the shock wave connects magnetically with spacecraft making in situ measurements of SEPs. This allows us to compare modeled shock parameters deduced at the magnetically well-connected regions, with different key parameters of SEPs such as their maximum intensity. This approach accounts for projection effects associated with remote-sensing observations and constitutes the most extensive study to date of shock waves in the corona and their relation to SEPs. We find a high correlation between the maximum flux of SEPs and the strength of coronal shock waves quantified, for instance, by the Mach number. We discuss the implications of that work for understanding particle acceleration in the corona. **13 Dec 2006, 2012 July 23**
Table 1 List of the SEP Events Analyzed in This Study (2011-2017)

MULTI-VIEWPOINT OBSERVATIONS OF A WIDELY DISTRIBUTED SOLAR ENERGETIC PARTICLE EVENT: THE ROLE OF EUV WAVES AND WHITE-LIGHT SHOCK SIGNATURES

A. **Kouloumvakos**1, S. Patsourakos1, A. Nindos1, A. Vourlidas2, A. Anastasiadis3, A. Hillaris4, andI. Sandberg3
2016 ApJ 821 31 DOI: 0004-637X/821/1/31
On **2012 March 7**, two large eruptive events occurred in the same active region within 1 hr from each other. Each consisted of an X-class flare, a coronal mass ejection (CME), an extreme-ultraviolet (EUV) wave, and a shock wave. The eruptions gave rise to a major solar energetic particle (SEP) event observed at widely separated (~120°) points in the heliosphere. From multi-viewpoint energetic proton recordings we determine the proton release times atSTEREO B and A (STB, STA) and the first Lagrange point (L1) of the Sun–Earth system. Using EUV and white-light data, we determine the evolution of the EUV waves in the low corona and reconstruct the global structure and kinematics of the first CME's shock, respectively. We compare the energetic proton release time at each spacecraft with the EUV waves' arrival times at the magnetically connected regions and the timing and location of the CME shock. We find that the first flare/CME is responsible for the SEP event at all three locations. The proton release at STB is consistent with arrival of the EUV wave and CME shock at the STBfootpoint. The proton release time at L1 was significantly delayed compared to STB. Three-dimensional modeling of the CME shock shows that the particle release at L1 is consistent with the timing and location of the shock's western flank. This indicates that at L1 the proton release did not occur in low corona but farther away from the Sun. However, the extent of the CME shock fails to explain the SEP event observed at STA. A transport process or a significantly distorted interplanetary magnetic field may be responsible.

Properties of solar energetic particle events inferred from their associated radio emission

A. **Kouloumvakos**, A. Nindos, E. Valtonen, C.E. Alissandrakis, O. Malandraki, P. Tsitsipis, A. Kontogeorgos, X. Moussas, A. Hillaris

A&A 580, A80 **2015**
http://arxiv.org/pdf/1507.03776v1.pdf
https://www.aanda.org/articles/aa/pdf/2015/08/aa24397-14.pdf
We study selected properties of Solar Energetic Particle (SEP) events as inferred from their associated radio emissions. We used a catalogue of 115 SEP events that consists of entries of proton intensity enhancements at one AU, with complete coverage over solar cycle 23, based on high-energy (~68 MeV) protons from SOHO/ERNE and we calculated the proton release time at the Sun using velocity dispersion analysis (VDA). After an initial rejection of cases with unrealistic VDA path lengths, we assembled composite radio spectra for the remaining events using data from ground-based and space-borne radio-spectrographs. For every event we registered the associated radio emissions and we divided the events in groups according to their associated radio emissions. The proton release was found to be most often accompanied by both type III and II radio bursts, but a good association percentage was also registered in cases accompanied by type IIIs only. The worst association was found for the cases with type II only association. ***These radio association percentages support the idea that both flare- and shock-resident particle release processes are observed in high-energy proton events.*** In cases of type III-associated events we extended our study to the timings between the type III radio emission, the proton release, and the electron release as inferred from VDA based on Wind/3DP 20-646 keV data. Typically, the protons are released after the start of the associated type III bursts and simultaneously or before the release of energetic electrons. For the cases with type II radio association we found that the distribution of the proton release heights had a maximum at ~2.5 Rs. Most (69%) of the flares associated to our SEP events were located at the western hemisphere, with a peak within the well-connected region of 50-60 deg western longitude.
Appendices are available in electronic form at http://www.aanda.org
Table B.1 Events with "inferred radio association".

Observation of galactic cosmic ray spallation events from the SoHO mission 20-Year operation of LASCO

S. **Koutchmy**, E. Tavabi, O. Urtado
MNRAS **2018**
https://arxiv.org/ftp/arxiv/papers/1805/1805.04930.pdf
A shower of secondary Cosmic Ray (CR) particles is produced at high altitudes in the Earth's atmosphere, so the primordial Galactic Cosmic Rays (GCRs) are never directly measured outside the Earth magnetosphere and atmosphere. They approach the Earth and other planets in the complex pattern of rigidity's dependence, generally excluded by the magnetosphere. GCRs revealed by images of single nuclear reactions also called spallation events are described here. Such an event was seen on **Nov. 29, 2015** using a unique LASCO C3 space coronagraph routine image taken during the Solar and Heliospheric Observatory (SoHO) mission observing uninterruptedly at the Lagrangian L1 point. The spallation signature of a GCR identified well outside the Earth's magnetosphere is obtained for the 1st time. The resulting image includes different diverging linear "tracks" of varying intensity, leading to a single pixel, this frame identifies the site on the silicon CCD chip of the coronagraph camera. There was no solar flare reported at that time, nor Coronal Mass Ejection (CME) and no evidence of optical debris around the spacecraft. More examples of smaller CR events have been discovered through the 20 years of continuous observations from SoHO. This is the first spallation event from a CR, recorded outside the Earth's magnetosphere. We evaluate the probable energy of these events suggesting a plausible galactic source. **14th July 2000**
RHESSI Science Nuggets #322 May **2018**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Observation_of_Cosmic_Ray_Spallation_Events_from_SoHO

Forward Mapping of Solar Energetic Proton Distributions through the Geomagnetic Field†

A. **Kouznetsov**, D. J. Knudsen
JGR, **2013**
During solar proton events, large ejections of energetic protons spread throughout the interplanetary medium, penetrate the geomagnetic field and are deposited in the upper polar atmosphere where they play important roles in its physical and chemical processes. We develop a model of direct proton propagation through a static geomagnetic field based on a generalized leapfrog method, and validate it through comparison with Störmer theory. We then apply the algorithm to two ideal cases representing the late and early phases of a solar particle event, for proton energies of 10, 100 and 1000 MeV. The late-phase case is represented by an isotropic infinite bath of protons surrounding the magnetosphere; in this case most protons reaching the polar cap originate within ± 20∘ of the magnetic equatorial plane, with pronounced peaks near ± 20∘. The early-phase case is represented by broad, mono-directional proton beams; these sources are highly focused by the geomagnetic field, with all particles mapping to small regions in the polar cap only a few hundred kilometers across, and with low-energy particles being focused

more than higher energy ones. Pure dipole and IGRF-11 magnetic field models lead to very similar fluence patterns in the polar cap, though the latter are somewhat less focused.

Peculiarities of the Isotope Composition of Solar Cosmic Rays.

Koval'tsov, G.A., Ostryakov, V.M. & Sharag, S.P.

Geomagn. Aeron. 63, 1031–1037 (**2023**).

https://doi.org/10.1134/S0016793223070149

An analytical solution of the stationary Fokker–Planck equation describing the acceleration and leakage of ions from some flare region on the Sun is given. It is assumed that the acceleration mechanism is stochastic acceleration during interaction with 1D Alfvén waves in a homogeneous magnetic field, while the leakage occurs during the spatial diffusion of particles from the acceleration region (in the exit-time approximation). In this case, the spatial and momentum diffusion coefficients depend on the charge-to-mass ratio of ions, Q/A, as well as on the turbulence spectrum exponent, s. It is shown that even in this simple model it is possible to explain the observed enrichment of solar cosmic rays with rare isotopes in comparison with their distribution in the solar wind (1.3–4.4 times) for s = 2.5–3. The high index of the turbulence spectrum most likely corresponds to the unsteady process of generation of this turbulence in the acceleration region during the solar flare itself.

Fluence Ordering of Solar Energetic Proton Events Using Cosmogenic Radionuclide Data

G. A. **Kovaltsov**, I. G. Usoskin, E. W. Cliver, W. F. Dietrich, A. J. Tylka

Solar Phys. **2014**

While data on the cosmogenic isotopes 14C and 10Be made it possible to evaluate extreme solar proton events (SPEs) in the past, their relation to standard parameters quantifying the SPE strengths, viz. the integrated fluence of protons with energy above 30 MeV, F 30, is ambiguous and strongly depends on the assumed shape of the energy spectrum. Here we propose a new index, the integral fluence of an SPE above 200 MeV, F 200, which is related to the production of the cosmogenic isotopes 14C and 10Be in the Earth atmosphere, independently of the assumptions on the energy spectrum of the event. The F 200 fluence is reconstructed from past cosmogenic isotope data, which provides an assessment of the occurrence probability density function for extreme SPEs. In particular, we evaluate that extreme SPEs with F 200>1010 cm−2 occur no more frequently than once per 10 – 15 kyr.

Occurrence probability of large solar energetic particle events: Assessment from data on cosmogenic radionuclides in lunar rocks,

Kovaltsov, G. A., and I. G. Usoskin

Sol. Phys., *289*,211–220,**2014**

http://arxiv.org/pdf/1305.5088v1.pdf

We revisited assessments of the occurrence probability distribution of large events in solar energetic particles (SEP), based on measurements of cosmogenic radionuclides in lunar rocks. We present a combined cumulative occurrence probability distribution of SEP events based on three time scales: directly measured SEP fluences for the last 60 years; estimates based on terrestrial cosmogenic radionuclides 10Be and 14C for the multi-millennial (Holocene) time scale; and cosmogenic radionuclides measured in lunar rocks on the time scale of up to 1 Myr. All the three time scales yield a consistent distribution. The data suggest a strong rollover of the occurrence probability so that SEP events with the fluence of protons with energy >30 MeV greater than 10^{11} (protons /cm2/yr) are not expected at the Myr time scale.

A Multi-Event Study of Early-Stage SEP Acceleration by CME-Driven Shocks -- Sun to 1 AU

Kamen **Kozarev**, Mohamed Nedal, Rositsa Miteva, Momchil Dechev, Pietro Zucca

Frontiers in Astronomy and Space Sciences **9:** 801429. **2022**

https://www.frontiersin.org/articles/10.3389/fspas.2022.801429/full

https://arxiv.org/pdf/2202.06013.pdf

doi: 10.3389/fspas.2022.801429

The solar corona below 10 solar radii is an important region for early acceleration and transport of solar energetic particles (SEPs) by coronal mass ejection-driven shock waves. There, these waves propagate into a highly variable dynamic medium with steep gradients and rapidly expanding coronal magnetic fields, which modulates the particle acceleration near the shock or wave surfaces, and the way SEPs spread into the heliosphere. We present a study modelling the acceleration of SEPs in global coronal shock events in the corona, as well as their transport to 1 au, based on telescopic observations coupled with dynamic physical models. **May 11, 2011**

Early-stage Solar Energetic Particle Acceleration by Coronal Mass Ejection-driven Shocks with Realistic Seed Spectra. I. Low Corona

Kamen A. **Kozarev**1, Maher A. Dayeh2,3, and Ashraf Farahat4

2019 ApJ 871 65

https://arxiv.org/pdf/1910.03286.pdf

sci-hub.ru/10.3847/1538-4357/aaf1ce

An outstanding problem in heliospheric physics is understanding the acceleration of solar energetic particles (SEPs) in coronal mass ejections (CMEs) and flares. A fundamental question is whether the acceleration occurs in interplanetary space or near the Sun. Recent work has shown that CME-driven shocks may produce SEPs while still below five solar radii. In this work we explore SEP acceleration during the onset of CMEs and shocks even lower in the corona, using realistic suprathermal spectra, for a selection of events. We have calculated quiet-time, pre-event suprathermal particle spectra from 1 au observations, and scaled them back to the low corona to serve as seed spectra. For each event, AIA observations and the CASHeW framework were used to model the compressive/shock wave kinematics and its interaction with the corona. The proton acceleration was then modeled using an analytic diffusive shock acceleration model as the shock waves propagate between ~1.05 and ~1.3 solar radii. We demonstrate the capability of low coronal shock-related extreme ultraviolet waves to accelerate protons to multi-MeV energies in a matter of minutes, in the very early stages of the associated solar eruptions. We find that strong proton energization occurs for high values of the density jump, Alfvén Mach number, and shock speed. In future work the results of this early-stage shock acceleration will be used to model the continued acceleration higher in the corona. **15.05.2011. 7 June 2011, 4 Aug 2011, 20 Oct 2011, 2012 May 26, 8 Jan 2013, 19 Nov 2013, 7 Dec 2013, 12 Dec 2013, Table (2011-2014)**

Presentation of the project "An investigation of the early stages of solar eruptions - from remote observations to energetic particles"

Kozarev, Kamen; Veronig, Astrid; Duchlev, Peter; Koleva, Kostadinka; Dechev, Momchil; Miteva, Rositsa; Temmer, Manuela; Dissauer, Karin

Space, Ecology, Safety - SES 2017, Thirteenth International Scientific conference "Space, Ecology, Safety - SES1027", held 2-4 November 2017 in Sofia, Bulgaria. Edited by G. Mardirossian, Ts. Srebrova and G. Jelev. ISSN: 1313-3888, p. 63-67, **2017**

http://www.astro.bas.bg/SES2017/Kozarevetal_SES2017.pdf

Coronal mass ejections (CMEs), one of the most energetic manifestations of solar activity, are complex events, which combine multiple related phenomena occurring on the solar surface, in the extended solar atmosphere (corona), as well as in interplanetary space. We present here an outline of a new collaborative project between scientists from the Bulgarian Academy of Sciences (BAS), Bulgaria and the University of Graz, Austria. The goal of the this research project is to answer the following questions: 1) What are the properties of erupting filaments, CMEs, and CME-driven shock waves near the Sun, and of associated solar energetic particle (SEP) fluxes in interplanetary space? 2) How are these properties related to the coronal acceleration of SEPs? To achieve the scientific goals of this project, we will use remote solar observations with high spatial and temporal resolution to characterize the early stages of coronal eruption events in a systematic way - studying the pre-eruptive behavior of filaments and flares during energy build-up, the kinematics and morphology of CMEs and compressive shock waves, and the signatures of high energy non-thermal particles in both remote and in situ observations.

A Data-Driven Analytic Model for Proton Acceleration by Large-Scale Solar Coronal Shocks

Kamen A. **Kozarev**, Nathan A. Schwadron

ApJ 831 120 **2016**

http://arxiv.org/pdf/1608.00240v1.pdf

We have recently studied the development of an eruptive filament-driven, large-scale off-limb coronal bright front (OCBF) in the low solar corona (Kozarev et al. 2015), using remote observations from Solar Dynamics Observatory's Advanced Imaging Assembly EUV telescopes. In that study, we obtained high-temporal resolution estimates of the OCBF parameters regulating the efficiency of charged particle acceleration within the theoretical framework of diffusive shock acceleration (DSA). These parameters include the time-dependent front size, speed, and strength, as well as the upstream coronal magnetic field orientations with respect to the front's surface normal direction. Here we present an analytical particle acceleration model, specifically developed to incorporate the coronal shock/compressive front properties described above, derived from remote observations. We verify the model's performance through a grid of idealized case runs using input parameters typical for large-scale coronal shocks, and demonstrate that the results approach the expected DSA steady-state behavior. We then apply the model to the event of **May 11, 2011** using the OCBF time-dependent parameters derived in Kozarev et al. (2015). We find that the compressive front likely produced energetic particles as low as 1.3 solar radii in the corona. Comparing the modeled and observed fluences near Earth, we also find that the bulk of the acceleration during this event must have occurred above 1.5 solar radii. With this study we have taken a first step in using direct observations of shocks and compressions in the innermost corona to predict the onsets and intensities of SEP events.

Properties of a Coronal Shock Wave as A Driver of Early SEP Acceleration

Kamen A. **Kozarev**, John C. Raymond, Vasili V. Lobzin, Michael Hammer

2015 ApJ 799 167

http://arxiv.org/pdf/1406.2363v1.pdf

Coronal mass ejections (CMEs) are thought to drive collisionless shocks in the solar corona, which in turn have been shown capable of accelerating solar energetic particles (SEPs) in minutes. It has been notoriously difficult to extract information about energetic particle spectra in the corona, due to lack of in-situ measurements. It is possible, however, to combine remote observations with data-driven models in order to deduce coronal shock properties relevant to the local acceleration of SEPs and their heliospheric connectivity to near-Earth space. We present such novel analysis applied to the **May 11, 2011** CME event on the western solar limb, focusing on the evolution of the eruption-driven, dome-like shock wave observed by the Atmospheric Imaging Assembly (AIA) EUV telescopes on board the Solar Dynamics Observatory spacecraft. We analyze the shock evolution and estimate its strength using emission measure modeling. We apply a new method combining a geometric model of the shock front with a potential field source surface model to estimate time-dependent field-to-shock angles and heliospheric connectivity during shock passage in the low corona. We find that the shock was weak, with an initial speed of ~450 km/s. It was initially mostly quasi-parallel, but significant portion of it turned quasi-perpendicular later in the event. There was good magnetic connectivity to near-Earth space towards the end of the event as observed by the AIA instrument. The methods used in this analysis hold a significant potential for early characterization of coronal shock waves and forecasting of SEP spectra based on remote observations.

Global Numerical Modeling of Energetic Proton Acceleration in a Coronal Mass Ejection Traveling through the Solar Corona

Kamen A. **Kozarev**1,2, Rebekah M. Evans3, Nathan A. Schwadron4, Maher A. Dayeh5, Merav Opher1, Kelly E. Korreck2, and Bart van der Holst

2013 ApJ 778 43

http://arxiv.org/pdf/1406.2377v1.pdf

The acceleration of protons and electrons to high (sometimes GeV/nucleon) energies by solar phenomena is a key component of space weather. These solar energetic particle (SEP) events can damage spacecraft and communications, as well as present radiation hazards to humans. In-depth particle acceleration simulations have been performed for idealized magnetic fields for diffusive acceleration and particle propagation, and at the same time the quality of MHD simulations of coronal mass ejections (CMEs) has improved significantly. However, to date these two pieces of the same puzzle have remained largely decoupled. Such structures may contain not just a shock but also sizable sheath and pileup compression regions behind it, and may vary considerably with longitude and latitude based on the underlying coronal conditions. In this work, we have coupled results from a detailed global three-dimensional MHD time-dependent CME simulation to a global proton acceleration and transport model, in order to study time-dependent effects of SEP acceleration between 1.8 and 8 solar radii in the **2005 May 13** CME. We find that the source population is accelerated to at least 100 MeV, with distributions enhanced up to six orders of magnitude. Acceleration efficiency varies strongly along field lines probing different regions of the dynamically evolving CME, whose dynamics is influenced by the large-scale coronal magnetic field structure. We observe strong acceleration in sheath regions immediately behind the shock.

OFF-LIMB SOLAR CORONAL WAVEFRONTS FROM SDO/AIA EXTREME-ULTRAVIOLET OBSERVATIONS—IMPLICATIONS FOR PARTICLE PRODUCTION

K. A. **Kozarev**1,5, K. E. Korreck2, V. V. Lobzin3, M. A. Weber2 and N. A. Schwadron

2011 ApJ 733 L25, **File**

http://arxiv.org/pdf/1406.2372v1.pdf

We derive kinematic properties for two recent solar coronal transient waves observed off the western solar limb with the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) mission. The two waves occurred over ~10 minute intervals on consecutive days—**2010 June 12 and 13**. For the first time, off-limb waves are imaged with a high 12 s cadence, making possible detailed analysis of these transients in the low corona between ~1.1 and 2.0 solar radii (RS). We use observations in the 193 and 211 Å AIA channels to constrain the kinematics of both waves. We obtain initial velocities for the two fronts of ~1287 and ~736 km s–1, and accelerations of –1170 and –800 m s–2, respectively. Additionally, differential emission measure analysis shows the June 13 wave is consistent with a weak shock. Extreme-ultraviolet (EUV) wave positions are correlated with positions from simultaneous type II radio burst observations. We find good temporal and height association between the two, suggesting that the waves may be the EUV signatures of coronal shocks. Furthermore, the events are associated with significant increases in proton fluxes at 1 AU, possibly related to how waves propagate through the coronal magnetic field. Characterizing these coronal transients will be key to connecting their properties with energetic particle production close to the Sun.

Modeling the 2003 Halloween events with EMMREM: Energetic particles, radial gradients, and coupling to MHD

Kozarev, K.; Schwadron, N. A.; Dayeh, M. A.; Townsend, L. W.; Desai, M. I.; PourArsalan, M.
Space Weather, Vol. 8, No. 0, S00E08, **2010**

The Earth-Moon-Mars Radiation Environment Module (EMMREM) is a comprehensive numerical framework for characterizing and predicting the radiation environment of the inner heliosphere. We present a study of the October/November 2003 Halloween solar energetic particle events with an energetic particle acceleration and propagation model that is part of EMMREM, highlighting the current ability of the framework to make predictions at various locations of the inner heliosphere. We compare model predictions with Ulysses observations of protons at energies above 10 MeV in order to obtain realistic proton fluxes and calculate radial gradients for peak fluxes, event fluences, and radiation dosimetric quantities. From our study, we find that a power law with an index of −3.55 at energy of 200 MeV describes the time-integrated energetic proton fluence dependence on radial distances beyond 1 AU for the 2003 Halloween events, and an index of −4.18 is appropriate for peak proton fluxes at that energy. Calculations of radiation doses based on these simulations show average power law indices of −4.32 and −3.64 for peak dose rates and accumulated doses, respectively. In an effort to improve the predictions, we have coupled our kinetic code to results from a 3-D heliospheric magnetohydrodynamic model, WSA/Enlil. While predictions with the coupled model overall show worse agreement than simulations with steady state solar wind conditions for these large events, the capability to couple energetic particle propagation and numerical models of the solar wind is an important step in the future development of space weather modeling.

Preferential Acceleration of Heavy Ions in a Spontaneously Fragmenting Flare Current Sheet

David **Kramoliš**1, Miroslav Bárta2, Michal Varady1,2, and Radoslav Bučík3
2022 ApJ 927 177
https://iopscience.iop.org/article/10.3847/1538-4357/ac4fc9/pdf

We study the ion acceleration in a mesoscale, spontaneously fragmenting flare current sheet (SFCS) characterized by the presence of a plasmoid cascade. The main subject of our investigation is to determine whether and how plasmoid cascades at intermediate scales in a fragmented current sheet of a solar flare can impact the (preferential) acceleration of specific ions. The time evolution of the SFCS is obtained from high-resolution 2.5D MHD simulations. The ion trajectories (in the background fields resulting from the MHD model), energies, and pitch angles are calculated using a relativistic test-particle code based on the half-acceleration–rotation–half-acceleration method. For light ions, the main acceleration effects of electromagnetic fields within the SFCS are analyzed using the guiding center approximation. We identify regions with the most-efficient ion acceleration within the SFCS, the accelerator efficiency, and spectra of the accelerated ions. The influence of the charge-to-mass ratio on ion behavior is also studied and resulting ion abundances are compared with observational data. The main ion acceleration takes place in the regions with a strong polarization term, which is part of the first-order Fermi acceleration. Because the term is mass dependent, heavier ions undergo preferential acceleration. The ion energy spectra, abundance-enhancement factors, and differential fluxes, obtained from the model, exhibit power-law profiles, in agreement with observed solar energetic particle events. Nonetheless, the obtained slopes for the abundance-enhancement factor do not exactly match the observed data. The computed slopes and profiles are not sensitive to changes in the initial plasma temperature.

Ground level enhancements of cosmic rays in solar cycle 24

M V **Kravtsova** and V E Sdobnov
Astronomy Letters   July **2017**, Volume 43, Issue 7, pp 501–506
Original Russian Text: Pis'ma v Astronomicheskii Zhurnal, **2017**, Vol. 43, No. 7, pp. 550–556.
https://link.springer.com/article/10.1134/S1063773717070040?wt_mc=alerts.TOCjournals

Using data from ground-based observations of cosmic rays (CRs) on the worldwide network of stations and spacecraft, we have investigated the proton spectra and the CR anisotropy during the ground level enhancements of CRs on **May 17, 2012** (GLE71) and **January 6, 2014** (GLE72) occurred in solar cycle 24 by the spectrographic global survey method. We provide the CR rigidity spectra and the relative changes in the intensity of CRs with a rigidity of 2 GV in the solar–ecliptic geocentric coordinate system in specific periods of these events. We show that the proton acceleration during GLE71 and GLE72 occurred up to rigidities R ~ 2.3−2.5 GV, while the differential rigidity spectra of solar CRs are described neither by a power nor by an exponential function of particle rigidity. At the times of the events considered the Earth was in a loop-like structure of the interplanetary magnetic field.

Cosmic ray rigidity spectrum and anisotropy during GLE on 14 July 2000

M V **Kravtsova** and V E Sdobnov

2013 J. Phys.: Conf. Ser. 409 012143

Using the method of spectrographic global survey, rigidity spectrum and anisotropy of galactic cosmic rays during GLE on 14 July 2000 have been studied with the data from ground-based observations of cosmic rays (CR) at the world-wide network of stations. The CR rigidity spectrum observed during this period over the range 1 to ~ 20 GV is shown to be described not only by power function of particle rigidity: distribution of CRs in the earthward direction varies with time and depends on their energy.

Observations from NOAA's Newest Solar Proton Sensor

B. T. **Kress**, J. V. Rodriguez, A. Boudouridis, T. G. Onsager, B. K. Dichter, G. E. Galica, S. Tsui

Space Weather **Volume19, Issue12** e2021SW002750 **2021**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002750

https://doi.org/10.1029/2021SW002750

Space weather instrumentation on board the National Oceanic and Atmospheric Administration's (NOAA's) newest Geostationary Operational Environmental Satellite (GOES)-R series includes the Solar and Galactic Proton Sensor (SGPS), which has been collecting data since 8 January 2017. SGPS supports real-time alerts of solar energetic particle (SEP) events at the NOAA Space Weather Prediction Center (SWPC) and provides data to the space science community, advancing basic space science research and understanding of space weather effects on satellite systems. The first GOES-R series spacecraft, GOES-16, was launched on 19 November 2016. A series of solar particle events in September 2017 enabled cross calibration of GOES-16 SGPS with the Energetic Particle Sensors (EPS) on GOES-13 and -15. This paper is intended as a resource for SGPS data users, including comparisons with legacy GOES energetic particle measurements, corrections applied to SGPS Level-2 data, important caveats, background level fluxes, and measurements of trapped magnetospheric protons. **10 Sep 2017**

Solar energetic particle cutoff variations during the 29-31 October 2003 geomagnetic storm

Kress, B. T.; Mertens, C. J.; Wiltberger, M.

Space Weather, Vol. 8, No. 5, S05001, **2010**

http://dx.doi.org/10.1029/2009SW000488

At low latitudes to midlatitudes the Earth's magnetic field usually shields the upper atmosphere and spacecraft in low Earth orbit from solar energetic particles (SEPs). During severe geomagnetic storms, distortion of the Earth's field suppresses geomagnetic shielding, allowing SEPs access to the midlatitudes. A case study of the 26–31 October 2003 solar-geomagnetic event is used to examine how a severe geomagnetic storm affects SEP access to the Earth. Geomagnetic cutoffs are numerically determined in model geomagnetic fields using code developed by the Center for Integrated Space Weather Modeling (CISM) at Dartmouth College. The CISM-Dartmouth geomagnetic cutoff model is being used in conjunction with the High Energy and Charge Transport code (HZETRN) at the NASA Langley Research Center to develop a real-time data-driven prediction of radiation exposure at commercial airline altitudes. In this work, cutoff rigidities are computed on global grids and along several high-latitude flight routes before and during the geomagnetic storm. It is found that significant variations in SEP access to the midlatitudes and high latitudes can occur on time scales of an hour or less in response to changes in the solar wind dynamic pressure and interplanetary magnetic field. The maximum suppression of the cutoff is ~1 GV occurring in the midlatitudes during the main phase of the storm. The cutoff is also significantly suppressed by the arrival of an interplanetary shock. The maximum suppression of the cutoff due to the shock is approximately one half of the maximum suppression during the main phase of the storm.

Recurrent Solar Energetic Particle Flux Enhancements Observed near Earth and Mars

C. **Krishnaprasad**, Smitha V. Thampi, Anil Bhardwaj, Christina O. Lee, K. Kishore Kumar, Tarun K. Pant

ApJ **902** 13 **2020**

https://arxiv.org/pdf/2010.04122.pdf

https://doi.org/10.3847/1538-4357/abb137

August 1 to November 15, 2016 period was characterized by the presence of Corotating Interaction Regions (CIRs) and a few weak Coronal Mass Ejections (CMEs) in the heliosphere. In this study we show recurrent energetic electron and proton enhancements observed near Earth (1 AU) and Mars (1.43-1.38 AU) during this period. The observations near Earth are using data from instruments aboard ACE, SOHO, and SDO whereas those near Mars are by the SEP, SWIA, and MAG instruments aboard MAVEN. During this period, the energetic electron fluxes observed near Earth and Mars showed prominent periodic enhancements over four solar rotations, with major periodicities of ~27 days and ~13 days. Periodic radar blackout/weakening of radar signals at Mars are observed by MARSIS/MEX, associated with these solar energetic electron enhancements. During this period, a weak CME and a High Speed Stream (HSS)-related interplanetary shock could interact with the CIR and enhance energetic proton fluxes near 1.43-1.38 AU, and as a result, ~27 day periodicity in proton fluxes is significantly diminished at 1.43-1.38 AU. These events also cause unexpected impact on the Martian topside ionosphere, such as topside ionospheric depletion and compression observed by LPW and NGIMS onboard MAVEN. These observations are unique not only because of the recurring nature of electron enhancements seen at two vantage points, but also because they reveal unexpected impact of the weak CME and interplanetary shock on the Martian ionosphere, which provide new insight into the impact of CME-HSS interactions on Martian plasma environment. **2016: 2 August, 2 September, 29 September, 9 October, 26 October 2016**

DRIFT ORBITS OF ENERGETIC PARTICLES IN AN INTERPLANETARY MAGNETIC FLUX ROPE

W. Krittinatham1,2 and D. Ruffolo1,2

ApJ 704 831-841, **2009**

Interplanetary magnetic flux ropes have significant effects on the distribution of energetic particles in space. Flux ropes can confine solar energetic particles (SEPs) for hours, and have relatively low densities of Galactic cosmic rays (GCRs), as seen during second-stage Forbush decreases. As particle diffusion is apparently inhibited across the flux rope boundary, we suggest that guiding center drifts could play a significant role in particle motion into and out of the flux ropes. We develop an analytic model of the magnetic field in an interplanetary magnetic flux rope attached to the Sun at both ends, in quasi-toroidal coordinates, with the realistic features of a flux rope cross section that is small near the Sun, expanding with distance from the Sun, and field lines that are wound less tightly close to the Sun due to stretching by the solar wind. We calculate the particle drift velocity field due to the magnetic field curvature and gradient as a function of position and pitch-angle cosine, and trace particle guiding center orbits numerically, assuming conservation of the first adiabatic invariant. We find that SEPs in the interior of a flux rope can have drift orbits that are trapped for long times, as in a tokamak configuration, with resonant escape features as a function of the winding number. For Forbush decreases of GCRs, the drifts should contribute to a unidirectional anisotropy and net flow from one leg of the loop to the other, in a direction determined by the poloidal field direction.

Solar Flare Electron Spectra at the Sun and near the Earth

S. **Krucker**, E. P. Kontar, S. Christe, and R. P. Lin

The Astrophysical Journal, 663:L109-L112, **2007**

Interplanetary particle transport simulation for warning system for aviation exposure to solar energetic particles

Yûki **Kubo**, Ryuho Kataoka, Tatsuhiko Sato

Earth, Planets and Space **2015**

http://arxiv.org/pdf/1506.00825v1.pdf

Solar energetic particles (SEPs) are one of the extreme space weather phenomena. A huge SEP event increases the radiation dose received by aircrews, who should be warned of such events as early as possible. We developed a warning system for aviation exposure to SEPs. This article describes one component of the system, which calculates the temporal evolution of the SEP intensity and the spectrum immediately outside the terrestrial magnetosphere. To achieve this, we performed numerical simulations of SEP transport in interplanetary space, in which interplanetary SEP transport is described by the focused transport equation. We developed a new simulation code to solve the equation using a set of stochastic differential equations. In the code, the focused transport equation is expressed in a magnetic field line coordinate system, which is a non-orthogonal curvilinear coordinate system. An inverse Gaussian distribution is employed as the injection profile of SEPs at an inner boundary located near the Sun. We applied the simulation to observed SEP events as a validation test. The results show that our simulation can closely reproduce observational data for the temporal evolution of particle intensity. By employing the code, we developed the WArning System for AVIation Exposure to Solar energetic particles (WASAVIES**). 27th January 2012, 13th March 2012, 17th May 2012, 6th January 2014,**

Existence of thresholds in proton flares and application to solar energetic particle alerts,

Kubo, Y., and M. Akioka,

Space Weather, 2, S01002, (**2004**)

This article discusses our statistical investigations into the occurrence of proton events for solar energetic particle (SEP) alerts in space weather forecasts. We analyzed X-ray flux and proton intensity data obtained with the GOES satellite in the 23rd solar cycle. We found that the total soft X-ray flux (1–8Å) of almost all flares related to proton events exceeded a threshold value, which was ~20 ergs cm−2. This means that there is a threshold in flare duration in regard to peak X-ray flux and this is ~30 min for an M1.0 flare and/or 3 min for an X1.0 flare. We also confirmed this threshold with data in the 22nd solar cycle. These results will provide some of the most important criteria for SEP alerts and solar proton event forecasts in the future.

Variability of Low Energy Cosmic Rays Near Earth **A Review**
Karel **Kudela**
In: Exploring the Solar Wind, Ed. Marian Lazar, **2012, File**
http://www.intechopen.com/books/exploring-the-solar-wind

ON ENERGETIC PARTICLES IN SPACE **A Review**
K. **Kudela**1
Acta physica slovaca vol. 59 No. 5, 537 – 652, **2009, File**
Particles energized above the Earth's atmosphere provide unique informations about specific physical processes in the outer space. This is an attempt to present a short **review** of the knowledge of the characteristics of the cosmic energetic particles in wide energy range as observed on the ground, in the atmosphere, on Earth's satellites and on space probes. However, the review is related only to selected problems of cosmic ray physics and space physics. The bias is especially towards lower energies. After the historical introduction the features of primary cosmic rays is described. The heliosphere, in which the direct measurements of cosmic energetic particles takes place, is modulating the primary flux by magnetic fields controlled by the processes on solar surface and, is contributing to the low energy population by acceleration via transient processes as well as by solar flares. Important processes occur near the heliospheric outer boundary from where recently the space probes provided new information. Heliospheric influence is summarized in the third chapter. Another important object, the magnetosphere, is changing trajectories of incoming charged particles by "magnetospheric optics". Magnetosphere iself by the acceleration, transport, trapping as well as losses of lower energy particles alternates significantly the radiation environment near the Earth. The knowledge of particle population for which the condition of trapping are suitable in magnetospheres of giant planets of solar system, have increased thanks to space probes and planetary orbiters. Chapter four summarizes few important points of the magnetospheric influence on energetic particles. The measurements of temporal variability of the flux, energy spectra and angular distribution of cosmic ray particles influenced by solar-terrestrial effects, provides a unique tool for monitoring and eventual prediction of space weather effects, in addition to the investigations of the photon flux of various wavelength from the Sun, solar wind plasma and the magnetic field in interplanetary space. This is the main part of the chapter five.

The Electron Proton Helium INstrument as an example for a Space Weather Radiation Instrument
Patrick **Kühl**, Bernd Heber, Raúl Gómez-Herrero, Olga Malandraki, Arik Posner and Holger Sierks
J. Space Weather Space Clim. **2020**, 10, 53
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200043.pdf
The near-Earth energetic particle environment has been monitored since the 1970's. With the increasing importance of quantifying the radiation risk for, e.g. for the human exploration of the Moon and Mars, it is essential to continue and further improve these measurements. The Electron Proton Helium INstrument (EPHIN) on-board SOHO continually provides these data sets to the solar science and space weather communities since 1995. Here, we introduce the numerous data products developed over the years and present space weather related applications. Important design features that have led to EPHINs success as well as lessons learned and possible improvements to the instrument are also discussed with respect to the next generation of particle detectors.

Revising More Than 20 Years of EPHIN Ion Flux Data—A New Data Product for Space Weather Applications
P. **Kühl** , B. Heber
Space Weather 17(1) p. 84-98 **2019**
sci-hub.tw/10.1029/2018SW002114
Solar energetic particle events and galactic cosmic rays are important aspects of space weather. Investigating them requires consistent measurements of electrons and ions over long time periods, that is, over more than a solar cycle. The Electron Proton Helium INstrument onboard the SOlar and Heliospheric Observatory is operational since 1995 and was designed to measure electrons in the energy range of 0.3 to 10 MeV as well as protons and helium ions in the energy range from 4 to 50 MeV per nucleon in four different coincidence channels with 1-min resolution. Early in the mission and in 2017 two of six detectors became noisy and had to be switched of reducing the number of

coincidence channels from 4 to 2, and thereby significantly reducing the energy resolution of the instrument. In order to restore the original count rate channels we present here a new data analysis applying the so called dE/dx − dE/dx method. A data set with different temporal resolutions from 1 min to a day has been generated for the whole ongoing SOlar and Heliospheric Observatory mission from 1995 to 2018. The resulting data sets are successfully validated against measurements from instruments close to Earth. Studies with regard to long-term variation of the measured flux with special emphasis on the contribution of individual solar energetic particle events to the fluence observed over more than two solar cycles are presented here.

Solar Energetic Particle Events with Protons Above 500 MeV Between 1995 and 2015 Measured with SOHO/EPHIN

P. **Kühl**, N. Dresing, B. Heber, A. Klassen

Solar Physics January **2017**, 292:10

http://link.springer.com/article/10.1007/s11207-016-1033-8

The Sun is an effective particle accelerator that produces solar energetic particle (SEP) events, during which particles of up to several GeVs can be observed. These events, when they are observed at Earth with the neutron monitor network, are called ground-level enhancements (GLEs). Although these events with their high-energy component have been investigated for several decades, a clear relation between the spectral shape of the SEPs outside the Earth's magnetosphere and the increase in neutron monitor count rate has yet to be established. Hence, an analysis of these events is of interest for the space weather and for the solar event community.

In this article, SEP events with protons accelerated to above 500 MeV were identified using data obtained with the Electron Proton Helium Instrument (EPHIN) onboard the Solar and Heliospheric Observatory (SOHO) between 1995 and 2015. For a statistical analysis, onset times were determined for the events and the proton energy spectra were derived and fitted with a power law.

As a result, we present a list of 42 SEP events with protons accelerated to above 500 MeV measured with the EPHIN instrument onboard SOHO. The statistical analysis based on the fitted spectral slopes and absolute intensities is discussed, with special emphasis on whether an event has been observed as a GLE. Furthermore, we are able to determine that the derived intensity at 500 MeV and the observed increase in neutron monitor count rate are correlated for a subset of events. **6 November 1997**

Table 1 Event list compiled in this article.

Table 3 Results of the power law fit to the proton spectra.

Proton intensity spectra during the solar energetic particle events of May 17, 2012 and January 6, 2014

P. **Kühl**1, S. Banjac1, N. Dresing1, R. Goméz-Herrero2, B. Heber1, A. Klassen1 and C. Terasa

A&A 576, A120 (**2015**)

Context. Ground-level enhancements (GLEs) are solar energetic particle events that show a significant intensity increase at energies that can be measured by neutron monitors. The most recent GLE-like events were recorded on May 17, 2012 and January 6, 2014. They were also measured by sophisticated instrumentation in space such as PAMELA and the Electron Proton Helium INstrument (EPHIN) onboard SOHO. Since neutron monitors are only sensitive to protons above 400 MeV with maximum sensitivity at 1 to 2 GeV, the spectra of such weak GLE-like events (January 6, 2014) can only be measured by space instrumentation.

Aims. We show that the SOHO/EPHIN is capable of measuring the solar energetic particle proton event spectra between 100 MeV and above 800 MeV.

Methods. We performed a GEANT Monte Carlo simulation to determine the energy response function of EPHIN. Based on this calculation, we derived the corresponding proton energy spectra. The method was successfully validated against previous PAMELA measurements.

Results. We present event spectra from EPHIN for May 17, 2012 and January 6, 2014. During the event in May 2012, protons were accelerated to energies above 700 MeV, while we found no significant increase for protons above 600 MeV during the event on January 6, 2014.

Characteristics of SEPs during Solar Cycle 21-24

Raj **Kumar**, Ramesh Chandra, Bimal Pande, Seema Pande

Journal of Astrophysics and Astronomy **2020**

https://arxiv.org/ftp/arxiv/papers/2002/2002.12708.pdf

The study of the solar energetic particle events (SEPs) and their association with solar flares and other activities are very crucial to understand the space weather. Keeping this in view, in this paper, we present the study of the SEPs (intensity equal to or greater than 10 pfu) during the solar cycle 21 to 24 (1976-2017) in > 10 MeV energy channels associated with solar flares. For our analysis, we have used the data from different instruments onboard SOHO satellite. We have examined the flare size, source location, CMEs characteristics of associated SEPs. About 31% and 69% of the SEPs were originated from the eastern and western solar hemisphere respectively. The average CME

speed and width were 1238 km/s and 253 deg respectively. About 58 % SEPs were associated with halo CMEs and 42% of SEPs associated with CMEs width varying from 10 deg to 250 deg respectively. **September 10, 2014**
Table 1. SEP events of solar cycle 23 & 24 associated with GLE.
Appendix (Data set) Data from 1976 to 1996 Data from 1977 to 2017, where CME data is available

Characteristics of Radio-Loud CMEs

Pankaj **Kumar**, P.K. Manoharan, K.S. Cho
2017
https://www.researchgate.net/publication/315637846_Characteristics_of_radio-loud_CMEs
In this paper, we study the characteristics of 46 radio-loud (RL) Coronal Mass Ejections (CMEs), which occurred during 1997-2006. All these RL CMEs were associated with M-and X-class flares. We selected 46 RL CMEs, out of which 26 events (57%) were associated with Solar Energetic Particle (SEP) events detected at 1 AU. Furthermore, we study the link between the flare accelerated electrons in the low corona and protons at 1 AU and found a positive correlation (30%). It suggests the link between the injection sites for electrons and protons, which are most likely accelerated at the flare current sheet. We also study the relation between the CME speed and peak proton flux (>10 MeV) at 1 AU and found a good correlation (∼60%), which suggests the proton acceleration by CME driven shocks. In addition, we found two branches (lower and upper) of SEP events with different characteristics. The lower branch SEP events are associated with impulsive rise along with more proton flux whereas the upper branch SEP events exhibit gradual rise and less proton flux. We suggest that flares (current sheet) and CMEs (shocks) both are involved in the particle acceleration for the lower branch, whereas in the upper branch mostly CME driven shocks play an important role in the particle acceleration. **2 May 1998, 29 March, 2001**

Preferential Heating and Acceleration of Heavy Ions in Impulsive Solar Flares

Rahul **Kumar**1,2, David Eichler2, Massimo Gaspari1,3, and Anatoly Spitkovsky1
2017 ApJ 835 295
http://sci-hub.cc/doi/10.3847/1538-4357/835/2/295
https://arxiv.org/pdf/1702.01789.pdf
We simulate decaying turbulence in a homogeneous pair plasma using a three-dimensional electromagnetic particle-in-cell method. A uniform background magnetic field permeates the plasma such that the magnetic pressure is three times larger than the thermal pressure and the turbulence is generated by counter-propagating shear Alfvén waves. The energy predominately cascades transverse to the background magnetic field, rendering the turbulence anisotropic at smaller scales. We simultaneously move several ion species of varying charge to mass ratios in our simulation and show that the particles of smaller charge to mass ratios are heated and accelerated to non-thermal energies at a faster rate. This is in accordance with the enhancement of heavy ions and a non-thermal tail in their energy spectrum observed in the impulsive solar flares. We further show that the heavy ions are energized mostly in the direction perpendicular to the background magnetic field, with a rate consistent with our analytical estimate of the rate of heating due to cyclotron resonance with the Alfvén waves, of which a large fraction is due to obliquely propagating waves.

Cosmic-Ray Modulation due to High-Speed Solar-Wind Streams of Different Sources, Speed, and Duration

Anand **Kumar**, Badruddin
Solar Physics, Volume 289, Issue 11, pp 4267-4296 **2014**
We study the modulation of galactic cosmic rays (GCR) due to high-speed streams (HSS) identified in the solar wind. We compare the GCR modulation due to i) streams with different speed, ii) streams of different duration, and iii) streams from different solar sources. We apply the method of superposed-epoch analysis to analyze the interplanetary plasma and field parameters during the passage of streams with distinct plasma and field characteristics. We use the plasma/field characteristics to distinguish various features of solar sources and interplanetary structures, and discuss the observed differences in the cosmic-ray response. We study the influence of speed, duration, and solar sources of the streams on the GCR modulation. We discuss the relative importance of different solar-wind parameters in the modulation process.

Interplanetary Coronal Mass Ejections, Associated Features, and Transient Modulation of Galactic Cosmic Rays

Anand **Kumar**, Badruddin
Solar Phys., Volume 289, Issue 6, pp 2177-2205**, 2014, File**

Interplanetary structures such as shocks, sheaths, interplanetary counterparts of coronal mass ejections (ICMEs), magnetic clouds, and corotating interaction regions (CIRs) are of special interest for the study of the transient modulation of galactic cosmic rays (GCRs). These structures modulate the GCR intensity with varying amplitudes and recovery-time profiles. It is known that ICMEs are mainly responsible for Forbush decreases in the GCR intensity. However, not all of the ICMEs produce such decreases in GCR intensity. We utilize GCR intensity data recorded by neutron monitors and solar-wind plasma/field data during the passage of ICMEs with different features and structures, and we perform a superposed-epoch analysis of the data. We also adopt the best-fit approach with suitable functions to interpret the observed similarities and differences in various parameters. Using the GCR-effectiveness as a measure of the cosmic-ray response to the passage of ICMEs, about half of the ICMEs identified during 1996 – 2009 are found to produce moderate to very large intensity depressions in GCR intensity. The ICMEs associated with halo CMEs, magnetic-cloud (MC) structures, bidirectional superthermal electron (BDE) signatures, and those driving shocks are 1.5 to 4 times more GCR effective than the ICMEs not associated with these structures/features. Further, the characteristic recovery time of GCR intensity due to shock/BDE/MC/halo-CME-associated ICMEs is larger than those due to ICMEs not associated with these structures/features.

Onset Time of the GLE 72 Observed at Neutron Monitors and its Relation to Electromagnetic Emissions

V. **Kurt**, A. Belov, K. Kudela, H. Mavromichalaki, L. Kashapova, B. Yushkov, C. Sgouropoulos
Solar Physics January **2019**, 294:22
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1407-9.pdf

We present an overview of the ground-level enhancement (GLE 72) of the cosmic-ray intensity associated with the recent powerful solar flare SOL**2017-09-10** (X-ray class X8.9) based on the available neutron monitor (NM) network observations and on data from the satellite GOES 13. The maximum increase at high-latitude near-sea-level NMs was ≈6--7%≈6--7% (2-min averages), greater with better time resolution. A scatter plot of the maximum increase of the GLE versussolar energetic-particle (SEP, proton) flux >100 MeV>100 MeV shows one of the softest spectra among GLEs relative to the SEP fluxes. However, at two high-mountain middle-latitude NMs the increase was ≈1%≈1%, indicating the possibility of proton acceleration up to 6 GeV. Among the analyzed NM data the Fort Smith (FSMT) NM shows the earliest and the rather high increase between 16:06 – 16:08 UT. This indicates an anisotropy in the first phase of the GLE event. We calculate the acceptance cones of several NM stations at high latitudes and contours of pitch angles corresponding to the interplanetary magnetic field (IMF). When employing the available data we find that pion-decay γγ-ray emission onset is in accordance with the time of the main flare energy release. The observed time interval of the impulsive burst of >100 MeV>100 MeVγγ-ray emission probably corresponds to the time of a turbulent current sheet creation. The observed location of the impulsive burst pion-decay emission source coincides with the active region and the cusp-shaped structure. It seems that models assuming sub-relativistic proton production beginning in a turbulent reconnecting current sheet are consistent with the observations. If these particles were released from the Sun during a type III emission with a pion-decay maximum at 16:00:30±30 UT16:00:30±30 UT, we get a plausible path length equal to 1.5±0.3 AU1.5±0.3 AU of the particles responsible for the onset of the SEP event and GLE. The time lag of GLE 72 corresponds to the most probable interval of the time difference between GLE onset and main flare energy release. Although other scenarios are not excluded *we attribute the protons that create the pion-decay emission and the protons responsible for the GLE and SEP event onset to a general population of accelerated particles.*

Some characteristics of the GLE on 10 September 2017

Viktoria **Kurt**, Anatoli Belov, Karel Kudela, Boris Yushkov
Contrib. Astron. Obs. Skalnat´e Pleso 48, 329 – 338, (**2018**)
https://arxiv.org/pdf/1806.00226.pdf
http://www.ta3.sk/caosp/Eedition/FullTexts/vol48no2/pp329-338.pdf **File**

We present a short overview of the event associated with the recent strong solar flare on 10 September 2017 (X 8.2) based on the available data both from satellite GOES-13 and from selected neutron monitors. The onset time of SPE/GLE at 1 AU was found between 16:06 and 16:08 UT. The GLE effect was anisotropic with a maximum increase of 6 %. The maximum energy of accelerated protons was about 6 GeV. We estimated the release time of sub-relativistic protons into open field lines as 15:53 to 15:55 UT.
See Belov et al. (2018)

On the Onset Time of Several SPE/GLE Events: Indications from High-Energy Gamma-Ray and Neutron Measurements by CORONAS-F

Viktoria **Kurt**,1 Karel Kudela,2 Boris Yushkov,1 and Vladimir Galkin1
Advances in Astronomy, Volume **2013**, Article ID 690921, 15 pages. **File**

We analyzed the high-energy gamma and neutron emissions observed by the SONG instrument onboard the CORONAS-F satellite during **August 25, 2001, October 28, 2003, November 4, 2003, and January 20, 2005** solar flares. These flares produced neutrons and/or protons recorded near Earth. The SONG response was consistent with detection of the pion-decay gamma emission and neutrons in these events. We supposed that a time profile of the soft X-ray derivative was a good proxy of time behavior of the flare energy release. Then we showed that time intervals of the maximum both of energy release and pion-decay-emission coincided well. We determined the onset time of GLEs 65, 69 on the basis of neutron monitor data using the superposed epoch method. The time of high-energy proton onset on November 4, 2003 was found from the GOES data. The time delay between the high-energy gamma ray observation and the high-energy protons onset time was **<**5 minutes. This time lag corresponds to the least possible proton propagation time. So, we conclude that in these events both protons interacted in the solar atmosphere and the first protons which arrived to Earth, belonged to one and the same population of the accelerated particles.

Determination of Acceleration Time of Protons Responsible for the GLE Onset

V **Kurt**, B Yushkov, A Belov, I Chertok, V Grechnev

Journal of Physics: Conference Series, v. 409, 012151, **2013**

http://iopscience.iop.org/1742-6596/409/1/012151

Appearance in the solar atmosphere of high-energy protons during major solar flares can be identified from the observation of a broad gamma-ray line in the 70-100 MeV range of the flare emission spectrum. This emission line results from the decay of neutral pions, which, in turn, are produced in interactions of high-energy (> 300 MeV) protons with dense layers of the solar atmosphere. We considered 12 events with clear observations of the pion-decay gamma emission and compared the light curves of this emission with time profiles of different emissions. In 9 events out of 12 we found the onset and peak times of high-energy gamma-rays to be close to the peak times of other electromagnetic emissions and the derivative of the soft X-ray emission. This closeness indicates that efficient acceleration of protons up to subrelativistic energies starts typically close to the time of the main flare energy release. The further study dealt with the data recorded since 1972 by the world neutron monitor network related to 44 Ground level enhancements (GLEs) and light curves of neutral emissions of the associated flares. It revealed that a delay of the earliest arrival time of high-energy protons at 1 AU with respect to the observed peak time of the solar bursts not to exceed 10 min in 30 events. This result indicates that in the majority of events efficient acceleration of protons responsible for the GLE onset has to be close to the time of the main energy release in flares.

A Relation between Solar Flare Manifestations and the GLE Onset

KURT, VICTORIA1, YUSHKOV, BORIS1, BELOV, ANATOLII2, CHERTOK, ILYA 2, GRECHNEV, VICTOR

32 ICRC, BEIJING **2011**

Signatures of protons with energies above several hundred of MeV associated with major solar flares are observed with the neutron monitor network as ground level enhancements (GLEs). The time of proton acceleration on the Sun can be found from observations of a gamma-ray emission with spectral peculiarity around 70-100 MeV that results from the decay of neutral pions, which, in turn, are produced in interactions of high-energy protons with dense layers of the solar atmosphere. We have found previously that the pion-decay emission in these events started and peaked close to the time of the main flare energy release manifested by hard X-ray/gamma-ray continuum, narrow gamma-ray lines and high-frequency radio emission bursts as well as the maximum of the soft X-ray flux derivative. We studied data of the world neutron monitor network and GOES measurements of protons with energies above 500 MeV related to 42 GLEs since 1972 and light curves of the available electromagnetic emissions of the associated flares. Our study has revealed that the delay of the earliest arrival time of high-energy protons at 1 AU with respect to the observed peak time of the solar bursts did not exceed 8 min in 28 events. This result indicates that efficient acceleration of protons responsible for the GLE onset is close to the time of the main flare energy release.

Statistical analysis of solar proton events,

Kurt, V., A. Belov, H. Mavromichalaki, and M. Gerontidou

(**2004**), Ann. Geophys., 22, 2255–2271, **File**.

A new catalogue of 253 solar proton events (SPEs) with energy >10MeV and peak intensity >10 protons/cm2.s.sr (pfu) at the Earth's orbit for three complete 11-year solar cycles (1970-2002) is given. A statistical analysis of this data set of SPEs and their associated flares that occurred during this time period is presented. It is outlined that 231 of these proton events are flare related and only 22 of them are not associated with Ha flares. It is also noteworthy that 42 of these events are registered as Ground Level

Enhancements (GLEs) in neutron monitors. The longitudinal distribution of the associated flares shows that a great number of these events are connected with west flares. This analysis enables one to understand the long-term dependence of the SPEs and the related flare characteristics on the solar cycle which are useful for space weather prediction.

Ground Level Enhancement of May 17, 2012 Observed at South Pole

Takao **Kuwabara**1,3; John Bieber1; John Clem1,3; Paul Evenson1,3; Tom Gaisser1,3; Roger Pyle2; Serap Tilav

http://neutronm.bartol.udel.edu/Talks/Kuwabara_FallAGU_2012.pdf

Determination of interplanetary coronal mass ejection geometry and orientation from ground-based observations of galactic cosmic rays

Kuwabara, T.; Bieber, J. W.; Evenson, P.; Munakata, K.; Yasue, S.; Kato, C.; Fushishita, A.; Tokumaru, M.; Duldig, M. L.; Humble, J. E.; Silva, M. R.; Dal Lago, A.; Schuch, N. J.

J. Geophys. Res., Vol. 114, No. A5, A05109, **2009**

http://dx.doi.org/10.1029/2008JA013717

We have developed a method for determining interplanetary coronal mass ejection (ICME) geometry from galactic cosmic ray data recorded by the ground-based muon detector network. The cosmic ray density depression inside the ICME, which is associated with a Forbush decrease, is represented by an expanding cylinder that is based on a theoretical model of the cosmic ray particle diffusion. ICME geometry and orientation are deduced from observed time variations of cosmic ray density and density gradient and are compared with those deduced from a magnetic flux rope model. From March 2001 to May 2005, 11 ICME events that produced Forbush decreases >2% were observed, and clear variations of the density gradient due to ICME passage were observed in 8 of 11 events. In five of the eight events, signatures of magnetic flux rope structure (large, smooth rotation of magnetic field) were also seen, and the ICME geometry and orientation deduced from the two methods were very similar in three events. This suggests that the cosmic ray-based method can be used as a complementary method for deducing ICME geometry especially for events where a large Forbush decrease is observed.

1. Development of a ground level enhancement alarm system based upon neutron monitors

2. Real-time cosmic ray monitoring system for space weather

Kuwabara, T., J. W. Bieber, J. Clem, P. Evenson, and R. Pyle

1. (**2006**), Space Weather, 4, S10001, doi:10.1029/2006SW000223.

2.. (**2006**), Space Weather, 4, Issue 8, S08001

We have developed a real-time system to monitor high-energy cosmic rays for use in space weather forecasting and specification. Neutron monitors and muon detectors are used for our system, making it possible to observe cosmic rays with dual energy range observations. In large solar energetic particle (SEP) events, the ground level enhancement (GLE) can provide the earliest alert for the onset of the SEP event. The loss cone precursor anisotropy predicts the arrival of interplanetary shocks and the associated interplanetary coronal mass ejections (ICMEs), while the occurrence of bidirectional cosmic ray streaming indicates that Earth is within a large ICME. This article describes a set of real-time Web displays that clearly show the appearance of the GLE, loss cone precursor, and other space weather phenomena related to cosmic rays.

Protons Acceleration in Solar Flares: The Results of the Analysis of Gamma-emission and Neutrons Recorded by the SONG Instrument Onboard the CORONAS-F Satellite

S. N. **Kuznetsov**, V. G. Kurt, B. Yu. Yushkov, I. N. Myagkova, V. I. Galkin, K. Kudela

The Coronas-F Space Mission, Astrophysics and Space Science Library Volume 400, **2014**, pp 301-325

http://link.springer.com/chapter/10.1007/978-3-642-39268-9_10

The SONG instrument onboard CORONAS-F satellite was the only experiment which observed neutral emissions with energies > 20 MeV from solar flares during the 23rd solar activity cycle. High-energy gamma emission was measured by SONG during four major flares, namely: **August 25, 2001, October 28, 2003, November 04, 2003, and January 20, 2005**. Spectra of this emission were restored in the energy range of 0.05–300 MeV and a broad line at energy range 40–100 MeV produced through π 0-decay was distinguished. Generation of this line is a direct indication of the appearance of protons accelerated to energies above 300 MeV in the flare volume. In this way we determined the onset of high-energy proton acceleration. The same protons produce simultaneously high-energy neutrons which can leave the Sun. These neutrons were recorded by the SONG instrument after the flares of August 25, 2001, October 28, 2003, and November 04, 2003. Comparison of protons acceleration time during the October 28, 2003 and January 20, 2005 flares with the onset time of Ground Level Enhancement (GLE) leads to a conclusion that protons responsible for the GLE onset escaped from the solar atmosphere without any delay after their acceleration. The obtained results allow one to understand in a new way a process of particle acceleration up to relativistic energy during flare development.

28 October 2003 flare: High Energy Gamma Emission, Type II Radio Emission and Solar Particle Observations

Kuznetsov, S. N.; Kurt, V. G.; Yushkov, B. Yu.; Myagkova, I. N.; Kudela, K.; Belov, A. V.; Caroubalos, C.; Hilaris, A.; Mavromichalaki, H.; Moussas, X.; Preka-Papadema, P.
International Journal of Modern Physics A, Volume 20, Issue 29, pp. 6705-6707 (**2005**).
http://arxiv.org/pdf/1009.3646v1.pdf
The **28 October 2003** flare gave us the unique opportunity to compare the acceleration time of high-energy protons with the escaping time of those particles which have been measured onboard spacecraft and by neutron monitors network as GLE event. High-energy emission time scale and shock wave height and velocity time dependencies were also studied.

CORONAS-F satellite data on the delay between the proton acceleration on the Sun and their detection at 1 AU.

S.N. **Kuznetsov**[1†], V.G. Kurt[1], B.Yu. Yushkov[1], K.Kudela[2]
ICRC, **2007**

The density compression ratio of shock fronts associated with coronal mass ejections

Ryun-Young **Kwon**, Angelos Vourlidas
Journal of Space Weather and Space Climate **2018**
https://arxiv.org/pdf/1801.04355.pdf
We present a new method to extract the three-dimensional electron density profile and density compression ratio of shock fronts associated with Coronal Mass Ejections (CMEs) observed in white light coronagraph images. We demonstrate the method with two examples of fast halo CMEs (∼ 2000 km s^{-1}) observed on **2011 March 7 and 2014 February 25**. Our method uses the ellipsoid model to derive the three-dimensional (3D) geometry and kinematics of the fronts. The density profiles of the sheaths are modeled with double-Gaussian functions with four free parameters and the electrons are distributed within thin shells behind the front. The modeled densities are integrated along the lines of sight to be compared with the observed brightness in COR2-A, and a χ^2 approach is used to obtain the optimal parameters for the Gaussian profiles. The upstream densities are obtained from both the inversion of the brightness in a pre-event image and an empirical model. Then the density ratio and Alfv´enic Mach number are derived. We find that the density compression peaks around the CME nose, and decreases at larger position angles. The behavior is consistent with a driven shock at the nose and a freely-propagating shock wave at the CME flanks. Interestingly, we find that the supercritical region extends over a large area of the shock and last longer (several tens of minutes) than past reports. *It follows that CME shocks are capable of accelerating energetic particles in the corona over extended spatial and temporal scales and are likely responsible for the wide longitudinal distribution of these particles in the inner heliosphere.* Our results also demonstrate the power of multi-viewpoint coronagraphic observations and forward modeling in remotely deriving key shock properties in an otherwise inaccessible regime.

Mean High-Energy Ionic Charge States during the September 2017 Solar Energetic Particle Events Observed by ACE and STEREO

A. **Labrador**, L. Sollitt, C. Cohen, E. Christian, A. Cummings, R. Leske, G. Mason, R. Mewaldt, E. Stone, T. von Rosenvinge and M. Wiedenbeck
PoS(ICRC**2019**)1102 pdf

Near realtime forecasting of MeV protons on the basis of sub relativistic electrons

Labrenz, Johannes; Heber, Bernd; Kuehl, Patrick; Sarlanis, Christos; Malandraki, Olga; Posner, Arik
EGU General Assembly 2016, held 17-22 April, **2016** in Vienna Austria, p.8076
A major impact on human and robotic space exploration activities is the sudden and prompt occurrence of solar energetic ion events. In order to provide up to an hour warning before these particles arrive at Earth, relativistic electron and below 50 MeV proton data from the Electron Proton Helium Instrument (EPHIN) on SOHO were used to implement the 'Relativistic Electron Alert System for Exploration (REleASE)'. It has been demonstrated that the analysis of relativistic electron time profiles provides a low miss and false alarm rate. High Energy Solar Particle

Events foRecastIng and Analysis (**HESPERIA**) is a project funded within the European Union's Horizon 2020 research and innovation programme (PROTEC-1-2014 Call: Space Weather). Within this project the REleASE forecasting scheme was rewritten in the open access programming language PYTHON and will be made public. As a next step, we have analyzed the possibility to also use, along with relativistic electrons (v > 0.9 c) provided by SOHO, near-relativistic (v <0.8 c) electron measurements from other instruments like the Electron Proton Alpha Monitor (EPAM) aboard the Advanced Composition Explorer (ACE). This would prove to be particularly useful during periods that SOHO does not provide continuous near real-time data. We show that the ACE/EPAM observations can be adapted to the REleASE forecasting scheme to provide reliable SEP forecasts. A comparison of measured and forecast proton intensities by SOHO/EPHIN and ACE/EPAM will be presented. In addition we investigated the false alarm rate and detection probability of solar ion events. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637324.

Interplay of large-scale drift and turbulence in the heliospheric propagation of solar energetic particles

T. **Laitinen** (1), S. Dalla (1) ((1) Jeremiah Horrocks Institute, University of Central Lancashire, UK)
ApJ **2024**
https://arxiv.org/pdf/2412.13895
The gradient and curvature of the Parker spiral interplanetary magnetic field give rise to curvature and gradient guiding centre drifts on cosmic rays. The plasma turbulence present in the interplanetary space is thought to suppress the drifts, however the extent to which they are reduced is not clear. We investigate the reduction of the drifts using a new analytic model of heliospheric turbulence where the dominant 2D component has both the wave vector and the magnetic field vector normal to the Parker spiral, thus fulfilling the main criterion of 2D turbulence. We use full-orbit test particle simulations of energetic protons in the modelled interplanetary turbulence, and analyse the mean drift velocity of the particles in heliolatitude. We release energetic proton populations of 10, 100 and 1000~MeV close to Sun and introduce a new method to assess their drift. We compare the drift in the turbulent heliosphere to drift in a configuration without turbulence, and to theoretical estimates of drift reduction. We find that drifts are reduced by a factor 0.2-0.9 of that expected for the heliospheric configuration without turbulence. This corresponds to a much less efficient suppression than what is predicted by theoretical estimates, particularly at low proton energies. We conclude that guiding centre drifts are a significant factor for the evolution of cosmic ray intensities in the heliosphere including the propagation of solar energetic particles in the inner heliosphere.

Solar Energetic Particle event onsets at different heliolongitudes: The effect of turbulence in Parker Spiral Geometry

T. **Laitinen** (1), S. Dalla (1), C.O.G. Waterfall (1), A. Hutchinson (1)
A&A 673, L8 **2023**
https://arxiv.org/pdf/2303.03168.pdf
https://www.aanda.org/articles/aa/pdf/2023/05/aa46384-23.pdf
Solar energetic particles (SEPs), accelerated during solar eruptions, are observed to rapidly reach a wide heliolongitudinal range in the interplanetary space. To access these locations, the SEPs must have either been accelerated at a wide particle source, or propagated across the mean Parker spiral magnetic field. We study the propagation of SEPs in a new model of heliospheric turbulence which takes the spiral geometry of the average magnetic field into account, to evaluate how this improved description affects the SEP path lengths and the overall evolution of SEP intensities at 1~au. We use full-orbit test particle simulations of 100-MeV protons in a turbulence model dominated by modes that are transverse and 2D with respect to the Parker spiral. ***We find that the SEPs spread along the meandering field lines to arrive at a 60∘ heliolongitudinal range at 1~au within an hour of their injection at the Sun, consistent with the extent of the meandering field lines.*** The SEP onset times are asymmetric with respect to the location connected to the source along the Parker spiral, with westward locations seeing earlier arrival and higher peak intensity. The inferred path length of the first-arriving SEPs is 1.5-1.7~au, 30-50\% longer than the Parker spiral, and 20\% longer than the length of the meandering field lines. Subsequently, the SEP distribution broadens, consistent with diffusive spreading of SEPs across the field lines. Our results indicate that SEPs can propagate rapidly across the mean Parker Spiral field to arrive at wide range of longitudes, even without a wide particle source. The modelled SEP onset times, the peak intensity and subsequent heliolongitudinal evolution replicate several observed SEP event features. Further studies are be required to investigate the relative importance of interplanetary transport and source size in different turbulence environments.

An Analytical Model of Turbulence in Parker Spiral Geometry and Associated Magnetic Field Line Lengths

T. **Laitinen**1, S. Dalla1, C. O. G. Waterfall1, and A. Hutchinson1
2023 ApJ 943 108

https://iopscience.iop.org/article/10.3847/1538-4357/aca892/pdf
Understanding the magnetic connections from the Sun to interplanetary space is crucial for linking in situ particle observations with the solar source regions of the particles. A simple connection along the large-scale Parker spiral magnetic field is made complex by the turbulent random walk of field lines. In this paper, we present the first analytical model of heliospheric magnetic fields where the dominant 2D component of the turbulence is transverse to the Parker spiral. The 2D wave field is supplemented with a minor wave field component that has asymptotic slab geometry at small and large heliocentric distances. We show that turbulence spreads field lines from a small source region at the Sun to a 60° heliolongitudinal and heliolatitudinal range at 1 au, with a standard deviation of the angular spread of the field lines of 14°. Small source regions map to an intermittent range of longitudes and latitudes at 1 au, consistent with dropouts in solar energetic particle intensities. The lengths of the field lines are significantly extended from the nominal Parker spiral length of 1.17 au up to 1.6 au, with field lines from sources at and behind the west limb considerably longer than those closer to the solar disk center. We discuss the implications of our findings for understanding charged particle propagation and the importance of understanding the turbulence properties close to the Sun.

From Sun to interplanetary space: What is the pathlength of Solar Energetic Particles?

T. **Laitinen**, S. Dalla (Jeremiah Horrocks Institute, University of Central Lancashire, Preston, UK)
ApJ **887** 222 **2019**
https://arxiv.org/pdf/1912.01415.pdf
sci-hub.se/10.3847/1538-4357/ab54c7
Solar energetic particles (SEPs), accelerated during solar eruptions, propagate in turbulent solar wind before being observed with in situ instruments. In order to interpret their origin through comparison with remote-sensing observations of the solar eruption, we thus must deconvolve the transport effects due to the turbulent magnetic fields from the SEP observations. Recent research suggests that the SEP propagation is guided by the turbulent meandering of the magnetic fieldlines across the mean magnetic field. However, the lengthening of the distance the SEPs travel, due to the fieldline meandering, has so far not been included in SEP event analysis. This omission can cause significant errors in estimation of the release times of SEPs at the Sun. We investigate the distance travelled by the SEPs by considering them to propagate along fieldlines that meander around closed magnetic islands that are inherent in turbulent plasma. We introduce a fieldline randow walk model which takes into account the physical scales associated to the magnetic islands. Our method remedies the problem of the diffusion equation resulting in unrealistically short pathlengths, and the fractal dependence of the pathlength of random walk on the length of the random-walk step. We find that the pathlength from the Sun to 1 au can be below the nominal Parker spiral length for SEP events taking place at solar longitudes 45E to 60W, whereas the western and behind-the-limb particles can experience pathlengths longer than 2 au due to fieldline meandering.

Forecasting Solar Energetic Particle Fluence with Multi-Spacecraft Observations

T. **Laitinen** (1), S. Dalla (1), M. Battarbee (1), M. S. Marsh (2)
Proceedings of IAU Symposium 335: Space Weather of the Heliosphere: Processes and Forecasts **2018**
https://arxiv.org/pdf/1802.10086.pdf
Forecasting Solar Energetic Particle (SEP) fluence, as integrated over an SEP event, is an important element when estimating the effect of solar eruptions on humans and technology in space. Current real-time estimates are based on SEP measurements at a single location in space. However, the interplanetary magnetic field corotates with the Sun approximately 13 grad each day with respect to Earth, thus in 4 days a near-Earth spacecraft will have changed their connection about 60 grad from the original SEP source. We estimate the effect of the corotation on particle fluence using a simple particle transport model, and show that ignoring corotation can cause up to an order of magnitude error in fluence estimations, depending on the interplanetary particle transport conditions. We compare the model predictions with STEREO observations of SEP events.

The effect of turbulence strength on meandering field lines and Solar Energetic Particle event extents

T. **Laitinen** (1), F. Effenberger (2,3), A. Kopp (4), S. Dalla
Journal of Space Weather and Space Climate 8, A13 **2018**
https://arxiv.org/pdf/1801.03489.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170025.pdf
Insights into the processes of Solar Energetic Particle (SEP) propagation are essential for understanding how solar eruptions affect the radiation environment of near-Earth space. SEP propagation is influenced by turbulent magnetic fields in the solar wind, resulting in stochastic transport of SEPs to Earth. Multi-spacecraft observations suggest that the cross-field propagation shapes the SEP fluxes at Earth strongly. However, modelling SEP cross-field transport as spatial diffusion has been shown to be insufficient without use of unrealistically large cross-field diffusion coefficients. Recent work has shown that the early-time propagation of energetic particles across the mean field direction in turbulent fields is not diffusive, as the particles propagating along meandering field lines. This early-

time transport mode results in fast access of the particles across the mean field direction, in agreement with the SEP observations. In this work, we demonstrate the significance of turbulence strength on evolution of the SEP radiation environment near Earth. We calculate the transport parameters with a turbulence transport model, parametrised by the SEP parallel scattering mean free path at 1~AU, $\lambda_{*\parallel}$, and show that the parallel and cross-field transport are connected, with conditions resulting in slow parallel transport corresponding to wider events. We find a scaling $\sigma_{\phi,\max} \propto (1/\lambda_{*\parallel})^{1/4}$ for the Gaussian fitting of the longitudinal distribution of maximum intensities. The longitudes with highest intensities are shifted towards the west for strong scattering conditions. Our results emphasise the importance of understanding both the SEP transport and the interplanetary turbulence conditions for modelling and predicting the SEP radiation environment at Earth.

Early propagation of energetic particles across the mean field in turbulent plasmas

T. **Laitinen**, S. Dalla, D. Marriott

MNRAS **2017**

https://arxiv.org/pdf/1706.06580.pdf

Propagation of energetic particles across the mean field direction in turbulent magnetic fields is often described as spatial diffusion. Recently, it has been suggested that initially the particles propagate systematically along meandering field lines, and only later reach the time-asymptotic diffusive cross-field propagation. In this paper, we analyse cross-field propagation of 1--100 MeV protons in composite 2D-slab turbulence superposed on a constant background magnetic field, using full-orbit particle simulations, to study the non-diffusive phase of particle propagation with a wide range of turbulence parameters. We show that the early-time non-diffusive propagation of the particles is consistent with particle propagation along turbulently meandering field lines. This results in a wide cross-field extent of the particles already at the initial arrival of particles to a given distance along the mean field direction, unlike when using spatial diffusion particle transport models. The cross-field extent of the particle distribution remains constant for up to tens of hours in turbulence environment consistent with the inner heliosphere during solar energetic particle events. Subsequently, the particles escape from their initial meandering field lines, and the particle propagation across the mean field reaches time-asymptotic diffusion. Our analysis shows that in order to understand solar energetic particle event origins, particle transport modelling must include non-diffusive particle propagation along meandering field lines.

Energetic particle transport across the mean magnetic field: before diffusion

T. **Laitinen**, S. Dalla

ApJ 834 127 **2017**

https://arxiv.org/pdf/1611.05347v1.pdf

Current particle transport models describe the propagation of charged particles across the mean field direction in turbulent plasmas as diffusion. However, recent studies suggest that at short time-scales, such as soon after solar energetic particle (SEP) injection, particles remain on turbulently meandering field lines, which results in non-diffusive initial propagation across the mean magnetic field. In this work, we use a new technique to investigate how the particles are displaced from their original field lines, and quantify the parameters of the transition from field-aligned particle propagation along meandering field lines to particle diffusion across the mean magnetic field. We show that the initial decoupling of the particles from the field lines is slow, and particles remain within a Larmor radius from their initial meandering field lines for tens to hundreds of Larmor periods, for 0.1-10 MeV protons in turbulence conditions typical of the solar wind at 1~AU. Subsequently, particles decouple from their initial field lines and after hundreds to thousands of Larmor periods reach time-asymptotic diffusive behaviour consistent with particle diffusion across the mean field caused by the meandering of the field lines. We show that the typical duration of the pre-diffusive phase, hours to tens of hours for 10 MeV protons in 1~AU solar wind turbulence conditions, is significant for SEP propagation to 1~AU and must be taken into account when modelling SEP propagation in the interplanetary space.

Experimental overview on Future Solar and Heliospheric research

T. **Laitinen** (Jeremiah Horrocks Institute, University of Central Lancashire, Preston, UK)

XXV ECRS 2016 Proceedings - eConf C16-09-04.3 **2017**

https://arxiv.org/pdf/1702.05091.pdf

Solar and heliospheric cosmic rays provide a unique perspective in cosmic ray research: we can observe not only the particles, but also the properties of the plasmas in which the they are accelerated and propagate, using in situ and high-resolution remote sensing instruments. The heliospheric cosmic ray observations typically require space missions, which face stern competition against planetary and astrophysics missions, and it can take up to decades from the initial concept proposal until the actual observing of the cosmic rays can commence. Therefore it is important to have continuity in the cosmic ray mission timeline. In this overview, we review the current status and the future outlook in the experimental solar and heliospheric research. We find that the current status of the available cosmic ray observations is good, but that many of the spacecraft are near the end of their feasible mission life. We describe the three missions currently being prepared for launch, and discuss the future outlook of the solar and heliospheric cosmic ray missions.

Solar Energetic Particle Access to Distant Longitudes via Turbulent Field-Line Meandering

T. **Laitinen** (1), A. Kopp (2), F. Effenberger (3,4), S. Dalla (1), M.S. Marsh

A&A 591, A18 (**2016**)

http://www.aanda.org/articles/aa/pdf/2016/07/aa27801-15.pdf

See also http://arxiv.org/pdf/1508.03164v1.pdf

Context. Current solar energetic particle (SEP) propagation models describe the effects of interplanetary plasma turbulence on SEPs as diffusion, using a Fokker-Planck (FP) equation. However, FP models cannot explain the observed fast access of SEPs across the average magnetic field to regions that are widely separated in longitude within the heliosphere without using unrealistically strong cross-field diffusion.
Aims. We study whether the recently suggested early non-diffusive phase of SEP propagation can explain the wide SEP events with realistic particle transport parameters.
Methods. We used a novel model that accounts for the SEP propagation along field lines that meander as a result of plasma turbulence. Such a non-diffusive propagation mode has been shown to dominate the SEP cross-field propagation early in the SEP event history. We compare the new model to the traditional approach, and to SEP observations.
Results. Using the new model, we reproduce the observed longitudinal extent of SEP peak fluxes that are characterised by a Gaussian profile with $\sigma = 30-50°$, while current diffusion theory can only explain extents of 11° with realistic diffusion coefficients. Our model also reproduces the timing of SEP arrival at distant longitudes, which cannot be explained using the diffusion model.
Conclusions. The early onset of SEPs over a wide range of longitudes can be understood as a result of the effects of magnetic field-line random walk in the interplanetary medium and requires an SEP transport model that properly describes the non-diffusive early phase of SEP cross-field propagation. **Nov 3–4,**

Correcting for interplanetary scattering in velocity dispersion analysis of solar energetic particles

T. **Laitinen** (1), K. Huttunen-Heikinmaa (2), E. Valtonen (2), S. Dalla

ApJ **806** 114 **2015**

http://arxiv.org/pdf/1504.06166v1.pdf

To understand the origin of Solar Energetic Particles (SEPs), we must study their injection time relative to other solar eruption manifestations. Traditionally the injection time is determined using the Velocity Dispersion Analysis (VDA) where a linear fit of the observed event onset times at 1 AU to the inverse velocities of SEPs is used to derive the injection time and path length of the first-arriving particles. VDA does not, however, take into account that the particles that produce a statistically observable onset at 1 AU have scattered in the interplanetary space. We use Monte Carlo test particle simulations of energetic protons to study the effect of particle scattering on the observable SEP event onset above pre-event background, and consequently on VDA results. We find that the VDA results are sensitive to the properties of the pre-event and event particle spectra as well as SEP injection and scattering parameters. In particular, a VDA-obtained path length that is close to the nominal Parker spiral length does not imply that the VDA injection time is correct. We study the delay to the observed onset caused by scattering of the particles and derive a simple estimate for the delay time by using the rate of intensity increase at the SEP onset as a parameter. We apply the correction to a magnetically well-connected SEP event of **June 10 2000**, and show it to improve both the path length and injection time estimates, while also increasing the error limits to better reflect the inherent uncertainties of VDA.

Energetic particle cross-field propagation early in a solar event

T. **Laitinen**, S. Dalla, and M.S. Marsh

E-print, July **2013**; **2013** ApJ 773 L29

Solar energetic particles (SEPs) have been observed to easily spread across heliographic longitudes, and the mechanisms responsible for this behavior remain unclear. We use full-orbit simulations of a 10 MeV proton beam in a turbulent magnetic field to study to what extent the spread across the mean field can be described as diffusion early in a particle event. We compare the full-orbit code results to solutions of a Fokker-Planck equation including spatial and pitch angle diffusion, and of one including also propagation of the particles along random-walking magnetic field lines. We find that propagation of the particles along meandering field lines is the key process determining their cross-field spread at 1 AU at the beginning of the simulated event. The mean square displacement of the particles an hour after injection is an order of magnitude larger than that given by the diffusion model, indicating that models employing spatial cross-field diffusion cannot be used to describe early evolution of an SEP event. On the other hand, the diffusion of the particles from their initial field lines is negligible during the first 5 hr, which is consistent with the observations of SEP intensity dropouts. We conclude that modeling SEP events must take into account the particle propagation along meandering field lines for the first 20 hr of the event.

Role of Structured Turbulence in Energetic Particle Propagation

Timo **Laitinen**, Silvia Dalla and James Kelly,
UKSP nugget: 25, Aug **2012**
http://www.uksolphys.org/?p=4977
How clumps and structures in the solar wind affect SEPs and Cosmic Rays.
Typically, studies of solar energetic particles use a very idealised description of the interplanetary magnetic field through which the particles propagate. In this nugget we investigate how a moreT realistic model of the field, which includes structured, nonlinearly evolving turbulence, affects energetic particle transport. We investigate particle propagation in this field, and compare our results on cross-field propagation to those obtained from an idealised field description. To describe the field, we have introduce the concept of turbulent envelopes [3].

Element Abundances in Impulsive Solar Energetic Particle Events

J. Martin **Laming**, Natsuha Kuroda
ApJ **951** 86 **2023**
https://arxiv.org/pdf/2305.11816.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/acd69a/pdf
We outline and discuss a model for the enhanced abundances of trans-Fe elements in impulsive Solar Energetic Particle (SEP) events, where large mass dependent abundance enhancements are frequently seen. It comes about as a variation of the ponderomotive force model for the First Ionization Potential (FIP) Effect, i.e. the increase in coronal abundance of elements like Fe, Mg, and Si that are ionized in the solar chromosphere relative to those that are neutral. In this way, the fractionation region is placed in the chromosphere, and is connected to the solar envelope allowing the huge abundance variations to occur, that might otherwise be problematic with a coronal fractionation site. The principal mechanism behind the mass-independent FIP fractionation becoming the mass dependent impulsive SEP fractionation is the suppression of acoustic waves in the chromosphere. The ponderomotive force causing the fractionation must be due to torsional Alfven waves, which couple much less effectively to slow modes than do shear waves, and upward propagating acoustic waves deriving from photospheric convection must be effectively mode converted to fast modes at the chromospheric layer where Alfven and sound speeds are equal, and subsequently totally internally reflected. We further discuss observations of the environments thought to be the source of impulsive SEPs, and the extent to which the real Sun might meet these conditions.

Critical Mach Numbers for Magnetohydrodynamic Shocks with Accelerated Particles and Waves

J. Martin **Laming**
ApJ **940** 98 **2022**
https://arxiv.org/pdf/2210.09365.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac98bb/pdf
The first critical fast Mach number is defined for a magnetohydrodynamic shock as the Mach number where the shock transitions from subcritical, laminar, behavior to supercritical behavior, characterized by incident ion reflection from the shock front. The ensuing upstream waves and turbulence are convected downstream leading to a turbulent shock structure. Formally this is the Mach number where plasma resistivity can no longer provide sufficient dissipation to establish a stable shock, and is characterized by the downstream flow speed becoming subsonic. We revisit these calculations, including in the MHD jump conditions terms modeling the plasma energy loss to accelerated particles and the presence of waves associated with these particles. The accelerated particle contributions make an insignificant change, but the associated waves have a more important effect. Upstream waves can be strongly amplified in intensity on passing through the shock, and represent another means of shock dissipation. The presence of such waves therefore increases the first critical fast Mach number, especially at quasi-parallel shock where wave excitation is strongest. These effects may have significance for the solar regions where shock waves accelerate particles and cause Type II and Type III radio bursts, and also contribute to the event-to-event variability of SEP acceleration.

ON THE REMOTE DETECTION OF SUPRATHERMAL IONS IN THE SOLAR CORONA AND THEIR ROLE AS SEEDS FOR SOLAR ENERGETIC PARTICLE PRODUCTION

J. Martin **Laming**1, J. Daniel Moses1, Yuan-Kuen Ko1, Chee K. Ng2, Cara E. Rakowski4, and Allan J. Tylka
2013 ApJ 770 73

Forecasting large solar energetic particle (SEP) events associated with shocks driven by fast coronal mass ejections (CMEs) poses a major difficulty in the field of space weather. Besides issues associated with CME initiation, the SEP intensities are difficult to predict, spanning three orders of magnitude at any given CME speed. Many lines of indirect evidence point to the pre-existence of suprathermal seed particles for injection into the acceleration process as a key ingredient limiting the SEP intensity of a given event. This paper outlines the observational and theoretical basis for the inference that a suprathermal particle population is present prior to large SEP events, explores various scenarios for generating seed particles and their observational signatures, and explains how such suprathermals could be detected through measuring the wings of the H I Lyα line.

Perpendicular Transport in the Inner Heliosphere: A Quick and Dirty Approach

F. **Lampa**1 and M.-B. Kallenrode1

Solar Phys., 269(2), 423-440, **2009**

In previous studies, transport of solar energetic particles in the inner heliosphere was regarded as one-dimensional along the Archimedean field spiral; *i.e.*, any perpendicular transport is neglected. We extend Roelof's equation of focused transport for solar energetic particles to accommodate perpendicular transport in the plane of the ecliptic. Numerically, this additional term is solved with an implicit Laasonen scheme. In this first approximation, it is solved for azimuthal instead of perpendicular transport – these are similar in the inner heliosphere where the Archimedean field is almost radial. The intent of the study is to estimate the possible influence of perpendicular transport, but not to fit energetic particle events; thus, the particle source stays fixed on the Sun. For typical ratios $\kappa_{\perp}/\kappa_{\parallel}$ between 0.02 and 0.1 at 1 AU scaled with r^2 as suggested in nonlinear guiding-center theory, we find that *i*) an azimuthal spread over some 10° occurs within a few hours, *ii*) the variation of maximum intensities with longitude is comparable to the ones inferred from multispacecraft observations, and *iii*) on a given field line, intensity and anisotropy-time profiles are modified such that fits with the two-dimensional transport model give different combinations of injection profiles and mean free paths. Implications for the interpretation of intensity and anisotropy-time profiles observed in interplanetary space and consequences for our understanding of particle propagation and acceleration in space are discussed.

A detailed survey of the parallel mean free path of solar energetic particle protons and electrons

J.T. **Lang**, R.D. Strauss, N.E. Engelbrecht, J.P. van den Berg, N. Dresing, D. Ruffolo, R. Bandyopadhyay

ApJ **971** 105 **2024**

https://arxiv.org/pdf/2406.05765

https://iopscience.iop.org/article/10.3847/1538-4357/ad55c3/pdf

In this work, more than a dozen solar energetic particle (SEP) events are identified where the source region is magnetically well-connected to at least one spacecraft at 1~au. The observed intensity-time profiles, for all available proton and electron energy channels, are compared to results computed using a numerical 1D SEP transport model in order to derive the parallel mean free paths (pMFPs) as a function of energy (or rigidity) at 1~au. These inversion results are then compared to theoretical estimates of the pMFP, using observed turbulence quantities with observationally-motivated variations as input. For protons, a very good comparison between inversion and theoretical results is obtained. It is shown that the observed inter-event variations in the inversion pMFP values can be explained by natural variations in the background turbulence values. For electrons, there is relatively good agreement with pMFPs derived assuming the damping model of dynamical turbulence, although the theoretical values are extremely sensitive to the details of the turbulence dissipation range which themselves display a high level of variation. **20 January 2022**

Table 1. Information on each solar event and magnetically connected spacecraft used in the results presented in this study.

A Rapid Sequence of Solar Energetic Particle Events Associated with a Series of Extreme-ultraviolet Jets: Solar Orbiter, STEREO-A, and Near-Earth Spacecraft Observations

D. **Lario**1, L. A. Balmaceda1,2, R. Gómez-Herrero3, G. M. Mason4, V. Krupar1,5, C. Mac Cormack1,6, A. Kouloumvakos4, I. Cernuda3, H. Collier7, I. G. Richardson1,8

2024 ApJ 975 84

https://iopscience.iop.org/article/10.3847/1538-4357/ad6c47/pdf

A series of solar energetic electron (SEE) events was observed from **2022 November 9 to November 15** by Solar Orbiter, STEREO-A, and near-Earth spacecraft. At least 32 SEE intensity enhancements at energies >10 keV were clearly distinguishable in Solar Orbiter particle data, with 13 of them occurring on **November 11**. Several of these events were accompanied by ≲10 MeV proton and ≲2 MeV nucleon−1 heavy-ion intensity enhancements. By combining remote-sensing and in situ data from the three viewpoints (Solar Orbiter and STEREO-A were ∼20° and

∼15° east of Earth, respectively), we determine that the origin of this rapid succession of events was a series of brightenings and jetlike eruptions detected in extreme ultraviolet (EUV) observations from the vicinity of two active regions. We find a close association between these EUV phenomena, the occurrence of hard X-ray flares, type III radio bursts, and the release of SEEs. For the most intense events, usually associated with extended EUV jets, the distance between the site of these solar eruptions and the estimated magnetic connectivity regions of each spacecraft with the Sun did not prevent the arrival of electrons at the three locations. The capability of jets to drive coronal fronts does not necessarily imply the observation of an SEE event. Two peculiar SEE events on **November 9 and 14**, observed only at electron energies ≲50 keV but rich in ≲1 MeV nucleon−1 heavy ions, originated from slow-rising confined EUV emissions, for which the process resulting in energetic particle release to interplanetary space is unclear.

High-energy (>40 MeV) Proton Intensity Enhancements Associated with the Passage of Interplanetary Shocks at 1 au

D. **Lario**1, I. G. Richardson1,2, A. Aran3, and N. Wijsen1,2

2023 ApJ 950 89

https://iopscience.iop.org/article/10.3847/1538-4357/acc9c5/pdf **File**

We analyze periods with elevated >40 MeV proton intensities observed near Earth over a time span of 43 yr (1973–2016) that coincide with the passage of interplanetary (IP) shocks. Typically, elevated proton intensities result from large solar energetic particle (SEP) events. The IP shocks observed during these elevated-intensity periods may or may not be related to the origin of the SEP events. By choosing those cases when the shocks can be confidently associated with the solar eruption that generated the SEP event, we analyze the components of these SEP events that are localized in the vicinity of the shock (so-called "energetic storm particles", ESPs), focusing on those events where the ESP component exceeds 40 MeV. We examine the interdependence of these high-energy ESPs with (i) the properties of the solar eruptions that generated the shocks and the SEP events, and (ii) the parameters of the shocks at their arrival at 1 au. The solar eruptions at the origin of the shocks producing >40 MeV proton ESP intensity enhancements are within ±50° longitude of central meridian and are associated with fast coronal mass ejections (plane-of-sky speeds ≳1000 km s−1). The ESP events with the largest >40 MeV proton intensity increases tend to occur when there are structures such as intervening IP coronal mass ejections and other unrelated shocks present in the solar wind through which the shock is propagating. Among the various local shock parameters considered, only the shock speed shows a certain degree of correlation with the observed ESP intensity increase.

14 Oct 1981, 16-17 Aug 1989, 19-20 Oct 1989, 20-21 Feb 1994, 25-26 Aug 1998, 10-12 Sep 2014

Table 1 Selected Shock Passages Occurring During Enhanced ∼40 MeV Proton Intensities 1974-1978

Influence of Large-scale Interplanetary Structures on the Propagation of Solar Energetic Particles: The Multispacecraft Event on 2021 October 9

D. **Lario**1, N. Wijsen2, R. Y. Kwon3, B. Sánchez-Cano4, I. G. Richardson1,5, D. Pacheco6, E. Palmerio7, M. L. Stevens8, A. Szabo1, D. Heyner9Show full author list

2022 ApJ 934 55

https://iopscience.iop.org/article/10.3847/1538-4357/ac6efd/pdf

An intense solar energetic particle (SEP) event was observed on **2021 October 9** by multiple spacecraft distributed near the ecliptic plane at heliocentric radial distances R ≲ 1 au and within a narrow range of heliolongitudes. A stream interaction region (SIR), sequentially observed by Parker Solar Probe (PSP) at R = 0.76 au and 48° east from Earth (ϕ = E48°), STEREO-A (at R = 0.96 au, ϕ = E39°), Solar Orbiter (SolO; at R = 0.68 au, ϕ = E15°), BepiColombo (at R = 0.33 au, ϕ = W02°), and near-Earth spacecraft, regulated the observed intensity-time profiles and the anisotropic character of the SEP event. PSP, STEREO-A, and SolO detected strong anisotropies at the onset of the SEP event, which resulted from the fact that PSP and STEREO-A were in the declining-speed region of the solar wind stream responsible for the SIR and from the passage of a steady magnetic field structure by SolO during the onset of the event. By contrast, the intensity-time profiles observed near Earth displayed a delayed onset at proton energies ≳13 MeV and an accumulation of ≲5 MeV protons between the SIR and the shock driven by the parent coronal mass ejection (CME). Even though BepiColombo, STEREO-A, and SolO were nominally connected to the same region of the Sun, the intensity-time profiles at BepiColombo resemble those observed near Earth, with the bulk of low-energy ions also confined between the SIR and the CME-driven shock. This event exemplifies the impact that intervening large-scale interplanetary structures, such as corotating SIRs, have in shaping the properties of SEP events.

Comparative Analysis of the 2020 November 29 Solar Energetic Particle Event Observed by Parker Solar Probe

D. **Lario**1, I. G. Richardson1,2, E. Palmerio3,4, N. Lugaz5, S. D. Bale3,6,7,8, M. L. Stevens9, C. M. S. Cohen10, J. Giacalone11, D. G. Mitchell12, A. Szabo1Show full author list

2021 ApJ 920 123

https://iopscience.iop.org/article/10.3847/1538-4357/ac157f/pdf
https://doi.org/10.3847/1538-4357/ac157f
We analyze two specific features of the intense solar energetic particle (SEP) event observed by Parker Solar Probe (PSP) between 2020 November 29 and 2020 December 2. The interplanetary counterpart of the coronal mass ejection (CME) on 2020 November 29 that generated the SEP event (hereafter ICME-2) arrived at PSP (located at 0.8 au from the Sun) on 2020 December 1. ICME-2 was preceded by the passage of an interplanetary shock at 18:35 UT on 2020 November 30 (hereafter S2), that in turn was preceded by another ICME (i.e., ICME-1) observed in situ on 2020 November 30. The two interesting features of this SEP event at PSP are the following: First, the presence of the intervening ICME-1 affected the evolution of the ≲8 MeV proton intensity-time profiles resulting in the observation of inverted energy spectra throughout the passage of ICME-1. Second, the sheath region preceding ICME-2 was characterized by weak magnetic fields compared to those measured immediately after the passage of the shock S2 and during the passage of ICME-2. Comparison with prior SEP events measured at 1 au but with similar characteristics indicates that (1) low-energy particles accelerated by S2 were excluded from propagating throughout ICME-1, and (2) the low magnetic fields measured in the sheath of ICME-2 resulted from the properties of the upstream solar wind encountered by ICME-2 that was propagated into the sheath, whereas the energy density of the high-energy particles in the sheath did not play a dominant role in the formation of these low magnetic fields.
29 Nov-2 Dec 2020

Fast and Wide CMEs without Observed >20 MeV Protons

D. **Lario**1, R. Y. Kwon2, L. Balmaceda1,3, I. G. Richardson1,4, V. Krupar1,5,6, B. J. Thompson1, O. C. St Cyr1, L. Zhao7, and M. Zhang7
2020 ApJ 889 92 **File**
sci-hub.si/10.3847/1538-4357/ab64e1
Statistical studies have found a close association between large solar energetic particle (SEP) events and fast and wide coronal mass ejections (CMEs).However, not all fast and wide CMEs have an associated SEP event. From the Coordinated Data Analysis Web catalog of CMEs observed by the Solar and Heliospheric Observatory (SOHO) between 2009 January 1 and 2014 September 30, we select fast (plane-of-sky speed >1000 km s−1) and wide (plane-of-sky angular width >120°) CMEs and determine whether >20 MeV protons were detected by either SOHO or the Solar TErrestrial RElations Observatory (STEREO-A or STEREO-B). Among the 123 selected CMEs, only 11 did not produce a >20 MeV proton intensity increase at any of the three spacecraft. We use multispacecraft coronagraph observations to reevaluate the speeds and widths of the CMEs. The 11 CMEs without observed >20 MeV protons tend to be in the narrow and slow end of the distribution of the selected CMEs. We consider several factors that might play a role in the nonobservation of high-energy particles in these events, including (1) the ambiguous determination of the CME parameters, (2) the inefficiency of the particle sources to produce >20 MeV protons, (3) the lack of magnetic connection between particle sources and any spacecraft, and (4) the lack of particles accelerated and released during the parent solar eruptions. Whereas the extent of the high Mach number regions formed in front of the CME is limited, the characteristic that seems to distinguish those fast and wide CMEs that lack observed >20 MeV protons is a deficit in the release of particles during the solar eruptions.
2010 Mar 6, 2011 Mar 19, 2011 May 6, 2011 May 18, 2011 Oct 1, 2011 Dec 19, 2012 Jun 23, 2013 Feb 12, 2014 Feb 25, 2014 Apr 12, 2014 May 5, 2014 Jul 28
Table 1 Properties of the CME Events without Observed >20 MeV Proton Enhancements

On the Link between the Release of Solar Energetic Particles Measured at Widespread Heliolongitudes and the Properties of the Associated Coronal Shocks

D. **Lario**1, R.-Y. Kwon1,2, P. Riley3, and N. E. Raouafi1
2017 ApJ 847 103
http://sci-hub.cc/http://iopscience.iop.org/0004-637X/847/2/103/
Under the paradigm that the main agents in the acceleration of solar energetic particles (SEPs) are shocks initially driven by coronal mass ejections, we analyze whether the properties of the shocks in the corona inferred from combining extreme-ultraviolet (EUV) and white-light (WL) observations from multiple vantage points together with magnetohydrodynamic (MHD) simulations of the corona can be used to determine the release of SEPs into different regions of the heliosphere and hence determine the longitudinal extent of the SEP events. We analyze the SEP events observed on **2011 November 3, 2013 April 11, and 2014 February 25** over a wide range of heliolongitudes. MHD simulations provide the characteristics of the background medium where shocks propagate, in particular the Alfvén and sound speed profiles that allow us to determine both the extent of the EUV waves in the low corona and the fast magnetosonic Mach number (MFM) of the shocks. The extent of the EUV waves in the low corona is controlled by this background medium and does not coincide with the extent of the SEP events in the heliosphere. Within the uncertainties of (i) the extent and speed of the shock inferred from EUV and WL images and (ii) the assumptions made in the MHD models, we follow the evolution of M FM at the region of the shock magnetically connected to each spacecraft. *The estimated release times of the first SEPs measured by each spacecraft does not coincide with the time when the M FM at this region exceeds a given threshold.*

The Solar Energetic Particle Event of 2010 August 14: Connectivity with the Solar Source Inferred from Multiple Spacecraft Observations and Modeling

D. **Lario**1, R.-Y. Kwon1,2, I. G. Richardson3,4, N. E. Raouafi1, B. J. Thompson3, T. T. von Rosenvinge3, M. L. Mays3, P. A. Mäkelä3,5, H. Xie3,5, H. M. Bain6, M. Zhang7, L. Zhao7, H. V. Cane8, A. Papaioannou9, N. Thakur3,5, and P. Riley10

2017 ApJ 838 51 **File**

http://iopscience.iop.org.sci-hub.cc/0004-637X/838/1/51/

http://sci-hub.cc/10.3847/1538-4357/aa63e4

https://iopscience.iop.org/article/10.3847/1538-4357/aa63e4/pdf

We analyze one of the first solar energetic particle (SEP) events of solar cycle 24 observed at widely separated spacecraft in order to assess the reliability of models currently used to determine the connectivity between the sources of SEPs at the Sun and spacecraft in the inner heliosphere. This SEP event was observed on **2010 August 14** by near-Earth spacecraft, STEREO-A (~80° west of Earth) and STEREO-B (~72° east of Earth). In contrast to near-Earth spacecraft, the footpoints of the nominal magnetic field lines connecting STEREO-A and STEREO-B with the Sun were separated from the region where the parent fast halo coronal mass ejection (CME) originated by ~88° and ~47° in longitude, respectively. We discuss the properties of the phenomena associated with this solar eruption. Extreme ultraviolet and white-light images are used to specify the extent of the associated CME-driven coronal shock. We then assess whether the SEPs observed at the three heliospheric locations were accelerated by this shock or whether transport mechanisms in the corona and/or interplanetary space provide an alternative explanation for the arrival of particles at the poorly connected spacecraft. A possible scenario consistent with the observations indicates that the observation of SEPs at STEREO-B and near Earth resulted from particle injection by the CME shock onto the field lines connecting to these spacecraft, whereas SEPs reached STEREO-A mostly via cross-field diffusive transport processes. The successes, limitations, and uncertainties of the methods used to resolve the connection between the acceleration sites of SEPs and the spacecraft are evaluated.

LONGITUDINAL PROPERTIES OF A WIDESPREAD SOLAR ENERGETIC PARTICLE EVENT ON 2014 FEBRUARY 25: EVOLUTION OF THE ASSOCIATED CME SHOCK

D. **Lario**1, R.-Y. Kwon1,2, A. Vourlidas1, N. E. Raouafi1, D. K. Haggerty1, G. C. Ho1, B. J. Anderson1, A. Papaioannou3, R. Gómez-Herrero4, N. Dresing5

2016 ApJ 819 72

https://www.researchgate.net/profile/Ryun_Young_Kwon/publications

We investigate the solar phenomena associated with the origin of the solar energetic particle (SEP) event observed on **2014 February 25** by a number of spacecraft distributed in the inner heliosphere over a broad range of heliolongitudes. These include spacecraft located near Earth; the twin Solar TErrestrial RElations Observatory spacecraft, STEREO-A and STEREO-B, located at ~1 au from the Sun 153° west and 160° east of Earth, respectively; the MErcury Surface Space ENvironment GEochemistry and Ranging mission (at 0.40 au and 31° west of Earth); and the Juno spacecraft (at 2.11 au and 48° east of Earth). Although the footpoints of the field lines nominally connecting the Sun with STEREO-A, STEREO-B and near-Earth spacecraft were quite distant from each other, an intense high-energy SEP event with Fe-rich prompt components was observed at these three locations. The extent of the extreme-ultraviolet wave associated with the solar eruption generating the SEP event was very limited in longitude. However, the white-light shock accompanying the associated coronal mass ejection extended over a broad range of longitudes. As the shock propagated into interplanetary space it extended over at least ~190° in longitude. The release of the SEPs observed at different longitudes occurred when the portion of the shock magnetically connected to each spacecraft was already at relatively high altitudes (2 $R_\odot$ above the solar surface). The expansion of the shock in the extended corona, as opposite to near the solar surface, determined the SEP injection and SEP intensity-time profiles at different longitudes.

The Solar Energetic Particle Event on 2013 April 11: An Investigation of its Solar Origin and Longitudinal Spread

D. **Lario**, N.E. Raouafi, R.-Y. Kwon, J. Zhang, R. Gomez-Herrero, N. Dresing, P. Riley

2014 ApJ 797 **8**

http://arxiv.org/pdf/1410.5490v1.pdf

We investigate the solar phenomena associated with the origin of the solar energetic particle (SEP) event observed on **2013 April 11** by a number of spacecraft distributed in the inner heliosphere over a broad range of heliolongitudes. We use Extreme UltraViolet (EUV) and white-light coronagraph observations from the Solar Dynamics Observatory (SDO), the SOlar and Heliospheric Observatory (SOHO) and the twin Solar TErrestrial RElations Observatory spacecraft (STEREO-A and STEREO-B) to determine the angular extent of the EUV wave and coronal mass ejection (CME) associated with the origin of the SEP event. We compare the estimated release time of SEPs observed at each spacecraft with the arrival time of the structures associated with the CME at the footpoints of the field lines connecting each spacecraft with the Sun. Whereas the arrival of the EUV wave and CME-driven shock at the footpoint of STEREO-B is consistent, within uncertainties, with the release time of the particles observed by this spacecraft, the EUV wave never reached the footpoint of the field lines connecting near-Earth observers with the Sun, even though an intense SEP event was observed there. We show that the west flank of the CME-driven shock propagating at high altitudes above the solar surface was most likely the source of the particles observed near Earth, but it did not leave any EUV trace on the solar disk. **We conclude that the angular extent of the EUV wave on the solar surface did not agree with the longitudinal extent of the SEP event in the heliosphere. Hence EUV waves cannot be used reliably as a proxy for the solar phenomena that accelerates and injects energetic particles over broad ranges of longitudes.**

Influence of interplanetary coronal mass ejections on the peak intensity of solar energetic particle events

D. **Lario**[1],* andA. Karelitz

JGR, Volume 119, Issue 6, pages 4185–4209, June **2014; File**

We study whether the presence of coronal mass ejections (CMEs) in interplanetary space (ICMEs) affects the maximum intensity of solar energetic particle (SEP) events. We compute the maximum intensity of 175–315 keV electron and 9–15, 15–40, and 40–80 MeV proton fluxes measured during the prompt component of **147 western SEP events observed near Earth throughout solar cycle 23**. When using in situ observations to determine the presence and location of preceding ICMEs during SEP events, we find that, over the ensemble of events, those observed either within a preceding ICME or when a preceding ICME is beyond the observer's location have, on average, larger peak intensities than the events observed in absence of ICMEs. The few events observed when an Earth-directed ICME is located between the Sun and the observer tend to have lower 9–15 and 15–40 MeV proton peak intensities than the events without preceding ICMEs; the differences are not significant for 175–315 keV electron peak intensities. When using coronagraph observations to determine the presence of preceding CMEs, we find that, over the ensemble of events, those events (Case P) occurring within 24 h after the launch of a CME from the same active region as the primary CME generating the SEP event tend to have higher peak intensities than those events (Case NP) occurring without a preceding CME. The differences between the average peak intensities of these two event cases (P and NP) are smaller when we exclude events observed when a prior ICME is already located at or beyond Earth.

Table 1. SEP Events (Sep 1997–Dec 2006)

Table 2. Properties of the Primary and Preceding CMEs for the SEP Events Classified as P and NP*a

LONGITUDINAL AND RADIAL DEPENDENCE OF SOLAR ENERGETIC PARTICLE PEAK INTENSITIES: STEREO, ACE, SOHO, GOES, AND MESSENGER OBSERVATIONS

D. **Lario**[1], A. Aran[2], R. Gómez-Herrero[3,4], N. Dresing[3], B. Heber[3], G. C. Ho[1], R. B. Decker[1], and E. C. Roelof

2013 ApJ 767 41

http://iopscience.iop.org/0004-637X/767/1/41/pdf/apj_767_1_41.pdf

Simultaneous measurements of solar energetic particle (SEP) events by two or more of the spacecraft located near 1 AU during the rising phase of solar cycle 24 (i.e., STEREO-A, STEREO-B, and near-Earth spacecraft such as ACE, SOHO, and GOES) are used to determine the longitudinal dependence of 71-112 keV electron, 0.7-3 MeV electron, 15-40 MeV proton, and 25-53 MeV proton peak intensities measured in the prompt component of SEP events. Distributions of the peak intensities for the selected 35 events with identifiable solar origin are approximated by the form exp [– (– 0)2/2σ2], where is the longitudinal separation between the parent active region and the footpoint of the nominal interplanetary magnetic field (IMF) line connecting each spacecraft with the Sun, 0 is the distribution centroid, and σ determines the longitudinal gradient. The MESSENGER spacecraft, at helioradii R < 1 AU, allows us to determine a lower limit to the radial dependence of the 71-112 keV electron peak intensities measured along IMF lines. We find five events for which the nominal magnetic footpoint of MESSENGER was less than 20° apart from the nominal footpoint of a spacecraft near 1 AU. Although the expected theoretical radial dependence for the peak intensity of the events observed along the same field line can be approximated by a functional form R –α with α < 3, we find two events for which α > 3. These two cases correspond to SEP events occurring in a complex interplanetary medium that favored the enhancement of peak intensities near Mercury but hindered the SEP transport to 1 AU.

Intense solar near-relativistic electron events at 0.3 AU

David **Lario***, George C. Ho, Edmond C., Roelof, Brian J. Anderson, Haje Korth

Journal of Geophysical Research: Space Physics, Volume 118, Issue 1, pages 63–73, January **2013**

We study the two most intense electron events observed by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft during the rising phase of solar cycle 24. Both events occurred during intense periods of solar activity when sequences of coronal mass ejections (CMEs) emanated from the Sun. The first event occurred on **4 June 2011**, when two successive CMEs, spaced by 15 h, were released from the same active region. A possible interpretation for this event is that the first CME, located beyond MESSENGER's heliocentric distance (R = 0.33 AU) at the time of the second CME, acted as a magnetic barrier for solar energetic particles (SEPs) accelerated during the second CME. Elevated electron intensities at MESSENGER resulted from particle confinement between the two CME-driven shocks. This scenario is consistent with that proposed by Kallenrode and Cliver [2001a] to explain intense SEP events. The second event, observed by MESSENGER at R = 0.31 AU on **7 March 2012**, belonged to a series of events generated by a single active region. A fast (>1500 km s−1) CME occurred 45 h before the onset of the main electron event. That implies that the prior CME-driven shock was at such a distance that particle reflection from behind that shock might have not been sufficient to account for the initial onset of sunward-directed electrons at MESSENGER, and additional mirroring and/or scattering processes closer to MESSENGER were necessary. Elevated intensities in this event are consistent with strong injection of SEPs from close to the Sun and particle reflection at some point in interplanetary space.

STATISTICAL STUDY ON THE DECAY PHASE OF SOLAR NEAR-RELATIVISTIC ELECTRON EVENTS

D. **Lario**

Astrophysical Journal Supplement Series, 189:181–203, **2010** July

We study the decay phase of solar near-relativistic (53–315 keV) electron events as observed by the *Advanced Composition Explorer* (*ACE*) and the *Ulysses* spacecraft during solar cycle 23. By fitting an exponential function ($\exp{-t/\tau}$) to the time–intensity profile in the late phase of selected solar near-relativistic electron events, we examine the dependence of τ on electron energy, electron intensity spectra, event peak intensity, event fluence, and solar wind velocity, as well as heliocentric radial distance, heliolatitude, and heliolongitude of the spacecraft with respect to the parent solar event. The decay rates are found to be either independent or slightly decrease with the electron energy.

No clear dependence is found between τ and the heliolongitude of the parent solar event, with the exception of well-connected events for which lowvalues of τ aremore commonly observed than for poorly-connected events. For those events concurrently observed by *ACE* and *Ulysses*, decay rates increase at distances>3AU. Eventswith similar decay rates at *ACE* and *Ulysses* were observed mainly when *Ulysses* was at high heliographic latitudes.We discuss the basic physical mechanisms that control the decay phase of the electron events and conclude that both solar wind convection and adiabatic deceleration effects influence the final shape of the decay phase of solar energetic particle events, but not as expressed by the models based on diffusive transport acting on an isotropic particle population.

Major Solar Energetic Particle Events of Solar Cycles 22 and 23: Intensities Close to the Streaming Limit

D. **Lario** · A. Aran · R.B. Decker

Solar Phys (**2009**) 260: 407–421, **File**

It has been argued that the highest intensities measured near 1 AU during large solar energetic particle events occur in association with the passage of interplanetary shocks driven by coronal mass ejections, whereas the intensities measured early in the events (known as the prompt component) are bounded by a maximum intensity plateau known as the streaming limit. A few events in Solar Cycle 23 showed prompt components with intensities above the previously determined streaming limit. One of the scenarios proposed to explain intensities that exceed this limit in these events invokes the existence of transient plasma structures beyond 1 AU able to confine and/or mirror energetic particles. We study whether other particle events with prompt-component intensities close to the previously determined streaming limit are similarly affected by the presence of interplanetary structures.

Whereas such structures were observed in four out of the nine events studied here, we conclude that only the events on 22 October 1989, 29 October 2003, and 17 January 2005 show interplanetary structures that can have modified the transport conditions in a way similar to those events with prompt components exceeding the previously determined streaming limit. The other six events with prompt components close to the previously determined streaming limit were characterized by either a low level of pre-event solar activity and/or the absence of transient interplanetary structures able to modify the transport of energetic particles.

Major solar energetic particle events of solar cycles 22 and 23: Intensities above the streaming limit

D. **Lario**, A. Aran, R. B. Decker

SPACE WEATHER, VOL. 6, S12001, doi:10.1029/2008SW000403, **2008**

Large solar energetic particle (SEP) events constitute a serious radiation hazard to astronauts and spacecraft systems. It is essential to determine the highest particle intensities reached in SEP events, especially at the energies that pose serious risks to human health and spacecraft performance. It has been argued that the highest particle intensities measured during large SEP events occur in association with the passage of shocks driven by coronal mass ejections known as the energetic storm particle (ESP) component. Furthermore, it has been argued that the intensities measured early in the SEP events (known as the prompt component) are bounded by a maximum intensity plateau that results from wave-particle interactions that restrict the free streaming of particles (also called the "streaming limit"). We analyze proton intensities measured by the GOES spacecraft at the energy channels P5 (∼39–82 MeV) and P7 (∼110–500 MeV) during solar cycles 22 and 23 and examine whether the highest intensities were measured during the prompt or the ESP components of the SEP events. We find three (one) SEP events in which the highest proton intensities measured during the prompt component at the energy channel P5 (P7) exceeded by a factor of 4 or more the previously determined "streaming limit". Arguments to explain intensities during the prompt components exceeding this limit invoke interplanetary conditions that inhibit the amplification of waves resonating with the streaming particles and/or the presence of interplanetary structures able to confine and/or mirror energetic particles. We analyze these possibilities for each one of these events.

Influence of large-scale interplanetary structures on energetic particle propagation: September 2004 event at Ulysses and ACE,

Lario, D., R. B. Decker, O. E. Malandraki, and L. J. Lanzerotti,

J. Geophys. Res., 113, A03105, (**2008**) http://dx.doi.org/10.1029/2007JA012721

Analysis of the Ground Level Enhancement GLE 60 on 15 April 2001, and Its Space Weather Effects: Comparison With Dosimetric Measurements

N. **Larsen**, A. L. Mishev

Space Weather Volume21, Issue8 August **2023** e2023SW003488

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003488

As a result of notable solar activity observed in April 2001, one of the strongest ground level enhancements (GLE) of solar cycle 23 occurred, namely GLE # 60 on **15 April 2001**. In this paper, we derived the spectral and angular characteristics, and apparent source position of the solar protons during the GLE # 60, using a verified by direct measurements model and employing the calibrated neutron monitor yield function. Subsequently, employing the updated and verified by balloon measurements dosimetric model: Oulu CRAC:DOMO (Cosmic Ray Atmospheric Cascade: Dosimetric Model) we computed the dose rates throughout the event at several altitudes using the obtained spectra as an input. A global map of the ambient dose at an altitude of 35 kft is computed. A comparison with direct dosimetric measurements obtained by a Liulin device during an intercontinental flight is performed and good agreement is achieved.

Estimation of the Particle Radiation Environment at the L1 Point and in Near-Earth Space

M. **Laurenza**1, T. Alberti1, M. F. Marcucci1, G. Consolini1, C. Jacquey2, S. Molendi3, C. Macculi1, and S. Lotti1

2019 ApJ 873 112

https://doi.org/10.3847/1538-4357/ab0410

To characterize the particle radiation environment at the Lagrangian point L1 and in the near-Earth space we performed a systematic analysis of the particle flux data recorded by different instruments on board different spacecraft (ACE EPAM/LEMS120, IMP-8 CPME, and Geotail EPIC-ICS). We focused on protons in the poorly explored energy range ~0.05–5 MeV, including energies of the so-called soft protons, which are critical for the Advanced Telescope for High Energy Astrophysics(ATHENA) mission, as well as the 145–440 MeV one, because high-energy particles affect all interplanetary missions. We estimated the energetic proton environment by computing the cumulative distribution functions for the different energy channels of each instrument and studied its variations with respect to solar activity. We obtained energetic proton spectra at cumulative probabilities (CPs) of 50% and 90% and worst-case scenarios, which can be used by the ATHENAmission for operational purposes and more generally for space weather hazards. We found an increase in the ~0.05–5 MeV proton spectrum at 90% CP during the maximum phase of solar cycle (SC) No. 23 of about a factor from 3 to 5, depending on the energy, with respect to the overall period (1997–2014). Moreover, the 300–500 keV proton flux at 90% CP is higher during SC

No. 21 by about a factor 1.5 and 3 compared to SC No. 22 and SC No. 23, respectively. Finally, variations with solar activity of the 145–440 MeV proton flux are within a factor of 2 at both 90% and 50% CPs, thus representing the low-energy galactic cosmic rays.

A Short-term ESPERTA-based Forecast Tool for Moderate-to-extreme Solar Proton Events

M. **Laurenza**1, T. Alberti1,2, and E. W. Cliver3,4

2018 ApJ 857 107 **File**

http://sci-hub.tw/http://iopscience.iop.org/0004-637X/857/2/107/

The ESPERTA (Empirical model for Solar Proton Event Real Time Alert) forecast tool has a Probability of Detection (POD) of 63% for all >10 MeV events with proton peak intensity ≥10 pfu (i.e., ≥S1 events, S1 referring to minor storms on the NOAA Solar Radiation Storms scale), from 1995 to 2014 with a false alarm rate (FAR) of 38% and a median (minimum) warning time (WT) of ~4.8 (0.4) hr. The NOAA space weather scale includes four additional categories: moderate (S2), strong (S3), severe (S4), and extreme (S5). As S1 events have only minor impacts on HF radio propagation in the polar regions, the effective threshold for significant space radiation effects appears to be the S2 level (100 pfu), above which both biological and space operation impacts are observed along with increased effects on HF propagation in the polar regions. We modified the ESPERTA model to predict ≥S2 events and obtained a POD of 75% (41/55) and an FAR of 24% (13/54) for the 1995–2014 interval with a median (minimum) WT of ~1.7 (0.2) hr based on predictions made at the time of the S1 threshold crossing. The improved performance of ESPERTA for ≥S2 events is a reflection of the big flare syndrome, which postulates that the measures of the various manifestations of eruptive solar flares increase as one considers increasingly larger events.

Table 2 …100 pfu SPE Flare List (1995–2014)

A technique for short-term warning of solar energetic particle events based on flare location, flare size, and evidence of particle escape

M. **Laurenza**, E. W. Cliver, J. Hewitt, M. Storini, A. G. Ling, C. C. Balch, M. L. Kaiser

Space Weather, 7, S04008, doi:10.1029/2007SW000379. **2009** **File**

http://sci-hub.cc/10.1029/2007SW000379

We have developed a technique to provide short‐term warnings of solar energetic proton (SEP) events that meet or exceed the Space Weather Prediction Center threshold of J (>10 MeV) = 10 pr cm^{-2} s^{-1} sr^{-1}. The method is based on flare location, flare size, and evidence of particle acceleration/escape as parameterized by flare longitude, time‐integrated soft X‐ray intensity, and time‐integrated intensity of type III radio emission at ~1 MHz, respectively. In this technique, warnings are issued 10 min after the maximum of ≥M2 soft X‐ray flares. For the solar cycle 23 (1995–2005) data on which it was developed, the method has a probability of detection of 63% (47/75), a false alarm rate of 42% (34/81), and a median warning time of ~55 min for the 19 events successfully predicted by our technique for which SEP event onset times were provided by Posner (2007). These measures meet or exceed verification results for competing automated SEP warning techniques but, at the present stage of space weather forecasting, fall well short of those achieved with a human (aided by techniques such as ours) making the ultimate yes/no SEP event prediction. We give some suggestions as to how our method could be improved and provide our flare and SEP event database in the auxiliary material to facilitate quantitative comparisons with techniques developed in the future.

ESPERTA model (acronym of Empirical model for Solar Proton Events Real Time Alert)

See T. **Alberti**1, M. Laurenza2, E. W. Cliver3, M. Storini2, G. Consolini2, and F. Lepreti

2017 ApJ 838 59 **File**

Assessing the Predictability of Solar Energetic Particles with the Use of Machine Learning Techniques

E. **Lavasa**, G. Giannopoulos, A. Papaioannou, A. Anastasiadis, I. A. Daglis, A. Aran, D. Pacheco & B. Sanahuja

Solar Physics volume 296, Article number: 107 (**2021**)

https://link.springer.com/content/pdf/10.1007/s11207-021-01837-x.pdf

https://doi.org/10.1007/s11207-021-01837-x

A consistent approach for the inherently imbalanced problem of solar energetic particle (SEP) events binary prediction is being presented. This is based on solar flare and coronal mass ejection (CME) data and combinations of both thereof. We exploit several machine learning (ML) and conventional statistics techniques to predict SEPs. The methods used are logistic regression (LR), support vector machines (SVM), neural networks (NN) in the fully connected multi-layer perceptron (MLP) implementation, random forests (RF), decision trees (DTs), extremely randomized trees (XT) and extreme gradient boosting (XGB). We provide an assessment of the methods employed and conclude that RF could be the prediction technique of choice for an optimal sample comprised by both flares and CMEs. The best-performing method gives a Probability of Detection (POD) of 0.76(±0.06), False Alarm Rate

(FAR) of 0.34(±0.10), true skill statistic (TSS) 0.75(±0.05), and Heidke skill score (HSS) 0.69(±0.04). We further show that the most important features for the identification of SEPs, in our sample, are the CME speed, width and flare soft X-ray (SXR) fluence.

The 4 June 2011 neutron event at Mercury: A defense of the solar origin hypothesis

David J. **Lawrence**, William C. Feldman, Patrick N. Peplowski, Sean C. Solomon

JGR Volume 120, Issue 7 July **2015** Pages 5284–5289

We address the claim that an increase in the flux of neutrons detected by the Neutron Spectrometer (NS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft in orbit about Mercury at 15:45 UTC on 4 June 2011 was generated by the impact of energetic ions onto spacecraft. We find this claim to be unwarranted. The claim is grounded on the erroneous assumption that the NS singles count rate is triggered only by energetic ions. Rather, because any mix of energetic ions, electrons, photons, and neutrons can trigger NS singles, these data do not provide a reliable constraint on the presence of energetic ions. The absence of an enhancement in the count rate of 1635-keV gamma rays, as monitored by the MESSENGER Gamma-Ray Spectrometer, provides independent evidence that a fluence of energetic protons sufficiently high to generate the neutron enhancement was not present during the neutron event. The interpretation that currently best matches the available data is that the neutron enhancement on **4 June 2011** was the result of solar neutrons.

Detection and characterization of 0.5–8 MeV neutrons near Mercury: Evidence for a solar origin

David J. **Lawrence**1, William C. Feldman2, John O. Goldsten1, Patrick N. Peplowski1, Douglas J. Rodgers1 and Sean C. Solomon3

JGR, Volume 119, Issue 7, pages 5150–5171, July **2014**

Data from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Neutron Spectrometer (NS) have been used to identify energetic neutrons (0.5–8 MeV energy) associated with solar events that occurred on **4 June 2011**. Multiple lines of evidence, including measurements from the NS and the MESSENGER Gamma-Ray Spectrometer, indicate that the detected neutrons have a solar origin. This evidence includes a lack of time-coincident, energetic (>45 MeV) charged particles that could otherwise create local neutrons from nearby spacecraft material and a lack of proton-induced gamma rays that should be seen if energetic protons were present. NS data cannot rule out the presence of lower-energy ions (<30 MeV) that can produce local neutrons. However, the ion spectral shape required to produce the measured neutron count rate locally is softer than any known ion spectral shape. The neutron energy spectrum shows a relative enhancement in the energy range 0.8–3 MeV compared with cosmic-ray-generated neutrons from the spacecraft or Mercury. The spectral shape of the measured neutron fluence spectrum is consistent with a previously modeled fluence spectrum of neutrons that originate at the Sun and are propagated through the MESSENGER spacecraft to the NS. These measurements provide strong evidence for a solar origin of the detected neutrons and suggest that a large number of low-energy threshold ion evaporation reactions were taking place on the Sun during the neutron event.

See **Comment on ``Detection and characterization of 0.5--8 MeV neutrons near Mercury: Evidence for a solar origin"**

Gerald H. **Share**, Ronald J. Murphy, Allan J. Tylka, Brian R. Dennis, and James M. Ryan

E-print, Sept **2014**; JGR, **2014**

Extreme space weather events caused by super active regions during solar cycles 21-24

Gui-Ming **Le**, Gui-Ang Liu, Ming-Xian Zhao, Tian Mao, Ping-Guo Xu

Research in Astronomy and Astrophysics **2021**

https://arxiv.org/pdf/2103.00670.pdf **File**

Extreme space weather events including ≥X5.0 flares, ground level enhancement (GLE) events and super geomagnetic storms (Dst ≤ -250 nT) caused by super active regions (SARs) during solar cycles 21-24 were studied. The total number of ≥X5.0 solar flares was 62, 41 of them were X5.0-X9.9 flares and 21 of them were ≥X10.0 flares. We found that 83.9\% of the ≥X5.0 flares were produced by SARs. 78.05\% of the X5.0-X9.9 and 95.24\% of the ≥X10.0 solar flares were produced by SARs. 46 GLEs registered during solar cycles 21-24, and 25 GLEs were caused by SARs, indicating that 54.3\% of the GLEs were caused by SARs. 24 super geomagnetic storms were recorded during solar cycles 21-24, and 12 of them were caused by SARs, namely 50\% of the super geomagnetic storms are caused by SARs. It is found that only 29 SARs can produce ≥X5.0 flares, 15 SARs can produce GLEs and 10 SARs can produce super geomagnetic storms. Of the 51 SARs, only 33 SARs can produce at least one extreme space weather event, while none of the rest 18 SARs can produce an extreme space weather event. There were only 4 SARs, each of them can produce not only a ≥X5.0 flare, but also a GLE event and a super geomagnetic storm. Most of the extreme space weather events caused by the SARs appeared during solar cycles 22 and 23, especially for GLE events and super geomagnetic storms. The longitudinal distributions of source locations for the extreme space weather events caused by SARs were also studied. **28-30, October 2003**

Table 1: The flares with intensities ≥X5.0 caused by SARs during solar cycles 21-24.
Table 2: The GLE events caused by SARs during solar cycles 21-24.
Table 3: The SGSs and the related ARs during solar cycles 21-24.

Statistical and Solar Cycle Distribution of Daily Flux ≥109 cm−2 cm−2 d−1 sr−1 for E>2 MeV Electrons Observed by GOES During 1987 – 2019

Gui-Ming **Le**, Yi-Ning Zhang, Ming-Xian Zhao

Solar Physics volume 296, Article number: 16 (**2021**)

https://link.springer.com/content/pdf/10.1007/s11207-020-01758-1.pdf

We studied the statistical and solar cycle distribution of daily flux ≥109 cm−2 sr−1 for E>2 MeV electrons Observed by GOES from 1987 to 2019. There were 282 days with daily flux ≥109 cm−2 d−1 sr−1 for E>2 MeV electrons during this period. Of the 282 days, 71.63% of them have the daily flux <2.0×109 cm−1×109 cm−1d−1sr−1, 19.86% of them with the daily flux fall in the interval ≥2.0×109 cm−2 cm−2 d−1 sr−1 and <3.0×109 cm−2 cm−2 d−1 sr−1, 4.26% of them have the daily flux in the interval between ≥3.0×109 cm−2 cm−2 d−1 sr−1 and <4.0×109 cm−2 cm−2 d−1 sr−1, and 4.26% of them have the daily flux ≥4.0×109 cm−2 cm−2 d−1 sr−1. The daily flux ≥109 cm−2 cm−2 d−1 sr−1 for E>2 MeV electrons that lasted for 1, 2, 3, 4, 5, 6, 7 and 10 days accounted for 18.44%, 17.02%, 20.21%, 15.6%, 8.87%, 6.38%, 9.93% and 3.55%, respectively. Among all the daily fluxes ≥109 cm−2 cm−2 d−1 sr−1, 47.79% of them occurred in the northern hemisphere spring, 36.03% of them occurred in the fall, and 16.18% of them occurred in the other months. More than 82% of the daily flux ≥109 cm−2 cm−2 d−1 sr−1 for E>2E>2 MeV electrons appeared in the descending phase for each solar cycle. The greater percentage of the electrons of daily flux ≥109 cm−2 cm−2 d−1 sr−1 for E>2E>2 MeV occurred during the descending phase for the solar cycle with higher amplitude. Also, for the solar cycle with higher amplitude, the lower the percentage of the electrons of daily flux ≥109 cm−2 cm−2 d−1 sr−1 of E>2 MeV occurred in the period from two years before to three years after the solar cycle peak.

The Properties of Source Locations and Solar Cycle Distribution of GLEs During 1942–2017

Gui-Ming **Le** & Gui-Ang Liu

Solar Physics volume 295, Article number: 35 (**2020**)

sci-hub.si/10.1007/s11207-020-01600-8

During 1942–2017, 72 ground level events (GLEs) have been registered. Source location and solar cycle distribution of GLEs during 1942–2017 have been investigated. The GLEs that occurred during 1942–2017 are mainly distributed in the longitudinal area ranged from E30 to W150. The northern hemisphere has many more GLEs than the southern hemisphere during Solar Cycles 19 and 20, while the northern hemisphere has slightly more GLEs than the southern hemisphere of the Sun during Solar Cycles 21 and 22. However, the southern hemisphere has more GLEs than the northern hemisphere during Solar Cycle 23. The latitudinal area ranged from N20 to N40 of the northern hemisphere of the Sun has many more GLEs than the latitudinal area ranging from S20 to S40 of the southern hemisphere of the Sun. The latitudinal area ranging from N0 to N20 of the northern hemisphere of the Sun has slightly more GLEs than the latitudinal area ranged from S0 to S20 of the southern hemisphere of the Sun. 46 GLEs came from the northern hemisphere, while 26 GLEs came from the southern hemisphere of the Sun, suggesting that GLEs dominated in the northern hemisphere of the Sun during 1942–2017. Statistical results show that 44.3% and 55.7% of the GLEs appeared in the ascending and descending phases of the solar cycles, respectively, and about 83% of the GLEs appeared during the period from the two years before solar cycle peak and the three years after solar cycle peak time. The number of GLEs during a solar cycle has a poor correlation with the amplitude of the solar cycle.

Dependence of large gradual solar energetic particles on the associated flares and CMEs

Guiming **Le**, Xuefeng Zhang

Proc. of 35th International Cosmic Ray Conference — ICRC2017 10–20 July, **2017**

https://pos.sissa.it/301/131/pdf

To investigate the dependence of large gradual solar energetic particle (SEP) events on the associated flares and coronal mass ejections (CMEs), the correlation coefficients (CC) between the peak intensities of E>10 MeV (I10), E>30 MeV (I30) and E>50 MeV (I50) protons and soft X-ray (SXR) emission of associated flares and the speeds of associated CMEs in the three longitudinal areas W0-W39, W40-W70(hereafter well connected region) and W71-W90 have been calculated respectively. The classical correlation analysis shows CCs between SXR emission and the peak intensities of SEP events always reach their largest value in the well connected region and then decline dramatically in the longitudinal area outside the well connected region. For SEP events with source location in the well connected region, the CC between SXR fluence and the peak intensities of SEP events is always larger than the

CC between SXR peak flux and the peak intensities of SEP events, suggesting that SXR fluence is a better parameter describing the relationship between flare and SEP events. For SEP events with source location in the well connected region, the CC between SXR fluence and I10 is 0.58±0.12, while the CC between CME speed and I10 is 0.56±0.12. For SEP events with source location in the well connected region, the CC between SXR fluence and I30 is 0.80±0.06, while the CC between CME speed and I30 is 0.52±0.13. For SEP events with source location in the well connected region, the CC between SXR fluence and I50 is 0.83±0.06, while the CC between CME speed and I30 is 0.48±0.13. The correlation analysis suggests that for SEP events with source location in the well connected region, CME shock is only an effective accelerator for E30 MeV protons may be mainly accelerated by concurrent flares

Geoeffectiveness of the coronal mass ejections associated with solar proton events

Gui-Ming **Le**, Chuan Li, Yu-Hua Tang, Liu-Guan Ding, Zhi-Qiang Yin, Yu-Lin Chen, Yang-Ping Lu, Min-Hao Chen, Zhong-Yi Li

Research in Astronomy and Astrophysics (RAA) Vol 16, No 1 (**2016**) paper 14, **File**

The intensity-time profiles of solar proton events (SPEs) are grouped into three types in the present study. The Type-I means that the intensity-time profile of an SPE has one peak, which occurs shortly after the associated solar flare and coronal mass ejection (CME). The Type-II means that the SPE profile has two peaks: the first peak occurs shortly after the solar eruption, the second peak occurs at the time when the CME-driven shock reaches the Earth, and the intensity of the second peak is lower than the first one. If the intensity of the second peak is higher than the first one, or the SPE intensity increases continuously until the CME-driven shock reaches the Earth, this kind of intensity-time profile is defined as Type-III. It is found that most CMEs associated with Type-I SPEs have no geoeffectiveness and only a small part of CMEs associated with Type-I SPEs can produce minor (–50 nT ≤ Dst ≤ –30 nT) or moderate geomagnetic storms (–100 nT≤ Dst ≤ –50 nT), but never an intense geomagnetic storm (–200 nT ≤ Dst < −100 nT). However, most of the CMEs associated with Type-II and Type-III SPEs can produce intense or great geomagnetic storms (Dst ≤ −200 nT). The solar wind structures responsible for the geomagnetic storms associated with SPEs with different intensity-time profiles have also been investigated and discussed. **1998 May 2, 1998 May 6, 2001 January 28, 2003 October 28 , 2004 July 25, 2006 December 13**

Table 1 Geoeffectiveness of CMEs Associated with Type-I SPEs during Solar Cycle 23

Table 2 Geoeffectiveness of CMEs Associated with Type-II SPEs during Solar Cycle 23

Solar Energetic Particle Charge States and Abundances with Nonthermal Electrons

Jin-Yi **Lee**, Stephen Kahler, John C. Raymond, Yuan-Kuen Ko

ApJ **963** 70 **2024**

https://arxiv.org/pdf/2401.01604.pdf **File**

https://iopscience.iop.org/article/10.3847/1538-4357/ad1ab6/pdf

An important aspect of solar energetic particle (SEP) events is their source populations. Elemental abundance enhancements of impulsive SEP events, originating in presumed coronal reconnection episodes, can be fitted to steep power laws of A/Q, where A and Q are the atomic mass and ionic charge. Since thermal electron energies are enhanced and nonthermal electron distributions arise in the reconnection process, we might expect that ionic charge states Q would be increased through ionization interactions with those electron populations during the acceleration process. The temperature estimated from the SEPs corresponds to the charge state during the acceleration process, while the actual charge state measured in situ may be modified as the SEPs pass through the corona. We examine whether the temperature estimation from the A/Q would differ with various kappa values in a kappa function representing high-energy tail deviating from a Maxwellian velocity distribution. We find that the differences in the A/Q between a Maxwellian and an extreme kappa distribution are about 10-30. We fit power-law enhancement of element abundances as a function of their A/Q with various kappa values. Then, we find that the derived source region temperature is not significantly affected by whether or not the electron velocity distribution deviates from a Maxwellian, i.e., thermal, distribution. Assuming that electrons are heated in the acceleration region, the agreement of the SEP charge state during acceleration with typical active region temperatures suggests that SEPs are accelerated and leave the acceleration region in a shorter time than the ionization time scale.

MAVEN observations of the solar cycle 24 space weather conditions at Mars.

Lee, C. O., Hara, T., Halekas, J. S., Thiemann, E., Chamberlin, P., Eparvier, F., … Jakosky, B. M. (**2017**). Journal of Geophysical Research: Space Physics. 122, 2768-2794

sci-hub.tw/10.1002/2016JA023495

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has been continuously observing the variability of solar soft X-rays and EUV irradiance, monitoring the upstream solar wind and interplanetary magnetic field conditions and measuring the fluxes of solar energetic ions and electrons since its arrival to Mars. In this paper, we provide a comprehensive overview of the space weather events observed during the first ~1.9 years of the science mission, which includes the description of the solar and heliospheric sources of the space weather activity. To illustrate the variety of upstream conditions observed, we characterize a subset of the event periods by describing the

Sun-to-Mars details using observations from the MAVEN solar Extreme Ultraviolet Monitor, solar energetic particle (SEP) instrument, Solar Wind Ion Analyzer, and Magnetometer together with solar observations using near-Earth assets and numerical solar wind simulation results from the Wang-Sheeley-Arge-Enlil model for some global context of the event periods. The subset of events includes an extensive period of intense SEP electron particle fluxes triggered by a series of solar flares and coronal mass ejection (CME) activity in December 2014, the impact by a succession of interplanetary CMEs and their associated SEPs in March 2015, and the passage of a strong corotating interaction region (CIR) and arrival of the CIR shock-accelerated energetic particles in June 2015. However, in the context of the weaker heliospheric conditions observed throughout solar cycle 24, these events were moderate in comparison to the stronger storms observed previously at Mars.

Particle Acceleration in the Sun and Beyond **Review**

Jeongwoo **Lee**

Proc. of 35th International Cosmic Ray Conference — ICRC2017 10–20 July, **2017** **File**

https://pos.sissa.it/301/1088/pdf

This article reviews recent studies on cosmic rays originating in the heliosphere with emphasis on **the role played by solar flares**. In the first part, the physical drivers for high-energy particle acceleration in the heliosphere including solar flares, coronal mass ejections (CMEs), corotating interaction regions (CIR) and solar wind termination shocks are briefly discussed. We then introduce solar particle acceleration mechanisms in which shocks, turbulence, Alfvén waves, and magnetic reconnection respectively play a role. It is demonstrated that the properties of accelerated particles in the Sun are known in considerable detail because magnetic reconnection geometry is visible through electromagnetic radiations, and imaging spectroscopy at hard X-ray and radio wavelengths is available. In the second part, we attempt to relate our knowledge of solar flare particles to several research topics on solar energetic particles (SEPs). The topics include: (1) possible influence of solar magnetic field structure upon the energy spectra and time profiles of the resulting SEPs, (2) temporal, spatial and spectral properties of SEP electrons measured in interplanetary space in comparison with those remotely observed in the Sun, and (3) the energydependent onset time of SEP protons and its implication on the proton acceleration beyond the Sun. It is argued that we should take advantage of solar imaging spectroscopy at X-ray and radio wavelengths to complement the cosmic ray studies largely based on in-situ observations in order to disentangle the roles played by solar flares and CMEs in accelerating SEPs and better understand the relationship between solar flares and SEPs.

Shock Acceleration of Ions in the Heliosphere **Review**

Martin A. **Lee** · R.A. Mewaldt · J. Giacalone

Space Sci. Rev., 173, Issue 1-4, pp 247-281, **2012, File**

https://link.springer.com/content/pdf/10.1007/s11214-012-9932-y.pdf

Energetic particles constitute an important component of the heliospheric plasma environment. They range from solar energetic particles in the inner heliosphere to the anomalous cosmic rays accelerated at the interface of the heliosphere with the local interstellar medium. Although stochastic acceleration by fluctuating electric fields and processes associated with magnetic reconnection may account for some of the particle populations, the majority are accelerated by the variety of shock waves present in the solar wind. This review focuses on “gradual” solar energetic particle (SEP) events including their energetic storm particle (ESP) phase, which is observed if and when an associated shock wave passes Earth. Gradual SEP events are the intense long-duration events responsible for most space weather disturbances of Earth’s magnetosphere and upper atmosphere. The major characteristics of gradual SEP events are first described including their association with shocks and coronal mass ejections (CMEs), their ion composition, and their energy spectra. In the context of acceleration mechanisms in general, the acceleration mechanism responsible for SEP events, diffusive shock acceleration, is then described in some detail including its predictions for a planar stationary shock, shock modification by the energetic particles, and wave excitation by the accelerating ions. Finally, some complexities of shock acceleration are addressed, which affect the predictive ability of the theory. These include the role of temporal and spatial variations, the distinction between the plasma and wave compression ratios at the shock, the injection of thermal plasma at the shock into the process of shock acceleration, and the nonlinear evolution of ion-excited waves in the vicinity of the shock.

Sources of SEP Acceleration during a Flare–CME Event

N.J. **Lehtinen** · S. Pohjolainen, K. Huttunen-Heikinmaa · R. Vainio, E. Valtonen · A.E. Hillaris

E-print, Nov 2007, Solar Phys.

Solar Phys (**2008**) 247: 151–169, **File**

http://www.springerlink.com/content/q8262j85pj35p663/fulltext.pdf

A high-speed halo-type coronal mass ejection (CME), associated with a GOES M4.6 soft X-ray flare in NOAA AR 0180 at S12W29 and an EIT wave and dimming, occurred on **9 November 2002**. A complex radio event was observed during the same period. It included narrow-band fluctuations and frequency drifting features in the metric wavelength range, type III burst groups at metric–hectometric wavelengths, and an interplanetary type II radio burst, which was visible in the dynamic radio spectrum below 14 MHz. To study the association of the recorded solar energetic particle (SEP) populations with the propagating CME and flaring, we perform a multi-wavelength analysis using radio spectral and imaging observations combined with white-light, EUV, hard X-ray, and magnetogram data. Velocity dispersion analysis of the particle distributions (SOHO and Wind in situ observations) provides estimates for the release times of electrons and protons. Our analysis indicates that proton acceleration was delayed compared to the electrons. The dynamics of the interplanetary type II burst identify the burst source as a bow shock created by the fast CME. The type III burst groups, with start times close to the estimated electron release times, trace electron beams travelling along open field lines into the interplanetary space. The type III bursts seem to encounter a steep density gradient as they overtake the type II shock front, resulting in an abrupt change in the frequency drift rate of the type III burst emission. *Our study presents evidence in support of a scenario in which electrons are accelerated low in the corona behind the CME shock front, while protons are accelerated later, possibly at the CME bow shock high in the corona.*

Self-consistent Energetic Particle Acceleration by Contracting and Reconnecting Small-scale Flux Ropes: The Governing Equations

J. A. **le Roux**1,2, G. P. Zank1,2, and O. V. Khabarova3

2018 ApJ 864 158

http://sci-hub.tw/10.3847/1538-4357/aad8b3

Previous application of our focused transport equation for energetic ion test particle acceleration by numerous active small-scale flux ropes to solar wind conditions near 1 au yielded the formation of hard power-law spectra with high particle pressure. We present an extended theory where the focused transport equation is coupled to a new MHD turbulence transport equation for coherent, quasi-2D magnetic island structures, based on nearly incompressible (N i) MHD turbulence theory. The latter equation includes new expressions for the magnetic island damping/growth rates that enable a self-consistent description of energy exchange between energetic particles and flux ropes during flux-rope acceleration for four flux-rope acceleration scenarios identified in focused transport theory. Revised, more detailed expressions for coherent acceleration in response to mean dynamic flux-rope properties and for stochastic acceleration due to fluctuations in dynamic flux-rope properties are presented. A comparison is made between the efficiencies of the different flux-rope acceleration scenarios for suprathermal protons in the solar wind near 1 au. Dynamic flux-rope-induced pitch-angle scattering and stochastic acceleration rates are compared with the corresponding rates generated by interaction with parallel-propagating Alfvén waves. The results stress the importance of parallel guiding center motion acceleration by the parallel reconnection electric field formed in merging flux ropes, combined curvature drift and generalized betatron acceleration in contracting/merging flux ropes in the compressible limit (flux-rope compression acceleration), and the fluctuating magnetic mirroring force in flux ropes for pitch-angle scattering.

Acceleration of Solar Energetic Particles at a Fast Traveling Shock in Non-uniform Coronal Conditions

J A **Le Roux**1,2 and A D Arthur1

Journal of Physics: Conference Series, Volume 900, Number 1   012013   **2017**

http://iopscience.iop.org/article/10.1088/1742-6596/900/1/012013/pdf

Time-dependent solar energetic particle (SEP) acceleration is investigated at a fast, nearly parallel spherical traveling shock in the strongly non-uniform corona by solving the standard focused transport equation for SEPs and transport equations for parallel propagating Alfvén waves that form a set of coupled equations. This enables the modeling of self-excitation of Alfvén waves in the inertial range by SEPs ahead of the shock and its role in enhancing the efficiency of the diffusive shock acceleration (DSA) of SEPs in a self-regulatory fashion. Preliminary results suggest that, because of the highly non-uniform coronal conditions that the shock encounters, both DSA and wave excitation are highly time-dependent processes. Thus, DSA spectra of SEPs strongly deviate from the simple power-law prediction of standard steady-state DSA theory and initially strong wave excitation weakens rapidly. Consequently, the ability of DSA to produce high energy SEPs in the corona of ~1 GeV, as observed in the strongest gradual SEP events, appears to be strongly curtailed at a fast nearly parallel shock, but further research is needed before final conclusions can be drawn.

A FOCUSED TRANSPORT APPROACH TO THE TIME-DEPENDENT SHOCK ACCELERATION OF SOLAR ENERGETIC PARTICLES AT A FAST TRAVELING SHOCK

J. A. **le Roux** and G. M. Webb

2012 ApJ 746 104

Some of the most sophisticated models for solar energetic particle (SEP) acceleration at coronal mass ejection driven shocks are based on standard diffusive shock acceleration theory. However, this theory, which only applies when SEP pitch-angle anisotropies are small, might have difficulty in describing first-order Fermi acceleration or the shock pre-heating and injection of SEPs into first-order Fermi acceleration accurately at lower SEP speeds where SEP pitch-angle anisotropies upstream near the shock can be large. To avoid this problem, we use a time-dependent focused transport model to reinvestigate first-order Fermi acceleration at planar parallel and quasi-parallel spherical traveling shocks between the Sun and Earth with high shock speeds associated with rare extreme gradual SEP events. The focused transport model is also used to investigate and compare three different shock pre-heating mechanisms associated with different aspects of the nonuniform cross-shock solar wind flow, namely, the convergence of the flow (adiabatic compression), the shear tensor of the flow, and the acceleration of the flow, and a fourth shock pre-heating mechanism associated with the cross-shock electric field, to determine which pre-heating mechanism contributes the most to injecting shock pre-heated source particles into the first-order Fermi acceleration process. The effects of variations in traveling shock conditions, such as increasing shock obliquity and shock slowdown, and variations in the SEP source with increasing shock distance from the Sun on the coupled processes of shock pre-heating, injection, and first-order Fermi acceleration are analyzed. Besides the finding that the cross-shock acceleration of the solar wind flow yields the dominant shock pre-heating mechanism at high shock speeds, we find that first-order Fermi acceleration at fast traveling shocks differs in a number of respects from the predictions and assumptions of standard steady-state diffusive shock acceleration theory as is discussed below.

Observations of the 2019 April 4 Solar Energetic Particle Event at the Parker Solar Probe

R. A. **Leske**, E. R. Christian, C. M. S. Cohen, A. C. Cummings, A. J. Davis, M. I. Desai, J. Giacalone, M. E. Hill, C. J. Joyce, S. M. Krimigis, A. W. Labrador, O. Malandraki, W. H. Matthaeus, D. J. McComas, R. L. McNutt Jr., R. A. Mewaldt, D. G. Mitchell, A. Posner, J. S. Rankin, E. C. Roelof, N. A. Schwadron, E. C. Stone, J. R. Szalay, M. E. Wiedenbeck, A. Vourlidas, S. D. Bale, R. J. MacDowall, M. Pulupa, J. C. Kasper, R. C. Allen, A. W. Case, K. E. Korreck, R. Livi, M. L. Stevens, P. Whittlesey, B. Poduval

2020 *ApJS* **246** 35

https://arxiv.org/pdf/1912.03384.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/ab5712/pdf

A solar energetic particle event was detected by the Integrated Science Investigation of the Sun (ISOIS) instrument suite on Parker Solar Probe (PSP) on **2019 April 4** when the spacecraft was inside of 0.17 au and less than 1 day before its second perihelion, providing an opportunity to study solar particle acceleration and transport unprecedentedly close to the source. The event was very small, with peak 1 MeV proton intensities of ~0.3 particles (cm^2 sr s MeV)^-1, and was undetectable above background levels at energies above 10 MeV or in particle detectors at 1 au. It was strongly anisotropic, with intensities flowing outward from the Sun up to 30 times greater than those flowing inward persisting throughout the event. Temporal association between particle increases and small brightness surges in the extreme-ultraviolet observed by the Solar TErrestrial RElations Observatory, which were also accompanied by type III radio emission seen by the Electromagnetic Fields Investigation on PSP, indicates that the source of this event was an active region nearly 80 degrees east of the nominal PSP magnetic footpoint. This suggests that the field lines expanded over a wide longitudinal range between the active region in the photosphere and the corona.

Large Proton Anisotropies in the 18 August 2010 Solar Particle Event

R. A. **Leske**, C. M. S. Cohen, R. A. Mewaldt, E. R. Christian, A. C. Cummings, A. W. Labrador, E. C. Stone, M. E. Wiedenbeck, T. T. von Rosenvinge

Solar Physics, November **2012**, Volume 281, Issue 1, pp 301-318

The solar particle event observed at STEREO Ahead on **18 August 2010** displayed a rich variety of behavior in the particle anisotropies. Sectored rates measured by the Low Energy Telescope (LET) on STEREO showed very large bidirectional anisotropies in 4 – 6 MeV protons for the first ∼ 17 hours of the event while inside a magnetic cloud, with intensities along the field direction several hundred to nearly 1000 times greater than those perpendicular to the field. At the trailing end of the cloud, the protons became isotropic and their spectrum hardened slightly, while the He/H abundance ratio plunged by a factor of approximately four for about four hours. Associated with the arrival of a shock on 20 August was a series of brief (< 10 minute duration) intensity increases (commonly called “shock spikes”) with relatively narrow angular distributions (∼ 45∘ FWHM), followed by an abrupt decrease in particle intensities at the shock itself and a reversal of the proton flow to a direction toward the Sun and away from the receding shock.

Modelling Solar Energetic Neutral Atoms from Solar Flares and CME-driven Shocks

Gang **Li**, Albert Y. Shih, Robert C. Allen, George Ho, Christina M.S. Cohen, Mihir Desai, Maher A. Dayeh

2023 *ApJ* **944** 196

https://arxiv.org/pdf/2212.00283.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/acb494/pdf

We examine the production of energetic neutral atoms (ENAs) in solar flares and CME-driven shocks and their subsequent propagation to 1 au. Time profiles and fluence spectra of solar ENAs at 1 au are computed for two scenarios: 1) ENAs are produced downstream at CME-driven shocks, and 2) ENAs are produced at large-scale postflare loops in solar flares. Both the time profiles and fluence spectra for these two scenarios are vastly different. Our calculations indicate that we can use solar ENAs as a new probe to examine the underlying acceleration process of solar energetic particles (SEPs) and to differentiate the two accelertion sites: large loops in solar flares and downstream of CME-driven shocks, in large SEP events.

Interpreting the Observed Positive Correlation between the Event-integrated Fluence and the Rollover Energy of Solar Energetic Particle Events by the PAMELA Mission with Coupled Hydromagnetic Wave Excitation and Proton Acceleration at Shocks in the Low Corona

G. **Li**1, A. Bruno2,3, M. A. Lee1, N. Lugaz1, G. A. de Nolfo2, and J. M. Ryan1

2022 ApJ 936 91

https://iopscience.iop.org/article/10.3847/1538-4357/ac81c2/pdf

An analytical model for diffusive shock acceleration (DSA) at one-dimensional stationary planar shocks in the lower corona is presented. The model introduces an upstream escape boundary through which a constant flux of protons streaming upstream out of the system is allowed. The nonvanishing flux of streaming protons out of the system limits the maximum attainable energy of DSA and produces a rollover in the high-energy spectra of the shock-accelerated protons. The condition for the rollover energy derived from the model can account for the approximately linear relation between the natural logarithm of event-integrated fluences and the natural logarithm of rollover energies as demonstrated in Bruno et al. Solar energetic particle (SEP) events with higher integrated fluences in principle exhibit higher rollover energies since proton-excited hydromagnetic waves in the turbulent sheath reduce the proton diffusion coefficient and throttle the upstream streaming of protons. The consistency between the observation and the theory of DSA at shocks in the lower corona serves as evidence for the shock origin of protons of the highest energies in large SEP events.

Estimating the Injection Duration of 20 MeV Protons in Large Western Solar Energetic Particle Events

Gen **Li**1 and Noé Lugaz1

2022 ApJ 930 51

https://iopscience.iop.org/article/10.3847/1538-4357/ac609c/pdf

An ad hoc analytical calculation is presented to infer the duration of injection of 20 MeV protons in 21 selected western solar energetic particle (SEP) events. We convolve the solution of diffusion equation with a "triangle" source to model the time-intensity profiles over the onset and the peaking phase. The effects of "corotating" flux tubes and of solar wind convection are neglected. To accommodate these simplifications, only western events whose associated flares erupted between W15 and W90 are selected. The time-intensity profiles of these events are reconstructed from the timescales presented in Kahler (2005) and Kahler (2013) using the modified Weibull function. From the linear relation between the logarithm of the peak intensity and the logarithm of the fluence of 27–37 MeV protons presented in Kahler & Ling, we derive an optimal radial mean free path (λ_{mfp}) of 0.08 au and adopt this value to fit all selected events. The inferred duration of injection for the selected events, which in general increases with the initial speed of the associated coronal mass ejection (CME) (V_{cme}), is less than 1 hr for V_{cme} < 1000 km s^{-1} and varies from a few to ~10 hr for 1000 km s^{-1} < V_{cme} < 2000 km s^{-1}. We then estimate the distance that the associated CMEs have traveled over the duration of injection. Most CMEs in selected events have traveled to less than 60 solar radii by the time the majority of accelerated particles have been injected into the interplanetary space. **1998 May 9 , 2000 May 5**

Table 1 Selected Properties of 21 Western SEP Events 1997-2006

Solar Energetic Particles Produced during Two Fast Coronal Mass Ejections

Xiaolei **Li**1, Yuming Wang1,2,3, Jingnan Guo1,2, and Shaoyu Lyu1

2022 ApJL 928 L6

https://iopscience.iop.org/article/10.3847/2041-8213/ac5b72/pdf **File**

Two recent extremely fast coronal mass ejections (CMEs) are of particular interest. The first one originated from the southern hemisphere on **2021 October 28** and caused strong solar energetic particle (SEP) events over a wide longitude range from Earth, STEREO-A, to Mars. However, the other one, originating from the center of the Earth-viewed solar disk 5 days later, left weak SEP signatures in the heliosphere. Based on the white-light images of the CMEs from the Solar and Heliospheric Observatory (SOHO) and the Ahead Solar Terrestrial Relations Observatory (STEREO-A), in combination with the observations of the corresponding solar flares, radio bursts, and in situ magnetic fields and particles, we try to analyze the series of solar eruptions during October 28–November 2 as well as their correspondences with the in situ features. It is found that the difference in SEP features between the two CMEs is mainly due to (1) the seed particles probably supplied by associated flares and (2) the magnetic connection influenced by the preceding solar wind speed. **28 Oct 2021, 2 Nov 2021**

Particle-in-cell Simulation of 3He Enrichment in Solar Energetic Particle Events

T. M. **Li**1,2, C. Li1,2, W. J. Ding1,2, and P. F. Chen1,2

2021 ApJ 922 50

https://iopscience.iop.org/article/10.3847/1538-4357/ac2a40/pdf

https://doi.org/10.3847/1538-4357/ac2a40

3He enrichment is one distinctive feature of impulsive solar energetic particle events. This study is designed to investigate the process of plasma wave–particle resonance, which plays a key role in selectively accelerating heavy ions. We apply a 1.5 dimensional particle-in-cell simulation to model the electron-beam–plasma interaction that generates electron and ion cyclotron waves, namely proton and 4He cyclotron waves, whose dispersions are dependent on the magnetization parameter $\alpha = \omega pe/\Omega ce$ and the temperature ratio $\tau = Te/Tp$. The background particles, e.g., 3He and 4He, resonate with the excited cyclotron waves and experience selective heating or acceleration. Specifically, the resonant modes of 3He ions lead to a more effective acceleration rate compared to those of the 4He ions. The simulation results provide a potential solution for understanding the abundance of heavy ions in the solar wind.

Modeling the 2012 May 17 Solar Energetic Particle Event Using the AWSoM and iPATH Models

Gang **Li**1, Meng Jin2, Zheyi Ding1,3, A. Bruno4,5, G. A. de Nolfo4, B. M. Randol4, L. Mays6, J. Ryan7, and D. Lario4

2021 ApJ 919 146

https://iopscience.iop.org/article/10.3847/1538-4357/ac0db9/pdf

https://doi.org/10.3847/1538-4357/ac0db9

We model the 2012 May 17 solar energetic particle event by combining the AWSoM and iPATH codes. Using this combined approach, we investigate particle acceleration when the parent coronal mass ejection (CME) is still close to the Sun. We have obtained reasonable agreements between our simulation and observations made by multiple spacecraft. We follow the three-dimensional CME and the CME-driven shock from their initiation using the AWSoM code for a period of 3 hours when the shock is below ∼20 Rs. Above 20 Rs, iPATH2D is used to follow the CME-driven shock. The plasma properties from the AWSoM code are fed into the iPATH model, where particle acceleration at the shock front is modelled and the instantaneous energetic particle spectra are obtained. The subsequent transport of these energetic particles in the solar wind is followed using the iPATH model. We obtain both the instantaneous particle spectra and particle fluence at 1 au, and we then compare them with observations. To account for uncertainties of magnetic field connectivity from 1 au to the shock, as well as uncertainties of the shock profiles, our model's results are obtained as an ensemble average where, instead of considering Earth as a single point location, we consider multiple locations within 10 degrees in longitude and latitude from Earth. The effect of this model uncertainty mimics that of the field line meandering, as suggested by Bian & Li, but is of different origin. We suggest that a trustworthy solar energetic particle forecast should be made in an ensemble average approach.

Design and Realization of China Tianwen-1 Energetic Particle Analyzer

Cunhui **Li**, Shuwen Tang, […] Yali Ma

Space Science Reviews volume 217, Article number: 26 (**2021**)

https://doi.org/10.1007/s11214-021-00803-0

The Mars radiation environment, both in past and at present, plays a vital role in the evolution of Martian atmosphere, so it is necessary to detect the background radiation environment both in the Martian atmosphere and the transfer orbit from Earth to Mars. The Tianwen-1 Energetic Particle Analyzer (EPA) is designed to measure and analyze the energetic charged particles emitted to the Martian atmosphere. Mars-EPA consists of two parts: one is the Mars-EPA sensor head and the other is the Mars-EPA electronics system. This paper begins with an introduction of Mars-EPA structure and function of each part, followed by a simulation of how sensor head structure is designed. It then evaluates the performance of detection system using Geant4 software, to whether this sensor is capable of identifying the target particle and proposes a reasonable ground calibration procedure, which allows on overall detection performance to some degree. This Mars-EPA has demonstrated a potentially high capability and configurability which hopefully will shed light on future development of compact energetic detectors in deep space exploration.

An Analytical Treatment for Particle Acceleration at Shocks inside Coronal Mass Ejections near 1 au

G. **Li** and N. Lugaz

2020 ApJ 905 8

https://doi.org/10.3847/1538-4357/abc00c

We present an analytical treatment for time-dependent diffusive shock acceleration at shocks inside magnetic clouds (MCs) observed near 1 au. The model includes the effects of (i) spatial diffusion of test particles upstream and downstream of the shock, (ii) proton advection with the plasma inside MCs, (iii) a reflecting boundary at distance L upstream of the shock to mimic the boundary of the MCs, and (iv) particle leakage out of the system at a constant rate, possibly through open field lines introduced by magnetic reconnection between the closed field lines of the MC and open field lines in the corona or heliosphere. The analysis reveals that the mean time for accelerating particles from p 0 to p is naturally reduced if the MC characteristic length is much smaller than the spatial diffusion length of energetic protons upstream of the shock. However, because most shocks inside MCs observed at 1 au are located in the back half of the MC, the time that the shock has propagated into the MCs is not sufficient to cause significant SEP enhancement—even with a reflecting boundary—if particles are only injected from the low-beta plasma inside MCs. To cause large SEP enhancements inside the shock–MC structure, magnetic reconnection at the back MC is essential to allow particles energized by the shock prior to its interaction with the MC to enter the MC. These particles consequently become the seed energetic protons that are reaccelerated at the shock inside MC.

Observations of Outward-propagating and Mirroring of the Same Energetic Electrons by Wind

G. **Li**1, X. Wu1,2, L. Zhao3,4, and S. Yao2

2020 ApJL 905 L1

https://doi.org/10.3847/2041-8213/abca87

We report an energetic electron event observed by the Wind spacecraft in which electrons were first detected to propagate away from the Sun, and subsequently detected to propagate back toward the Sun. Using the recently developed fractional velocity dispersion analysis (FVDA), the path lengths corresponding to these two sequential electron signals were found to be ~1.5 and ~3.1 au. The inferred release times for both populations were found to be the same, within uncertainty. No bidirectional halo electrons were identified during the event, indicating that the electrons were not propagating within a closed magnetic field configuration (e.g., a magnetic flux rope). These observations suggest that the same energetic electrons were observed twice at 1 au, with the second time being due to reflection occurring beyond 1 au, by perhaps magnetic kinks caused by a coronal mass ejection–driven shock.

Identification of Two Distinct Electron Populations in an Impulsive Solar Energetic Electron Event

G. **Li**1, L. Zhao2, L. Wang3, W. Liu4, and X. Wu1,5

2020 ApJL 900 L16

https://doi.org/10.3847/2041-8213/abb098

We examine the release times of energetic electrons in the **2001 April 25** event. An M2.7 flare occurred on 2001 April 25, from AR 09433, located at N18W09. The flare was observed in X-rays by GOES and the Yohkoh spacecraft. The Yohkoh observation also included hard X-ray (HXR) images for all four energy channels: L, M1, M2, and H. We use Yohkoh observation times as a proxy for the release time of energetic electrons that propagated downward, which are responsible for the HXRs. In situ >~25 keV electrons were observed by the Wind spacecraft. For these electrons, we obtain the release time at the Sun using the recently developed Fractional Velocity Dispersion Analysis method. We find that the release times of outward-propagating energetic electrons are clearly delayed from those that propagated downward. Furthermore, these delayed releases are energy dependent. The implication of this delay on the underlying acceleration and trapping process of the >~25 keV electrons at solar flares is discussed.

Focused Transport of Solar Energetic Particles in Interplanetary Space and the Formation of the Anisotropic Beam-like Distribution of Particles in the Onset Phase of Large Gradual Events

Gen **Li** and Martin A. Lee

2019 ApJ 875 116

sci-hub.se/10.3847/1538-4357/ab0c98

In the onset phase of large gradual solar energetic particle (SEP) events, the first particles of a given rigidity to arrive at Earth are accelerated in the low corona, focused into a narrow cone of pitch angles by the diverging magnetic field, and transported from near the Sun to 1 au with minimal scattering. The effects of focused transport on the evolution of the beam-like SEPs are investigated analytically. The model assumes for simplicity a constant focusing length and a constant pitch-angle diffusion coefficient for SEPs at small pitch angles. Cross-field transport is ignored. This analytical approximation provides a reasonable representation of the spatial and pitch-angle distribution of the beam-like SEPs. Assuming an instantaneous injection of SEPs near the Sun, the model naturally reproduces several features of the SEP onset profiles observed at 1 au, including a spike-like time–intensity profile with rapid rising and declining edges that resemble a Reid–Axford profile. By assuming an extended injection profile with the shape of an isosceles triangle, we fit the onset phase data of the **2005 January 20** GLE event to our model. The derived mean free path (~4 au) for relativistic protons is much larger than the theoretical prediction based on the standard quasilinear theory but consistent with our assumption of nearly scatter-free transport and can be explained by a reduced scattering rate, due to particles interacting with ambient turbulence with a Goldreich–

Sridhar spectrum. Assuming that the SEPs that are scattered out of the beam are governed by spatial diffusive transport in interplanetary space, we perform an illustrative calculation to account for the nearly isotropic phase following the anisotropic onset as a natural result of the interplanetary transport of SEPs.

Small Ground-Level Enhancement of 6 January 2014: Acceleration by CME-Driven Shock?

C. **Li** , L. I. Miroshnichenko, V. E. Sdobnov

Solar Phys. Volume 291, Issue 3, pp 975-987 **2016**

Available spectral data for solar energetic particles (SEPs) measured near the Earth's orbit (GOES-13) and on the terrestrial surface (polar neutron monitors) on **6 January 2014** are analyzed. A feature of this solar proton event (SPE) and weak ground-level enhancement (GLE) is that the source was located behind the limb. For the purpose of comparison, we also use the Advanced Composition Explorer (ACE) data on sub-relativistic electrons and GOES-13 measurements of a strong and extended proton event on **8 – 9 January 2014**. It was found that the surface observations at energies >433 MeV>433 MeV and GOES-13 data at >30-->700 MeV>30-->700 MeV may be satisfactorily reconciled by a power-law time-of-maximum (TOM) spectrum with a characteristic exponential tail (cutoff). Some methodological difficulties of spectrum determination are discussed. Assuming that the TOM spectrum near the Earth is a proxy of the spectrum of accelerated particles in the source, we critically consider the possibility of shock acceleration to relativistic energies in the solar corona. Finally, it is suggested to interpret the observational features of this GLE under the assumption that small GLEs may be produced by shocks driven by coronal mass ejections. However, the serious limitations of such an approach to the problem of the SCR spectrum prevent drawing firm conclusions in this controversial field.

SCATTER-DOMINATED INTERPLANETARY TRANSPORT OF SOLAR ENERGETIC PARTICLES IN LARGE GRADUAL EVENTS AND THE FORMATION OF DOUBLE POWER-LAW DIFFERENTIAL FLUENCE SPECTRA OF GROUND-LEVEL EVENTS DURING SOLAR CYCLE 23

Gen **Li** and Martin A. Lee

2015 ApJ 810 82 **File**

The effects of scatter-dominated interplanetary transport on the spectral properties of the differential fluence of large gradual solar energetic particle (SEP) events are investigated analytically. The model assumes for simplicity radial constant solar wind and radial magnetic field. The radial diffusion coefficient is calculated with quasilinear theory by assuming a spectrum of Alfvén waves propagating parallel to the magnetic field. Cross-field transport is neglected. The model takes into consideration several essential features of gradual event transport: nearly isotropic ion distributions, adiabatic deceleration in a divergent solar wind, and particle radial scattering mean free paths increasing with energy. Assuming an impulsive and spherically symmetric injection of SEPs with a power-law spectrum near the Sun, the predicted differential fluence spectrum exhibits at 1 AU three distinctive power laws for different energy domains. The model naturally reproduces the spectral features of the double power-law proton differential fluence spectra that tend to be observed in extremely large SEP events. We select nine western ground-level events (GLEs) out of the 16 GLEs during Solar Cycle 23 and fit the observed double power-law spectra to the analytical predictions. The compression ratio of the accelerating shock wave, the power-law index of the ambient wave intensity, and the proton radial scattering mean free path are determined for the nine GLEs. The derived parameters are generally in agreement with the characteristic values expected for large gradual SEP events.

Table 1 Selected Properties of the 16 GLE Events of Solar Cycle 23a

Waiting time distribution of solar energetic particle events modeled with a non-stationary Poisson process

Chuan **Li**, Sijia Zhong, Linghua Wang, Wei Su, Cheng Fang

ApJL, 792 L26, **2014**

http://arxiv.org/pdf/1408.2306v1.pdf

We present a study of the waiting time distributions (WTDs) of solar energetic particle (SEP) events observed with the spacecraft WIND and GOES. Both the WTDs of solar electron events (SEEs) and solar proton events (SPEs) display a power-law tail $\sim\Delta t^{-\gamma}$. The SEEs display a broken power-law WTD. The power-law index is $\gamma_1 = 0.99$ for the short waiting times (<70 hours) and $\gamma_2 = 1.92$ for large waiting times (>100 hours). The break of the WTD of SEEs is probably due to the modulation of the corotating interaction regions (CIRs). The power-law index $\gamma \sim 1.82$ is derived for the WTD of SPEs that is consistent with the WTD of type II radio bursts, indicating a close relationship between the shock wave and the production of energetic protons. The WTDs of SEP events can be modeled with a non-stationary Poisson process which was proposed to understand the waiting time statistics of solar flares (Wheatland 2000; Aschwanden & McTiernan 2010). We generalize the method and find that, if the SEP event rate $\lambda=1/\Delta t$ varies as the time distribution of event rate $f(\lambda)=A\lambda-\alpha\exp(-\beta\lambda)$, the time-dependent Poisson distribution can produce a power-law tail WTD $\sim\Delta t\ \alpha-3$, where $0\leq\alpha<2$.

Proton activity of the Sun in current solar cycle 24

Chuan **Li**, Leonty Miroshnichenko, Cheng Fang

RAA (Research in Astronomy and Astrophysics), **2014**

http://arxiv.org/pdf/1408.2308v1.pdf

We present a study of 7 large solar proton events (SPEs) of current solar cycle 24 (from 2009 January up to date). They were recorded by GOES spacecraft with highest proton fluxes **over 200 pfu** for energies >10 MeV. In situ particle measurements show that: (1) The profiles of the proton fluxes are highly dependent of the locations of their solar sources, namely flares or coronal mass ejections (CMEs); (2) The solar particle release (SPR) times fall in the decay phase of the flare emission, and are in accordance with the times when the CMEs travel to an average height of 7.9 solar radii; (3) The time differences between the SPR and the flare peak are also dependent of the locations of the solar active regions (ARs). The results tend to support the concept of proton acceleration by the CME-driven shock, even though there exists a possibility of particle acceleration at flare site with subsequent perpendicular diffusion of accelerated particles in the interplanetary magnetic field (IMF). We derive the integral time-of-maximum (TOM) spectra of solar protons in two forms: a single power-law distribution and a power law broken with an exponential tail. It is found that the unique Ground Level Enhancement (GLE) event on 2012 May 17 displays a hardest spectrum and a largest broken energy that may explain why the this event could extend to relativistic energy.

Table 1. Large Solar Proton Events of Solar Cycle 24. 2012/01/23, 2012/01/27, 2012/03/07, 2012/03/13, 2012/05/17, 2013/05/22, 2014/01/07

Energization of charged particle in a time-dependent chaotic magnetic field with an implication of the production of seed particles in solar energetic particle events

Xiaocan **Li**, Brahmananda Dasgupta, Gang Li

Advances in Space Research, Volume 53, Issue 8, 15 April **2014**, Pages 1153–1161

We investigate the acceleration of charged particles in a time-dependent chaotic magnetic field in this work. In earlier works, it has been demonstrated that in an asymmetric wire-loop current systems (WLCSs), the magnetic field is of chaotic in nature. Furthermore, observations also showed that there exist time-varying current loops and current filaments in solar corona. It is therefore natural to conceive that the magnetic field on the solar surface is chaotic and time-dependent. Here, we develop a numerical model to study the acceleration process of charged particles in a time-varying chaotic magnetic field that is generated by an ensemble of 8 WLCSs. We found that the motion of energetic particles in the system is of diffusive in nature and a power law spectrum can quickly develop. The mechanism examined here may serve as an efficient pre-acceleration mechanism that generates the so-called seed particles for diffusive shock acceleration at a coronal mass ejection (CME) driven shock in large solar energetic particle (SEP) events.

Coronal magnetic topology and the production of solar impulsive energetic electrons

C. **Li**, L. P. Sun, X. Y. Wang, and Y. Dai

E-print, July **2013;** A&A

We investigate two candidate solar sources or active regions (ARs) in association with a solar impulsive energetic electron (SIEE) event on **2002 October 20**. The solar particle release (SPR) times of SIEEs are derived by using their velocity dispersion with consideration of the instrumental effect. It is found that there are double electron injections at the Sun. The low-energy (<13 keV) electron injection coincides with a C6.6 flare in AR10154 and is accompanied with prominent type III radio bursts rather than a stronger M1.8 flare in AR10160. The M1.8 flare produces, however, faint type III radio bursts. Electrons of ~25 to ~300 keV are released ~9 min later when a jet-like CME travels to ~2.6 solar radii. We further examine the coronal magnetic configurations above the two ARs based on the potential field source surface (PFSS) model. It is found that open field lines, rooted in AR10154 and well connected to the Earth, provide escaping channels for energetic electrons. Only a small portion of magnetic fields are opened above AR10160, being responsible for the faint type III radio bursts. These lines are, however, not well connected, making it impossible for SIEEs detection by near-Earth spacecraft. The results appear to establish a physical link between coronal magnetic topology, formation of type III radio bursts, and production of SIEEs.

ELECTRON AND PROTON ACCELERATION DURING THE FIRST GROUND LEVEL ENHANCEMENT EVENT OF SOLAR CYCLE 24

C. **Li**1,2, Kazi A. Firoz3, L. P. Sun1, and L. I. Miroshnichenko
E-print, May **2013; 2013** ApJ 770 34
http://arxiv.org/pdf/1305.5606v1.pdf
High-energy particles were recorded by near-Earth spacecraft and ground-based neutron monitors (NMs) on **2012 May 17**. This event was the first ground level enhancement (GLE) of solar cycle 24. In this study, we try to identify the acceleration source(s) of solar energetic particles by combining in situ particle measurements from the WIND/3DP, GOES 13, and solar cosmic rays registered by several NMs, as well as remote-sensing solar observations from SDO/AIA, SOHO/LASCO, and RHESSI. We derive the interplanetary magnetic field (IMF) path length (1.25 ± 0.05 AU) and solar particle release time (01:29 ± 00:01 UT) of the first arriving electrons by using their velocity dispersion and taking into account contamination effects. We found that the electron impulsive injection phase, indicated by the dramatic change in the spectral index, is consistent with flare non-thermal emission and type III radio bursts. Based on the potential field source surface concept, modeling of the open-field lines rooted in the active region has been performed to provide escape channels for flare-accelerated electrons. Meanwhile, relativistic protons are found to be released ~10 minutes later than the electrons, assuming their scatter-free travel along the same IMF path length. Combining multi-wavelength imaging data of the prominence eruption and coronal mass ejection (CME), we obtain evidence that GLE protons, with an estimated kinetic energy of ~1.12 GeV, are probably accelerated by the CME-driven shock when it travels to ~3.07 solar radii. The time-of-maximum spectrum of protons is typical for shock wave acceleration.

A Twin-CME Scenario for Ground Level Enhancement Events

G. **Li** · R. Moore · R.A. Mewaldt · L. Zhao · A.W. Labrador
Space Sci Rev, 171, Numbers 1-4 (2012), 141-160, **2012, File**
Ground Level Enhancement (GLEs) events are extreme Solar Energetic Particle (SEP) events. Protons in these events often reach **~**GeV/nucleon. Understanding the underlying particle acceleration mechanism in these events is a major goal for Space Weather studies. In Solar Cycle 23, a total of 16 GLEs have been identified. Most of them have preceding CMEs and in-situ energetic particle observations show some of them are enhanced in ICME or flare-like material. Motivated by this observation, we discuss here a scenario in which two CMEs erupt in sequence during a short period of time from the same Active Region (AR) with a pseudo-streamer-like pre-eruption magnetic field configuration. The first CME is narrower and slower and the second CME is wider and faster. We show that the magnetic field configuration in our proposed scenario can lead to magnetic reconnection between the open and closed field lines that drape and enclose the first CME and its driven shock. The combined effect of the presence of the first shock and the existence of the open close reconnection is that when the second CME erupts and drives a second shock, one finds both an excess of seed population and an enhanced turbulence level at the front of the second shock than the case of a single CME-driven shock. Therefore, a more efficient particle acceleration will occur. The implications of our proposed scenario are discussed.
28 Oct 2003, 17 Jan 2005, Properties of CMEs in GLE events of solar cycle 23

Diffusive shock acceleration and ground level events.

G. **Li,**
Space Sci. Rev. (**2011**, submitted)

Particle acceleration and transport at an oblique CME-driven shock

G. **Li** , , A. Shalchi, X. Aoc, G. Zank, O.P. Verkhoglyadova
Advances in Space Research, Volume 49, Issue 6, 15 March **2012**, Pages 1067–1075
In gradual solar energetic particle (SEP) events, protons and heavy ions are often accelerated to >100 MeV/nucleon at a CME-driven shock. In this work, we study particle acceleration at an oblique shock by extending our earlier particle acceleration and transport in heliosphere (PATH) code to include shocks with arbitrary θ_{BN}, where θ_{BN} is the angle between the upstream magnetic field and the shock normal. Instantaneous particle spectra at the shock front are obtained by solving the transport equation using the total diffusion coefficient κ, which is a function of the parallel diffusion coefficient $\kappa_\parallel$ and the perpendicular diffusion coefficient $\kappa_\perp$. In computing $\kappa_\parallel$ and $\kappa_\perp$, we use analytic expressions derived previously. The particle maximum energy at the shock front as a function of time, the time intensity profiles and particle spectra at 1 AU for five θ_{BN}'s are calculated for an example shock.

CORONAL JETS, MAGNETIC TOPOLOGIES, AND THE PRODUCTION OF INTERPLANETARY ELECTRON STREAMS

C. **Li**1,2, S. A. Matthews1, L. van Driel-Gesztelyi1,3,4, J. Sun1 and C. J. Owen
2011 ApJ 735 43
We investigate the acceleration source of the impulsive solar energetic particle (SEP) events on **2007 January 24**. Combining the in situ electron measurements and remote-sensing solar observations, as well as the calculated magnetic fields obtained from a potential-field source-surface model, we demonstrate that the jets associated with

the hard X-ray flares and type-III radio bursts, rather than the slow and partial coronal mass ejections, are closely related to the production of interplanetary electron streams. The jets, originated from the well-connected active region (AR 10939) whose magnetic polarity structure favors the eruption, are observed to be forming in a coronal site, extending to a few solar radii, and having a good temporal correlation with the electron solar release. The open-field lines near the jet site are rooted in a negative polarity, along which energetic particles escape from the flaring AR to the near-Earth space, consistent with the in situ electron pitch angle distribution. The analysis enables us to propose a coronal magnetic topology relating the impulsive SEP events to their solar source.

Can multiple shocks trigger ground level events,

G. **Li**, R.A. Mewaldt,

in *Proceedings of the 31st ICRC SH (***2009**), p. 1362

A total of 16 Ground Level Events (GLE) occurred in solar cycle 23. These events, in which particle energies reach above 1 GeV/nuc, are the most energetic examples of Gradual Solar Energetic Particle (SEP) events. Over the past solar cycle, a great deal has been learned about these events observationally. However, the process by which particles are accelerated to these high energies is still presently unknown. We know the fact that they are often associated with both flares and Coronal Mass Ejection (CME) driven shocks, yet in many other SEP events where both strong flares and fast CMEs are found, the intensities and the maximum energies of energetic particles are often more than 10 to 100 times smaller. So questions such as what triggers a GLE and what differentiates a GLE from other gradual SEP events remain open. We discuss here a scenario in which two CMEs occur closely in time but offset in propagation direction. We show that the resulting magnetic field configuration can lead to magnetic reconnection. This reconnection process will provide both an excess of seed population and enhanced turbulence level at the shock front of the second CME-driven shock. Enhanced particle acceleration can therefore be achieved. The implications of our proposed scenario will be discussed.

Solar source of energetic particles in interplanetary space during the 2006 December 13 event

C. **Li**, Y. Dai, J. -C. Vial, C. J. Owen, S. A. Matthews, Y. H. Tang, C. Fang, and A. N. Fazakerley

E-print, July **2009; File**, A&A, 503 (**2009**) 1013-1021

http://www.aanda.org/10.1051/0004-6361/200911986

An X3.4 solar are and a fast halo coronal mass ejection (CME) occurred on 2006 December 13, accompanied by a high flux of energetic particles recorded both in near-Earth space and at ground level. **Our purpose is to provide evidence of flare acceleration in a major solar energetic particle (SEP) event**. We first present observations from ACE/EPAM, GOES, and the Apatity neutron monitor. It is found that the initial particle release time coincides with the flare emission and that the spectrum becomes softer and the anisotropy becomes weaker during particle injection, indicating that the acceleration source changes from a confined coronal site to a widespread interplanetary CME-driven shock. We then describe a comprehensive study of the associated flare active region. By use of imaging data from HINODE/SOT and SOHO/MDI magnetogram, we infer the flare magnetic reconnection rate in the form of the magnetic flux change rate. This correlates in time with the microwave emission, indicating a physical link between the flare magnetic reconnection and the acceleration of nonthermal particles. Combining radio spectrograph data from Huairou/NOAC, Culgoora/IPS, Learmonth/RSTN, and WAVES/WIND leads to a continuous and longlasting radio burst extending from a few GHz down to several kHz. Based on the photospheric vector magnetogram from Huairou/NOAC and the nonlinear force free field (NFFF) reconstruction method, we derive the 3D magnetic field configuration shortly after the eruption. Furthermore, we also compute coronal fi eld lines extending to a few solar radii using a potential- field source-surface (PFSS) model. ***Both the so-called type III-l burst and the magnetic field configuration suggest that open-fi eld lines extend from the are active region into interplanetary space, allowing the accelerated and charged particles escape.***

SHOCK GEOMETRY AND SPECTRAL BREAKS IN LARGE SEP EVENTS

G. Li[1], G. P. Zank[1], Olga Verkhoglyadova[2], R. A. Mewaldt[3], C. M. S. Cohen[3], G. M. Mason[4] and M. I. Desai[5]

ApJ 702 998-1004, **2009** doi: 10.1088/0004-637X/702/2/998

Solar energetic particle (SEP) events are traditionally classified as "impulsive" or "gradual." It is now widely accepted that in gradual SEP events, particles are accelerated at coronal mass ejection-driven (CME-driven) shocks. In many of these large SEP events, particle spectra exhibit double power law or exponential rollover features, with the break energy or rollover energy ordered as $(Q/A)^{\alpha}$, with Q being the ion charge in e and A the ion mass in units of proton mass m_p . This Q/A dependence of the spectral breaks provides an opportunity to study the underlying acceleration mechanism. In this paper, we examine how the Q/A dependence may depend on shock geometry. Using the nonlinear guiding center theory, we show that $\alpha \sim 1/5$ for a quasi-perpendicular shock. Such a weak Q/A dependence is in contrast to the quasi-parallel shock case where α can reach 2. This difference in α reflects the difference of the underlying parallel and perpendicular diffusion coefficients $\kappa_{\|}$ and $\kappa_{\perp}$. We also examine the Q/A dependence of the break energy for the most general oblique shock case. Our analysis offers a possible way to remotely examine the geometry of a CME-driven shock when it is close to the Sun, where the acceleration of particle to high energies occurs.

The acceleration characteristics of solar energetic particles in the 2000 July 14 event:

C. **Li**, Y. H. Tang, Y. Dai, W. G. Zong and C. Fang

A&A 461 (**2007**) 1115-1119, E-print **file**

the evolution of the X5.7 two-ribbon flare and the associated SEP event on 14 July 2000 are studied.
It is found that the **magnetic reconnection in this event consists of two parts, and the induced electric field Erec is temporally correlated with the evolution of hard X-ray and gamma-ray emission.**

Flare magnetic reconnection and relativistic particles in the 2003 October 28 event

C. **Li**, Y. H. Tang, Y. Dai, C. Fang and J. -C. Vial

E-print, June **2007, file** A&A 472 (**2007**) 283-286

It is found that the inferred magnetic reconnection electric field correlates well with the hard X-ray, gamma-ray, and neutron emission at the Sun. **Thus the flare's magnetic reconnection probably makes a crucial contribution to the prompt relativistic particles, which could be detected at 1 AU.**

Multiple CMEs and large gradual SEP events,

G. **Li**, G.P. Zank,

in *29th ICRC Proceedings*, vol. 1 (**2005**), p. 173

http://articles.adsabs.harvard.edu/full/2005ICRC....1..173L

Li and Zank (2005) further estimated the acceleration time scale at the second shock and showed that if the wave (turbulence) intensity downstream of the first shock (which is the upstream of the 2nd shock) is enhanced by a factor of 10, then a factor of 32 increase for the maximum particle kinetic energy may be reached at the second shock. In the work of Li and Zank (2005), the authors also noted that the preceding shock can provide the needed seed population at the second shock through pre-acceleration. Clearly, this requires the first shock and the second shock to occur closely in time so that the accelerated particles from the first shock do not propagate away before the second shock runs through them. However, putting an exact upper limit of the time separation between the two shocks is hard—as we will discuss later, however, 24 hours may be too long.

Some aspects of particle acceleration and transport at CME-driven shocks

G. **Li**, G.P. Zank

Coronal and Stellar Mass Ejections, IAU Symposium Proceedings of the International Astronomical Union 226, Held 13-17 September, Beijing, edited by K. Dere, J. Wang, and Y. Yan. Cambridge: Cambridge University Press, **2005**., pp.332-337, **book**

Gradual solar energetic particle (SEP) events are now believed to be associated with CME-driven shocks. As the shock propagates out from the Sun, particles are accelerated diffusively at the shock front and some will escape upstream and downstream into the interplanetary medium. This is in contrast with "impulsive" events, which are believed to be due to solar flares. However, recent observations have found that in some gradual SEP events, the time intensity profile show a two peak feature, suggesting a mixture of particles from solar flares with particles from CME-driven shock. Furthermore, the observed spectra of large SEP events show tremendous variability. The Fe/C (Fe/O) ratio behave oppositely in events which have similar solar progenitors. In this work, we use a numerical model to follow particle acceleration and transport at CME-driven shocks. We investigate a possible scenario for the re-acceleration of flare particles by CME-driven shocks and calculate the Fe/O ratio for two exemple shocks. These simulations are helpful in interpreting observations of particle data obtained in situ at 1 AU by spacecraft such as ACE and WIND.

Mixed particle acceleration at CME-driven shocks and flares

G. **Li**, G.P. Zank

Geophysical Research Letters, Volume 32, Issue 2, CiteID L02101, **2005**

A recent study of Cane et al. [2003] showed that in some intense SEP events, the time-intensity profiles exhibit two peaks, with an earlier one having a high Fe/O and a later one with a low Fe/O ratio. They suggested that these two-component events are due to CMEs and their accompanying flares occurring together, with the first peak being flare-related and the second peak being CME-driven shock related. In this paper, we develop a model which examines particle acceleration and transport when both flares and CME-driven shocks are present. We study time-intensity profiles for three different scenarios: a pure shock case, a pure flare case and a shock-flare-mixed case.

Using reasonable estimates of the relative timing between CMEs and associated flares, we find that a large portion of the flare accelerated material is subject to absorption and re-acceleration by the CME-driven shock. **Consequently, the time intensity profile for the shock-flare-mixed case shows an initial rapid increase, owing to particles accelerated at the flare and followed by a plateau similar to that of a pure shock case.**

Solar Eruptive Events (SEE) 2020 Mission Concept Review

R. P. **Lin**, A. Caspi, S. Krucker, H. Hudson, G. Hurford, S. Bandler, S. Christe, J. Davila, B. Dennis, G. Holman, R. Milligan, A. Y. Shih, S. Kahler, E. Kontar, M. Wiedenbeck, J. Cirtain, G. Doschek, G. H. Share, A. Vourlidas, J. Raymond, D. M. Smith, M. McConnell, G. Emslie

eprint arXiv:1311.5243, **2013**

http://arxiv.org/pdf/1311.5243v1.pdf

Major solar eruptive events (SEEs), consisting of both a large flare and a near simultaneous large fast coronal mass ejection (CME), are the most powerful explosions and also the most powerful and energetic particle accelerators in the solar system, producing solar energetic particles (SEPs) up to tens of GeV for ions and hundreds of MeV for electrons. The intense fluxes of escaping SEPs are a major hazard for humans in space and for spacecraft. Furthermore, the solar plasma ejected at high speed in the fast CME completely restructures the interplanetary medium (IPM) - major SEEs therefore produce the most extreme space weather in geospace, the interplanetary medium, and at other planets. Thus, understanding the flare/CME energy release process(es) and the related particle acceleration processes are major goals in Heliophysics. To make the next major breakthroughs, we propose a new mission concept, SEE 2020, a single spacecraft with a complement of advanced new instruments that focus directly on the coronal energy release and particle acceleration sites, and provide the detailed diagnostics of the magnetic fields, plasmas, mass motions, and energetic particles required to understand the fundamental physical processes involved. 23 July 2002,

Energy Release and Particle Acceleration in Flares: Summary and Future Prospects

R.P. **Lin**

Space Sci Rev (**2011**) 159:421–445, **File** **A Review**

RHESSI measurements relevant to the fundamental processes of energy release and particle acceleration in flares are summarized. RHESSI's precise measurements of hard X-ray continuum spectra enable model-independent deconvolution to obtain the parent electron spectrum. Taking into account the effects of albedo, these show that the low energy cut-off to the electron power-law spectrum is typically ≲tens of keV, confirming that the accelerated electrons contain a large fraction of the energy released in flares. RHESSI has detected a high coronal hard X-ray source that is filled with accelerated electrons whose energy density is comparable to the magnetic-field energy density. This suggests an efficient conversion of energy, previously stored in the magnetic field, into the bulk acceleration of electrons. A new, collisionless (Hall) magnetic reconnection process has been identified through theory and simulations, and directly observed in space and in the laboratory; it should occur in the solar corona as well, with a reconnection rate fast enough for the energy release in flares. The reconnection process could result in the formation of multiple elongated magnetic islands, that then collapse to bulk-accelerate the electrons, rapidly enough to produce the observed hard X-ray emissions. RHESSI's pioneering γ-ray line imaging of energetic ions, revealing footpoints straddling a flare loop arcade, has provided strong evidence that ion acceleration is also related to magnetic reconnection. Flare particle acceleration is shown to have a close relationship to impulsive Solar Energetic Particle (SEP) events observed in the interplanetary medium, and also to both fast coronal mass ejections and gradual SEP events. New instrumentation to provide the high sensitivity and wide dynamic range hard X-ray and γ-ray measurements, plus energetic neutral atom (ENA) imaging of SEPs above ~2 $R_\odot$, will enable the next great leap forward in understanding particle acceleration and energy release is large solar eruptions—solar flares and associated fast coronal mass ejections (CMEs).

Automatic detection method, forecast and alert of solar proton events

Ganghua **Lin**

Solar and Stellar Variability: Impact on Earth and Planets, Proceedings IAU Symposium No. 264, **2009**, p. 105-108, A.G. Kosovichev, A.H. Andrei & J.-P. Rozelot, eds.

Y:\obridko\otchet09

The methods of automatic solar active phenomenon or event detection have been researched and explored by people for many years, which have gone into actual services. The paper analyzes the relationship between these methods of automatic detection and the forecast or alert, using the solar short-term proton events predictions as an example. Using automatic method to conduct forecast or alert is under thinking.

PARTICLE ACCELERATION BY THE SUN: ELECTRONS, HARD X-RAYS/GAMMA-RAYS
R. P. **LIN,**
Space Science Reviews (**2006**) 124: 233–248, **File**
preliminary comparisons of the RHESSI observations with observations of both energetic electrons and ions near 1 AU are reviewed, and the implications for the particle acceleration and escape processes are discussed.
3. Energetic Ions at the Sun and SEPs at 1 AU

Relationship of solar flare accelerated particles to solar energetic particles (SEPs) observed in the interplanetary medium
R.P. **Lin**
Advances in Space Research 35 (**2005**) 1857–1863
sci-hub.se/10.1016/j.asr.2005.02.087
Observations of hard X-ray (HXR)/c-ray continuum and c-ray lines produced by energetic electrons and ions, respectively, colliding with the solar atmosphere, have shown that large solar flares can accelerate ions up to many GeV and electrons up to hundreds of MeV. Solar energetic particles (SEPs) are observed by spacecraft near 1 AU and by ground-based instrumentation to extend up to similar energies as in large SEP events, but it appears that a different acceleration process, one associated with fast coronal mass ejections is responsible. Much weaker SEP events are observed that are generally rich in electrons, 3He, and heavy elements. The energetic particles in these events appear to be similar to those accelerated in flares. The Ramaty high energy solar spectroscopic imager (RHESSI) mission provides high-resolution spectroscopy and imaging of flare HXRs and c-rays. Such observations can provide information on the location, energy spectra, and composition of the flare accelerated energetic particles at the Sun. Here, preliminary comparisons of the RHESSI observations with observations of both energetic electron and ion near 1 AU are reviewed, and the implications for the particle acceleration and escape processes are discussed.

The emission and propagation of ~ 40keV solar flare electrons I: The relationship of ~ 40 keV electron to energetic proton and relativistic electron emission by the Sun
R. P. **Lin**
Solar Physics volume 12, pages266–303(**1970**)
https://link.springer.com/content/pdf/10.1007/BF00227122.pdf
Observations of prompt ~ 40 keV solar flare electron events by the IMP series of satellites in the period August, 1966 to December, 1967 are tabulated along with prompt energetic solar proton events in the period 1964–1967. The interrelationship of the various types of energetic particle emission by the sun, including relativistic energy electrons reported by Cline and McDonald (1968) are investigated. Relativistic energy electron emission is found to occur only during proton events. The solar optical, radio and X-ray emission associated with these various energetic particle emissions as well as the propagation characteristics of each particle species are examined in order to study the particle acceleration and emission mechanisms in a solar flare. Evidence is presented for two separate particle acceleration and/or emission mechanisms, one of which produces ~ 40 keV electrons and the other of which produces solar proton and possibly relativistic energy electrons. It is found that solar flares can be divided into three categories depending on their energetic particle emission: (1) small flares with no accompanying energetic phenomena either in particles, radio or X-ray emission; (2) small flares which produce low energy electrons and which are accompanied by type III and microwave radio bursts and energetic (~ 20 keV) X-ray bursts; and (3) major solar flare eruptions characterized by energetic solar proton production and type II and IV radio bursts and accompanied by intense microwave and X-ray emission and relativistic energy electrons.

Peak Temperatures of Large Solar X-Ray Flares and Associated CME Speeds and Widths
A. G. **Ling** and S. W. Kahler
2020 ApJ 891 54
sci-hub.si/10.3847/1538-4357/ab6f6c **File**
We recently repeated an earlier analysis by Garcia showing that large (≥M3.0) solar X-ray flares associated with solar energetic particle (SEP) events have significantly lower peak X-ray flux ratios R = (0.04–0.5 nm)/(0.1–0.8 nm), proxies for flare peak temperatures, than those without SEP events. As we expect SEP events to be produced by shocks ahead of fast coronal mass ejections (CMEs), a smaller R for an X-ray flare of a given peak flux Fp should also be more likely to be accompanied by a fast (Vcme > 1000 km s−1) CME. We confirm this expectation, examine the role played by the ratios R in correlations between Fp and CME speeds Vcme, and then compare CME widths W, Vcme, and R with each other. We consider an apparent conflict between a global scaling model of eruptive events showing Vcme scaling with higher R and our confirmation that the Garcia analysis implies that faster CMEs are associated with flares of lower R. The R values are examined for 16 large flares of the well-

studied AR 12192, for which nearly all flares had no associated CMEs. Those flares share the same high values of R as other active region (AR) flares with no CMEs. We also find that small (<M3.0) flares of filament eruptions leading to SEP events share the lower R values of larger flares with fast CMEs.
Table 2 X-ray Flares and CME Speeds of FE SEP Events
Table 3 X-ray Flares > M3 and Associated CMEs and SEP Events (This table is available in its entirety in machine-readable form.)

The Propitious Role of Solar Energetic Particles in the Origin of Life

Manasvi **Lingam**, Chuanfei Dong, Xiaohua Fang, Bruce M. Jakosky, Abraham Loeb
ApJ **2018**
https://arxiv.org/pdf/1801.05781.pdf
We carry out 3-D numerical simulations to assess the penetration and bombardment effects of Solar Energetic Particles (SEPs), i.e. high-energy particle bursts during large flares and superflares, on ancient and current Mars. We demonstrate that the deposition of SEPs is non-uniform at the planetary surface, and that the corresponding energy flux is lower than other sources postulated to have influenced the origin of life. Nevertheless, SEPs may have been capable of facilitating the synthesis of a wide range of vital organic molecules (e.g. nucleobases and amino acids). Owing to the relatively high efficiency of these pathways, the overall yields might be comparable to (or even exceed) the values predicted for some conventional sources such as electrical discharges and exogenous delivery by meteorites. We also suggest that SEPs could have played a role in enabling the initiation of lightning. A notable corollary of our work is that SEPs may constitute an important mechanism for prebiotic synthesis on exoplanets around M-dwarfs, thereby mitigating the deficiency of biologically active ultraviolet radiation on these planets. Although there are several uncertainties associated with (exo)planetary environments and prebiotic chemical pathways, our study illustrates that SEPs represent a potentially important factor in understanding the origin of life.

Coupled MHD-Focused Transport Simulations for Modeling Solar Particle Events

Jon A. **Linker**, Ronald M. Caplan, Nathan Schwadron, Matthew Gorby, Cooper Downs, Tibor Torok, Roberto Lionello, Janvier Wijaya
Journal of Physics Conf. Ser. ASTRONUM 2018 **2019**
https://arxiv.org/pdf/1905.05299.pdf
We describe the initial version of the Solar Particle Event (SPE) Threat Assessment Tool or STAT. STAT relies on elements of Corona-Heliosphere (CORHEL) and the Earth-Moon-Mars Radiation Environment Module (EMMREM), and allows users to investigate coronal mass ejection (CME) driven SPEs using coupled magnetohydrodynamic (MHD) and focused transport solutions. At the present time STAT focuses on modeling solar energetic particle (SEP) acceleration in and transport from the low corona, where the highest energy SEP events are generated. We illustrate STAT's capabilities with a model of the **July 14, 2000** "Bastille Day" event, including innovative diagnostics for understanding the three-dimensional distribution of particle fluxes and their relation to the structure of the underlying CME driver. A preliminary comparison with NOAA GOES measurements is shown.

Solar Energetic Particle and the Heliospheric Current Sheet

Kan **Liou**1 and Chin-Chun Wu2
2024 ApJ 966 16
https://iopscience.iop.org/article/10.3847/1538-4357/ad33c2/pdf
The effect of the heliospheric current sheet (HCS) on the propagation of solar energetic particles (SEPs) remains poorly known. In this study we address this question by surveying energetic (∼2.0–9.6 MeV nucleon–1) helium data acquired by the energetic particle acceleration, composition, and transport (EPACT) sensor on board the Wind spacecraft. A superposed epoch analysis of 319 HCS crossings made by Wind reveals a sharp drop in the SEP fluxes at the HCS for the low-energy channels and little change across the HCS for the high-energy channels. To help understand the statistical result, we studied a total of 15 SEP flux dropout (a decrease of ∼50% or more) events that coincided with the crossing of the HCS. One of the common features of these SEP events is that they were initiated in the western hemisphere but far away from the longitude of HCS crossings, suggesting that the source of SEPs was well connected initially but was cut off later after Wind moved to the opposite hemisphere (e.g., HCS crossing). Further analysis of the events suggests that the percentage of flux dropouts decreases with increasing energy. It is suggested that a strong scattering of MeV helium may have occurred as the particle gyroradius is comparable to the thickness of the current sheet. This study clearly provides solid evidence for the HCS as a barrier to suppressing SEP flux of MeV energies from the onset hemisphere to the other. **2000 July 25 to August 2, 2000 September 12–19, 2000 October 22**

A Maximum Entropy Argument for the Slopes of Power-law Particle Spectra in Solar Flares

Yuri E. **Litvinenko**
2019 ApJ 880 20
sci-hub.se/10.3847/1538-4357/ab2760
The maximum entropy formalism is used to infer the spectral index of power-law particle spectra in the heliosphere. The entropy-maximization argument by Brown et al. is revisited and generalized by relaxing the assumption of a particle spectrum extending to an infinite energy. The results for particle spectra with a finite upper cutoff energy are shown to be qualitatively different from those for spectra extending to infinity. The dependence of the predicted spectral index on the upper cutoff energy is determined. The relevance of the predicted values of the spectral index to the observed spectra of accelerated electrons in solar flares and ion tails in the solar wind is discussed.

Analytical solutions of a fractional diffusion-advection equation for solar cosmic-ray transport

Yuri E. **Litvinenko**, Frederic Effenberger
ApJ, 796, 125 **2014**
http://arxiv.org/pdf/1410.1223v1.pdf
Motivated by recent applications of superdiffusive transport models to shock-accelerated particle distributions in the heliosphere, we solve analytically a one-dimensional fractional diffusion-advection equation for the particle density. We derive an exact Fourier transform solution, simplify it in a weak diffusion approximation, and compare the new solution with previously available analytical results and with a semi-numerical solution based on a Fourier series expansion. We apply the results to the problem of describing the transport of energetic particles, accelerated at a traveling heliospheric shock. Our analysis shows that significant errors may result from assuming an infinite initial distance between the shock and the observer. We argue that the shock travel time should be a parameter of a realistic superdiffusive transport model.

EFFECTS OF NON-ISOTROPIC SCATTERING, MAGNETIC HELICITY, AND ADIABATIC FOCUSING ON DIFFUSIVE TRANSPORT OF SOLAR ENERGETIC PARTICLES

Yuri E. **Litvinenko**
2012 ApJ 752 16
Transport of solar energetic particles in interplanetary space is analyzed. A new systematic derivation of the diffusion approximation is given, which incorporates the effects of non-isotropic scattering, magnetic helicity, and adiabatic focusing in a non-uniform large-scale magnetic field. The derivation is based on a system of stochastic differential equations, equivalent to the Fokker-Planck equation, and the new method is a generalization of the Smoluchowski approximation in the theory of the Brownian motion. Simple, physically transparent expressions for the transport coefficients are derived. Different results of earlier treatments of the problem are related to the assumptions regarding the evolving particle distribution.

Physics-Based Simulation of the 2013 April 11 SEP Event

Weihao **Liu**, Igor V. Sokolov, Lulu Zhao, Tamas I. Gombosi, Xiaohang Chen, Nishtha Sachdeva, Gábor Tóth, Ward B. Manchester IV, David Lario, Kathryn Whitman, Alessandro Bruno, Christina M. S. Cohen, M. Leila Mays, Hazel M. Bain
ApJ **2024**
https://arxiv.org/pdf/2412.07581 **File**
Solar energetic particles (SEPs) can pose hazardous radiation risks to both humans in space and spacecraft electronics. Numerical modeling based on first principles offers valuable insights into SEPs, providing synthetic observables for SEPs at any time and location in space. In this work, we present a high-resolution scheme based on integral relations for Poisson brackets to solve the kinetic equation for particle acceleration and transport processes. We implement this scheme within the Space Weather Modeling Framework (SWMF), developed at the University of Michigan, to conduct a comprehensive study of solar energetic protons during the 2013 April 11 SEP event. In addition, a shock capturing tool is developed to study the coronal-mass-ejection-driven shock starting from the low solar corona. Multi-point spacecraft observations, including SOHO/ERNE, SDO/AIA, GOES and ACE at Earth, and STEREO-A/B, are used for model-data comparison and validation. New synthetic observables such as white-light images, shock geometry and properties, as well as SEP intensity-time profiles and spectra provide insights for SEP studies. The influences of the mean free path on SEP intensity-time profiles and spectra are also discussed. The results demonstrate: (1) the successful implementation of the Poisson bracket scheme with a self-consistent particle tracker within the SWMF, (2) the capability of capturing the time-evolving shock surface in the SWMF, and (3) the complexity of the mean free path impacts on SEPs. Overall, this study contributes to both scientific research and operational objectives by advancing our understanding of particle behaviors and showing the readiness for more accurate SEP predictions.
Introduction

Predicting the Energy Spectra of Solar Energetic Particles with a Machine Learning Regression Algorithm

Jiajun **Liu**1, Zhendi Huang1, Jingnan Guo1,2, Yubao Wang1, and Jiajia Liu1,2
2024 ApJL 975 L43
https://iopscience.iop.org/article/10.3847/2041-8213/ad8bbc/pdf
Solar energetic particles (SEPs) are a major source of space radiation, especially within the inner heliosphere. These particles, originating from solar flares and coronal mass ejections (CMEs), propagate primarily along interplanetary magnetic fields. The energy spectra of SEP events are crucial for assessing radiation effects and understanding the acceleration and propagation mechanisms in their source regions. In this study, we employed a decision tree regression algorithm with cost complexity pruning to predict SEP energy spectra, including peak flux and integral fluence spectra. This approach uses only solar flares, CMEs, and solar wind data as input parameters and demonstrates strong performance to accurately predict SEP spectra. This method holds significant real-time application value for monitoring and forecasting radiation risks in both deep space and near-Earth environments.

Effects of Coronal Magnetic Field Configuration on Particle Acceleration and Release during the Ground Level Enhancement Events in Solar Cycle 24

Wenlong **Liu**, Xiangliang Kong, Fan Guo, Lulu Zhao, Shiwei Feng, Feiyu Yu, Zelong Jiang, Yao Chen, Joe Giacalone
ApJ **954** 203 **2023**
https://arxiv.org/pdf/2307.12191.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ace9d2/pdf
Ground level enhancements (GLEs) are extreme solar energetic particle (SEP) events that are of particular importance in space weather. In solar cycle 24, two GLEs were recorded on 2012 May 17 (GLE 71) and 2017 September 10 (GLE 72), respectively, by a range of advanced modern instruments. Here we conduct a comparative analysis of the two events by focusing on the effects of large-scale magnetic field configuration near active regions on particle acceleration and release. Although the active regions both located near the western limb, temporal variations of SEP intensities and energy spectra measured in-situ display different behaviors at early stages. By combining a potential field model, we find the CME in GLE 71 originated below the streamer belt, while in GLE 72 near the edge of the streamer belt. We reconstruct the CME shock fronts with an ellipsoid model based on nearly simultaneous coronagraph images from multi-viewpoints, and further derive the 3D shock geometry at the GLE onset. The highest-energy particles are primarily accelerated in the shock-streamer interaction regions, i.e., likely at the nose of the shock in GLE 71 and the eastern flank in GLE 72, due to quasi-perpendicular shock geometry and confinement of closed fields. Subsequently, they are released to the field lines connecting to near-Earth spacecraft when the shocks move through the streamer cusp region. This suggests that magnetic structures in the corona, especially shock-streamer interactions, may have played an important role in the acceleration and release of the highest-energy particles in the two events. **2012 May 17, 2017 September 10**

General Spectrum Fitting for Energetic Particles

Zixuan **Liu**, Linghua Wang, Haobo Fu, Krucker Sam, and Wimmer-Schweingruber Robert
EGU2020-8189 May **2020**
https://meetingorganizer.copernicus.org/EGU2020/displays/36057
We propose a general fitting formula of energy spectrum of suprathermal particles, J=AE-β1[1+(E/E0)α](β1-β2)/α, where J is the particle flux (or intensity), E is the particle energy, A is the amplitude coefficient, E0 represents the spectral break energy, α (>0) describes the sharpness of energy spectral break around E0, and the power-law index β1 (β2) gives the spectral shape before (after) the break. When α tends to infinity (zero), this spectral formula becomes a classical double-power-law (logarithmic-parabola) spectrum. When both β2 and E0 tend to infinity, this formula can be simplified to an Ellison-Ramaty-like equation. Under some other specific parameter conditions, this formula can be transformed to a Kappa or Maxwellian function. Considering the uncertainties both in particle intensity and energy, we fit this general formula well to the representative energy spectra of various suprathermal particle phenomena including solar energetic particles (electrons, protons, 3He and heavier ions), shocked particles, anomalous cosmic rays, hard X-rays, solar wind suprathermal particles, etc. Therefore, this general spectrum fitting formula would help us to comparatively examine the energy spectrum of different suprathermal particle phenomena and understand their origin, acceleration and transportation.
Presentation #8189 https://presentations.copernicus.org/EGU2020/presentations-ST1.7.zip

Kappa-tail technique: Modeling and application to Solar Energetic Particles observed by Parker Solar Probe

G. **Livadiotis**, A.T. Cummings, M.E. Cuesta, R. Bandyopadhyay, H.A. Farooki, L.Y. Khoo, D.J. McComas, J.S. Rankin, T. Sharma, M.M. Shen, C.M.S. Cohen, G.D. Muro, Z. Xu

2024
https://arxiv.org/pdf/2407.04188
We develop the kappa-tail fitting technique, which analyzes observations of power-law tails of distributions and energy-flux spectra and connects them to theoretical modeling of kappa distributions, to determine the thermodynamics of the examined space plasma. In particular, we (i) construct the associated mathematical formulation, (ii) prove its decisive lead for determining whether the observed power-law is associated with kappa distributions; and (iii) provide a validation of the technique using pseudo-observations of typical input plasma parameters. Then, we apply this technique to a case-study by determining the thermodynamics of solar energetic particle (SEP) protons, for a SEP event observed on **April 17, 2021**, by the PSP/ISOIS instrument suite onboard PSP. The results show SEP temperatures and densities of the order of ∼1 MeV and $\sim 5 \cdot 10^{-7}$ cm^{-3}, respectively.

List of Solar Proton Events in the 24 Cycle of Solar Activity (2009 – 2019)
Logachev Yu.I.1 , Bazilevskaya G.A.2 , Daibog E.I.1 , Ginzburg E.A.3, Ishkov V.N.4,5, Lazutin L.L.1 , Nguyen M.D.1 , Surova G.M.1 , Vlasova N.A.1 , Yakovchuk O.S.1
2020
http://www.wdcb.ru/stp/data/SPE/List_SPE_24_Cycle_SA.pdf
http://www.wdcb.ru/stp/data/SPE/List_SPE_24_Cycle_SA.ru.pdf

CATALOG of Solar Proton Events in the 23rd Cycle of Solar Activity (1996 – 2008)
Yu. I. **Logachev**, G. A. Bazilevskaya, E. V. Vashenyuk, E. I. Daibog, V. N. Ishkov, L. L. Lazutin, L. I. Miroshnichenko, M. N. Nazarova, I. E. Petrenko, A. G. Stupishin, G. M. Surova, O. S. Yakovchuk
2016
http://www.wdcb.ru/stp/data/SPE/Catalog_SPE_23_cycle_SA.pdf
http://www.wdcb.ru/stp/data/SPE/katalog_SPS_23_cikla_SA.pdf

New Parameter in the Description of Solar Cosmic Ray Events—Energy of Balance between Solar and Galactic Protons
Yu. I. **Logachev**, G. A. Bazilevskaya, E. I. Daibog, V. N. Ishkov, L. L. Lazutin, G. M. Surova
Physics of Atomic Nuclei May **2018**, Volume 81, Issue 3, pp 384–389
https://link.springer.com/content/pdf/10.1134%2FS106377881803016X.pdf
Solar proton events possess a wide variety of features that reflect the conditions of solar proton acceleration and propagation. Relevant investigations rely on statistical methods that make it possible to classify events with the aim of obtaining deeper insight into physical processes leading to the generation of solar cosmic rays. In classifying events in power, the intensity of particles with energy above 10MeV at the maximum of the event time profile or the fluence of particles throughout the event time is usually used. A new parameter, Eqm, that characterizes the proton event power and which is some kind of approximation of the maximum energy of accelerated particles is analyzed in the present study. Correlations of Eqm with properties of x-ray flares on the Sun and with the velocity of coronal mass ejections are examined. **April 18, 2001, September 15, 2001**

A Statistical Analysis of the Solar Phenomena Associated with Global EUV Waves (Review)
David M. **Long**, Pearse Murphy, Georgina Graham, Eoin P. Carley, David Pérez-Suárez
Solar Phys. **2017**
https://arxiv.org/pdf/1711.02530.pdf
Solar eruptions are the most spectacular events in our solar system and are associated with many different signatures of energy release including solar flares, coronal mass ejections, global waves, radio emission and accelerated particles. Here, we apply the Coronal Pulse Identification and Tracking Algorithm (CorPITA) to the high cadence synoptic data provided by the Solar Dynamic Observatory (SDO) to identify and track global waves observed by SDO. 164 of the 362 solar flare events studied (45%) are found to have associated global waves with no waves found for the remaining 198 (55%). A clear linear relationship was found between the median initial velocity and the acceleration of the waves, with faster waves exhibiting a stronger deceleration (consistent with previous results). No clear relationship was found between global waves and type II radio bursts, electrons or protons detected in-situ near Earth. While no relationship was found between the wave properties and the associated flare size (with waves produced by flares from B to X-class), more than a quarter of the active regions studied were found to produce more than one wave event. These results suggest that the presence of a global wave in a solar eruption is most likely determined by the structure and connectivity of the erupting active region and the surrounding quiet solar corona rather than by the amount of free energy available within the active region. **2010 August 14, 2011 January 27, 2011 June 7**

Table CorPITA analysis. 2010-2016

Fifty Years of Ground Level Solar Particle Event Observations

Lopate, C. **Review** **A comprehensive summary of GLE observations**
2006, in AGU Monograph, Vol. 165, Solar Eruptions and Energetic Particles, ed. N. Gopalswamy, R. Mewaldt, & Torsti, J. (Washington DC:
American Geophysical Union), 283–296

Solar Electron Beam -- Langmuir Wave Interactions and How They Modify Solar Electron Beam Spectra: Solar Orbiter Observations of a Match Made in the Heliosphere

Camille Y. **Lorfing**, Hamish A. S. Reid, Raul Gomez-Herrero, Milan Maksimovic, Georgios Nicolaou, Christopher J. Owen, Javier Rodriguez-Pacheco, Daniel F. Ryan, Domenico Trotta, Daniel Verscharen

2023 ApJ 959 128

https://iopscience.iop.org/article/10.3847/1538-4357/ad0be3/pdf

https://arxiv.org/pdf/2311.14444.pdf

Solar Orbiter's four in-situ instruments have recorded numerous energetic electron events at heliocentric distances between 0.5 and 1au. We analyse energetic electron fluxes, spectra, pitch angle distributions, associated Langmuir waves, and type III solar radio bursts for 3 events to understand what causes modifications in the electron flux and identify the origin and characteristics of features observed in the electron spectrum. We investigate what electron beam properties and solar wind conditions are associated with Langmuir wave growth and spectral breaks in the electron peak flux as a function of energy. We observe velocity dispersion and quasilinear relaxation in the electron flux caused by the resonant wave-particle interactions in the deca-keV range, at the energies at which we observe breaks in the electron spectrum, co-temporal with the local generation of Langmuir waves. We show, via the evolution of the electron flux at the time of the event, that these interactions are responsible for the spectral signatures observed around 10 and 50keV, confirming the results of simulations by Kontar & Reid (2009). These signatures are independent of pitch angle scattering. Our findings highlight the importance of using overlapping FOVs when working with data from different sensors. In this work, we exploit observations from all in-situ instruments to address, for the first time, how the energetic electron flux is modified by the beam-plasma interactions, and results into specific features to appear in the local spectrum. Our results, corroborated with numerical simulations, can be extended to a wider range of heliocentric distances. **2020 November 24, 2021 October 9, 2022 April 15**

The Interaction of Successive Coronal Mass Ejections: A Review

Noé **Lugaz** Manuela Temmer Yuming Wang Charles J. Farrugia

Sol Phys (**2017**) 292: 64. **File**

http://sci-hub.cc/10.1007/s11207-017-1091-6

We present a review of the different aspects associated with the interaction of successive coronal mass ejections (CMEs) in the corona and inner heliosphere, focusing on the initiation of series of CMEs, their interaction in the heliosphere, the particle acceleration associated with successive CMEs, and the effect of compound events on Earth's magnetosphere. The two main mechanisms resulting in the eruption of series of CMEs are sympathetic eruptions, when one eruption triggers another, and homologous eruptions, when a series of similar eruptions originates from one active region. CME – CME interaction may also be associated with two unrelated eruptions. The interaction of successive CMEs has been observed remotely in coronagraphs (with the Large Angle and Spectrometric Coronagraph Experiment – LASCO – since the early 2000s) and heliospheric imagers (since the late 2000s), and inferred from in situ measurements, starting with early measurements in the 1970s. The interaction of two or more CMEs is associated with complex phenomena, including magnetic reconnection, momentum exchange, the propagation of a fast magnetosonic shock through a magnetic ejecta, and changes in the CME expansion. The presence of a preceding CME a few hours before a fast eruption has been found to be connected with higher fluxes of solar energetic particles (SEPs), while CME – CME interaction occurring in the corona is often associated with unusual radio bursts, indicating electron acceleration. Higher suprathermal population, enhanced turbulence and wave activity, stronger shocks, and shock – shock or shock – CME interaction have been proposed as potential physical mechanisms to explain the observed associated SEP events. When measured in situ, CME – CME interaction may be associated with relatively well organized multiple-magnetic cloud events, instances of shocks propagating through a previous magnetic ejecta or more complex ejecta, when the characteristics of the individual eruptions cannot be easily distinguished. CME – CME interaction is associated with some of the most intense recorded geomagnetic storms. The compression of a CME by another and the propagation of a shock inside a magnetic ejecta can lead to extreme values of the southward magnetic field component, sometimes associated with high values of the dynamic pressure. This can result in intense geomagnetic storms, but can also trigger substorms and large earthward motions of the magnetopause, potentially associated with changes in the outer radiation belts. Future in situ measurements in the inner heliosphere by Solar Probe+ and Solar Orbiter may shed light on the evolution of CMEs as they interact, by providing opportunities for conjunction and evolutionary studies. **2000-06-10, 25-26 Nov 2000, 19-20 March 2001, 26 Mar-26 Apr 2001, 1 Apr 2001, 31March – 1 April 2001, 1 August 2010, 25 May 2010, e August 2010 events f, 2011-08-01, 10 November 2012, 2013-05-22, 2011-02-15, 19 Feb2014**

3. Effects of Successive CMEs on Particle Acceleration

3.2. Radio Signatures of CME – CME Interaction

Shock Connectivity and the Late Cycle 24 Solar Energetic Particle Events in July and September 2017

J. G. **Luhmann**, M. L. Mays, Yan Li , C. O. Lee, H. Bain, D. Odstrcil, R. A. Mewaldt, C. M. S. Cohen, D. Larson, Gordon Petrie

Space Weather **Volume16, Issue5** May 2018 pages 557-568

http://sci-hub.tw/10.1029/2018SW001860

As solar activity steadily declined toward the cycle 24 minimum in the early months of 2017, the expectation for major solar energetic particle (SEP) events diminished with the sunspot number. It was thus surprising (though not unprecedented) when a new, potentially significant active region rotated around the East limb in early July that by midmonth was producing a series of coronal eruptions, reaching a crescendo around 23 July. This series, apparently associated with the birth of a growing pseudostreamer, produced the largest SEP event(s) seen since the solar maximum years. Activity abated with the decay of the active region, but a second episode of magnetic flux emergence in the same area in early September initiated a new round of eruptions. The western longitude of the erupting region, together with its similar coronal setting in both cases, resulted in a set of nearly homologous multipoint SEP event periods at Earth, Solar TErrestrial RElations Observatory-A and Mars (Mars Atmosphere and Volatile EvolutioN) for July and September 2017. We use a combination of WSA-ENLIL-cone heliospheric simulation results, together with SEPMOD SEP event modeling, to illustrate how the event similarities at the three observer sites can be understood from their relative positions and their connectivities to the generated interplanetary shocks. **2017-07-12, 2017-07-14, 2017-07-23, 2017-07-28, 2017-09-04, 2017-09-06, 2017-09-09, 2017-09-10, 2017-09-17**

Modeling solar energetic particle events using ENLIL heliosphere simulations

J. G. **Luhmann,** M. L. Mays, D. Odstrcil, Yan Li, H. Bain, C. O. Lee, A. B. Galvin, R. A. Mewaldt, C. M. S. Cohen, R. A. Leske, et al

Space Weather Volume 15, Issue 7 July **2017** Pages 934–954

http://sci-hub.se/10.1002/2017SW001617

Solar energetic particle (SEP) event modeling has gained renewed attention in part because of the availability of a decade of multipoint measurements from STEREO and L1 spacecraft at 1 AU. These observations are coupled with improving simulations of the geometry and strength of heliospheric shocks obtained by using coronagraph images to send erupted material into realistic solar wind backgrounds. The STEREO and ACE measurements in particular have highlighted the sometimes surprisingly widespread nature of SEP events. It is thus an opportune time for testing SEP models, which typically focus on protons ~1–100 MeV, toward both physical insight to these observations and potentially useful space radiation environment forecasting tools. Some approaches emphasize the concept of particle acceleration and propagation from close to the Sun, while others emphasize the local field line connection to a traveling, evolving shock source. Among the latter is the previously introduced SEPMOD treatment, based on the widely accessible and well-exercised WSA-ENLIL-cone model. SEPMOD produces SEP proton time profiles at any location within the ENLIL domain. Here we demonstrate a SEPMOD version that accommodates multiple, concurrent shock sources occurring over periods of several weeks. The results illustrate the importance of considering longer-duration time periods and multiple CME contributions in analyzing, modeling, and forecasting SEP events. **2010.07.30-08.23, 2012.07.12-08.26, 2013.03.05-18, 2013.04.07-18, 2014.01.07-15, 2015.02.02-12**

Cone model-based SEP event calculations for applications to multipoint observations

J.G. **Luhmanna**, , , S.A. Ledvinaa, D. Odstrcilb, M.J. Owensc, X.-P. Zhaod, Yang Liud and Pete Rileye

Advances in Space Research

Volume 46, Issue 1, 1 July **2010**, Pages 1-21

sci-hub.se/10.1016/j.asr.2010.03.011

The problem of modeling solar energetic particle (SEP) events is important to both space weather research and forecasting, and yet it has seen relatively little progress. Most important SEP events are associated with coronal mass ejections (CMEs) that drive coronal and interplanetary shocks. These shocks can continuously produce accelerated particles from the ambient medium to well beyond 1 AU. This paper describes an effort to model real SEP events using a Center for Integrated Space weather Modeling (CISM) MHD solar wind simulation including a cone model of CMEs to initiate the related shocks. In addition to providing observation-inspired shock geometry and characteristics, this MHD simulation describes the time-dependent observer field line connections to the shock source. As a first approximation, we assume a shock jump-parameterized source strength and spectrum, and that scatter-free transport occurs outside of the shock source, thus emphasizing the role the shock evolution plays in determining the modeled SEP event profile. Three halo CME events on May 12, 1997, November 4, 1997 and December 13, 2006 are used to test the modeling approach. While challenges arise in the identification and characterization of the shocks in the MHD model results, this approach illustrates the importance to SEP event modeling of globally simulating the underlying heliospheric event. The results also suggest the potential utility of such a model for forcasting and for interpretation of separated multipoint measurements such as those expected from the STEREO mission.

A Numerical Study of the Effects of Corotating Interaction Regions on Cosmic-Ray Transport

Xi **Luo**1,2, Ming Zhang3, Xueshang Feng1, Marius S Potgieter4,6, Fang Shen1, and Galina Bazilevskaya5

2020 ApJ 899 90
https://doi.org/10.3847/1538-4357/aba7b5

The intensity of galactic cosmic rays (GCRs) is modulated by solar activity on various timescales. In this study, we performed comprehensive numerical modeling of the solar rotational recurrent variation in GCRs caused by a corotation interaction region (CIR). A recently developed magnetohydrodynamic numerical model is adapted to simulate the background solar wind plasma with a CIR structure present in the inner heliosphere. As for the outer heliospheric plasma background, from 27 to 80 au, the Parker interplanetary magnetic field model is utilized. The output of these plasma and magnetic field models is incorporated into a comprehensive Parker-type transport model for GCRs. The local interstellar spectrum for galactic protons is transported to 80 au, specifying the outer boundary condition. The obtained solutions of this hybrid model, for studying the CIR effect, are as follows: (1) the onset of the decrease in the GCR intensity inside the CIR coincides with the increase of the solar wind speed with the intensity depression accompanied by a magnetic field and plasma density enhancement. Additionally, the CIR effect weakens with increasing heliocentric radial distance. (2) This decrease in GCR intensity also appears at different heliolatitudes and varies with changing latitude; the amplitude of the GCR depression exhibits a maximum in the low-latitude region. (3) The CIR affects GCR transport at different energy levels as well. Careful analysis has revealed a specific energy dependence of the amplitude of the recurrent GCR variation in the range of 30–2000 MeV.

Gamma-ray lines in solar flares with proton spectra measured by PAMELA experiment

A L **Lysenko**1, E A Bogomolov1, G I Vasiliev1 and E P Ovchinnikova1

Journal of Physics: Conference Series, Volume 1400, Issue 2 (**2019**) 022042
https://iopscience.iop.org/article/10.1088/1742-6596/1400/2/022042/pdf

During the solar flares protons and heavier ions are accelerated up to GeV energies. Accelerated ions can escape the Sun and be registered directly on spacecraft or penetrate into the solar atmosphere and then produce gamma-ray lines as the result of nuclear reactions. Previous studies revealed very poor correlation between fluxes of interplanetary ions and gamma-ray line emission. In this work we focus on joint observations of interplanetary solar energetic particles registered by PAMELA experiment and gamma-ray emission registered by Konus-Wind instrument in hard X-ray and soft gamma-ray ranges. This study confirmed the previous results: during the period from 2006 to 2014 there were only two solar flares registered both by PAMELA and Konus-Wind at energies above 1 MeV. We analyze gamma-ray spectrum for one of these flares and make suggestions about the reasons for the low correlation between interplanetary solar accelerated ions and accelerated ions interacted in the solar atmosphere. **2012 Jul 06, 2014 Feb 25**

Specific features of solar cosmic ray fluxes and geomagnetic conditions on December 5–18, 2006

G. P. **Lyubimov**, N. A. Vlasova, V. I. Tulupov, E. A. Chuchkov, B. Ya. Shcherbovsky and S. I. Ermakov

Cosmic Research, Volume 49, Number 6, 477-484, **2011**

Results of the analysis of specific features of solar activity, dynamics of solar cosmic ray fluxes, and state of the interplanetary medium are presented for the period **December 5–18, 2006**. The data analysis is based on new model concepts on coronal and interplanetary propagation of solar cosmic rays: partial capture into the magnetic field traps and oscillations at reflections from magnetic mirrors. Some new hypotheses about possible relations of the features of the interplanetary medium with processes in the Earth’s magnetosphere are put forward: the influence of the discrete interplanetary medium on processes in the Earth’s magnetosphere does exist always and, in this sense, it is a

fundamental phenomenon; the discreteness of the inter-planetary medium can be one of the causes of geomagnetic substorms.

Re-examining the correlation of complex solar type III radio bursts and solar energetic particles,

MacDowall, R. J., Richardson, I. G., Hess, R. A., and Thejappa, G.,
in Proceedings of IAU Symposium No. 257, *Universal Heliophysical Processes*, eds. N. Gopalswamy and D. F. Webb , 4, p. 335, **2009, File**

Interplanetary radio observations provide important information on particle acceleration processes at the Sun and propagation of the accelerated particles in the solar wind. Cane et al. (2002) have drawn attention to a class of prominent radio bursts that accompany >20 MeV solar proton events. They call these bursts 'type III-L' because: they are fast drifting (like normal type III bursts associated with electrons accelerated at impulsive solar flares); they are Long-lasting compared to normal type III bursts; they occur Late compared to the onset of the related solar event; and, they commence at Lower frequencies (~100 MHz) than normal type III bursts, suggesting that they originate higher in the corona at ~0.5 Rs above the Sun. We report on an analysis of the correlated radio and SEP events during 1996-2006 using the Wind Waves and near-Earth SEP data sets, and discuss whether the characteristics of the complex type III bursts (at less than 14 MHz) will permit them to serve as proxies for SEP event occurrence and intensity.

Longduration hectometric type III radio bursts and their association with solar energetic particle (SEP) events.

MacDowall, R. J., A. Lara, P. K. Manoharan, N. V. Nitta, A. M. Rosas, and J. L. Bougeret.
Geophys. Res. Lett., 30, 8018, **2003**. 10.1029/2002GL016624.

Validation of community models: 3. Tracing field lines in heliospheric models

MacNeice, Peter; Elliott, Brian; Acebal, Ariel
Space Weather, Vol. 9, No. 10, S10003, **2011**

Forecasting hazardous gradual solar energetic particle (SEP) bursts at Earth requires accurately modeling field line connections between Earth and the locations of coronal or interplanetary shocks that accelerate the particles. We test the accuracy of field lines reconstructed using four different models of the ambient coronal and inner heliospheric magnetic field, through which these shocks must propagate, including the coupled Wang-Sheeley-Arge (WSA)/ENLIL model. Evaluating the WSA/ENLIL model performance is important since it is the most sophisticated model currently available to space weather forecasters which can model interplanetary coronal mass ejections and, when coupled with particle acceleration and transport models, will provide a complete model for gradual SEP bursts. Previous studies using a simpler Archimedean spiral approach above 2.5 solar radii have reported poor performance. We test the accuracy of the model field lines connecting Earth to the Sun at the onset times of 15 impulsive SEP bursts, comparing the foot points of these field lines with the locations of surface events believed to be responsible for the SEP bursts. We find the WSA/ENLIL model performance is no better than the simplest spiral model, and the principal source of error is the model's inability to reproduce sufficient low-latitude open flux. This may be due to the model's use of static synoptic magnetograms, which fail to account for transient activity in the low corona, during which reconnection events believed to initiate the SEP acceleration may contribute short-lived open flux at low latitudes. Time-dependent coronal models incorporating these transient events may be needed to significantly improve Earth/Sun field line forecasting.

Direct Evidence for Magnetic Reflection of Heavy Ions from High Mach Number Collisionless Shocks

Hadi **Madanian**1, Steven J. Schwartz2, Stephen A. Fuselier1,3, David Burgess4, Drew L. Turner5, Li-Jen Chen6, Mihir I. Desai1,3, and Michael J. Starkey1
2021 ApJL 915 L19
https://iopscience.iop.org/article/10.3847/2041-8213/ac0aee/pdf
https://doi.org/10.3847/2041-8213/ac0aee

Strong shocks in collisionless plasmas, such as supernovae shocks and shocks driven by coronal mass ejections, are known to be a primary source of energetic particles. Due to their different mass per charge ratio, the interaction of heavy ions with the shock layer differs from that of protons, and injection of these ions into acceleration processes is a challenge. Here we show the first direct observational evidence of magnetic reflection of alpha particles from a high Mach number quasi-perpendicular shock using in situ spacecraft measurements. The intense magnetic amplification at the shock front associated with nonstationarity modulates the trajectory of alpha particles, some of which travel back upstream as they gyrate in the enhanced magnetic field and experience further acceleration in the upstream region. Our results in particular highlight the important role of high magnetic amplification in seeding heavy ions into the energization processes at nonstationary reforming shocks. **2015 December 28**

Atmospheric effects on secondary cosmic ray muons observed by multi-wire muon detector at a high cutoff rigidity station

A.H. **Maghrabi,** A.F. Aldosari, M.M. Almutairi, M.I. Altilasi
Advances in Space Research Volume 64, Issue 8, 15 October **2019**, Pages 1629-1637
sci-hub.se/10.1016/j.asr.2019.07.027

In October 2017, a multi-layer small multi-wire (MW) detector for cosmic ray (CR) muon measurements was installed at King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia (Rc = 14.4 GV). This detector is considered to be the first of its kind used for long term CR measurements. In this study, CR data collected from KACST-MW detection system and radiosonde measurements were used to investigate the effect of atmospheric pressure, ground temperature, height of the muon production layer, temperature at that layer, and temperature weighted by atmospheric mass, on CR muons. Regression analyses between the observed muon count rate and these variables were carried out and the corresponding coefficients were obtained and used to correct the observed muon count rate for the temporal variation of these variables. The effect of the atmospheric pressure was conducted first and used to correct the data for this effect. The pressure corrected count rate is anti-correlated with the height of muon production, ground temperature, and atmospheric mass-weighted temperature. On the other hand, the temperature at the muon production layer is positively correlated with the muon count rate. The obtained results from this study are in good agreement with those reported by several researchers. Taking advantages of the relationship between the detected CR muons and the temperature at the muon production layer (stratospheric temperature), this relationship is inverted to calculate this temperature from muon observations. The proposed technique provides excellent predictability of the stratospheric temperatures.

On the properties of solar energetic particle events associated with metric type II radio bursts

Pertti **Mäkelä**, Nat Gopalswamy, Hong Xie, Sachiko Akiyama, Seiji Yashiro, Neeharika Thakur
Sun and Geosphere, **Vol.14, No. 2, p. 123-130   2019**
https://arxiv.org/ftp/arxiv/papers/2001/2001.10506.pdf
http://newserver.stil.bas.bg/SUNGEO//00SGArhiv/SG_v14_No2_2019-pp123-129.pdf   **File**

Metric type II solar radio bursts and solar energetic particles (SEPs) are both associated with shock fronts driven by coronal mass ejections (CMEs) in the solar corona. Recent studies of ground level enhancements (GLEs), regular large solar energetic particle (SEP) events and filament eruption (FE) associated large SEP events have shown that SEP events are organized by spectral index of proton fluence spectra and by the average starting frequencies of the associated type II radio bursts. Both these results indicate a hierarchical relationship between CME kinematics and SEP event properties. In this study, we expand the investigations to fluence spectra and the longitudinal extent of metric type II associated SEP events including low-intensity SEP events. We utilize SEP measurements of particle instruments on the Solar and Heliospheric Observatory (SOHO) and Solar Terrestrial Relations Observatory (STEREO) spacecraft together with radio bursts observations by ground-based radio observatories during solar cycle 24. Our results show that low-intensity SEP events follow the hierarchy of spectral index or the hierarchy of the starting frequency of type II radio bursts. We also find indications of a trend between the onset frequency of metric type II bursts and the estimated longitudinal extent of the SEP events although the scatter of data points is quite large. These two results strongly support the idea of SEP acceleration by shocks. Stronger shocks develop closer to the Sun.
Table 1 Parameters of radio bursts, small SEP events, flares and CMEs. (2009-2017)

FLUENCE SPECTRA OF SMALL SEP EVENTS WITH METRIC TYPE II RADIO BURSTS

Pertti **Makela**1 , Nat Gopalswamy2 , Sachiko Akiyama1 , Seiji Yashiro
Second VarSITI General Symposium (VarSITI-**2017**), Irkutsk
http://varsiti2017.iszf.irk.ru/presentations/VarSITI%20Abstracts.pdf

Gopalswamy et al. (2016, Astrophysical Journal, 833, 216) showed that the spectral index of the 10–100 MeV proton fluence spectra organizes the major solar energetic particle (SEP) events. Ground level enhancement (GLE) events and SEP events associated with filament eruptions outside active regions (FE SEP events) have respectively hard (gamma ~2.68) and soft (gamma ~4.89) fluence spectra. Between these two distinct groups fall the regular SEP events (gamma ~3.83). Here we report on a study of proton fluence spectra of small SEP events, i.e. events with the GOES 10 MeV peak flux below 10 pfu, that have an associated metric type II radio burst during solar cycle 24. We utilize the low-background measurements by the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the Solar and Heliospheric Observatory (SOHO). Preliminary results show that the distribution and the average value of spectral index of small SEP events resemble those of the regular SEP events.

Estimating the Height of CMEs Associated with a Major SEP Event at the Onset of the Metric Type II Radio Burst during Solar Cycles 23 and 24
P. **Mäkelä**, N. Gopalswamy, S. Akiyama, H. Xie, and S. Yashiro
ApJ **806** 13 **2015**
http://cdaw.gsfc.nasa.gov/publications/makela/makela2015ApJ.pdf
https://iopscience.iop.org/article/10.1088/0004-637X/806/1/13/pdf
We studied the coronal mass ejection (CME) height at the onset of 59 metric type II radio bursts associated with major solar energetic particle (SEP) events, excluding ground level enhancements (GLEs), during solar cycles 23 and 24. We calculated CME heights using a simple flare-onset method used by Gopalswamy et al. (2012b) to estimate CME heights at the metric type II onset for cycle-23 GLEs. We found the mean CME height for non-GLE events (1.72 R⊙) to be ∼12% greater than that (1.53 R⊙) for cycle-23 GLEs. The difference could be caused by more impulsive acceleration of the GLE-associated CMEs. For cycle-24 non-GLE events, we compared the CME heights obtained using the flare-onset method and the 3-D spherical-shock fitting method and found the correlation to be good (CC=0.68). We found the mean CME height for cycle 23 non-GLE events (1.79 R⊙) to be greater than for cycle 24 non-GLE events (1.58 R⊙), but statistical tests do not definitely reject the possibility of coincidence. We suggest that the lower formation height of the shocks during cycle 24 indicates a change in the Alfvén speed profile because solar magnetic fields are weaker and e plasma density levels are closer to the surface than usual during cycle 24. We also found that complex type III bursts showing diminution of type III emission in the 7-14 MHz frequency range are more likely associated with events with the CME height at the type II onset above 2 R⊙ , supporting suggestions that the CME/shock structure causes the feature. **Table. Event Data (1997-2014)**

Energetic storm particle events in coronal mass ejection-driven shocks
P. **Mäkelä**; Gopalswamy, N.; Akiyama, S.; Xie, H.; Yashiro, S.
J. Geophys. Res., Vol. 116, No. A8, A08101, **2011, File**
http://cdaw.gsfc.nasa.gov/publications/makela/makela2011JGR.pdf
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2011JA016683
We investigate the variability in the occurrence of energetic storm particle (ESP) events associated with shocks driven by coronal mass ejections (CMEs). The interplanetary shocks were detected during the period from 1996 to 2006. First, we analyze the CME properties near the Sun. The CMEs with an ESP-producing shock are faster (VCME = 1088 km/s) than those driving shocks without an ESP event (VCME = 771 km/s) and have a larger fraction of halo CMEs (67% versus 38%). The Alfvénic Mach numbers of shocks with an ESP event are on average 1.6 times higher than those of shocks without. We also contrast the ESP event properties and frequency in shocks with and without a type II radio burst by dividing the shocks into radio-loud (RL) and radio-quiet (RQ) shocks, respectively. The shocks seem to be organized into a decreasing sequence by the energy content of the CMEs: RL shocks with an ESP event are driven by the most energetic CMEs, followed by RL shocks without an ESP event, then RQ shocks with and without an ESP event. The ESP events occur more often in RL shocks than in RQ shocks: 52% of RL shocks and only ∼33% of RQ shocks produced an ESP event at proton energies above 1.8 MeV; in the keV energy range the ESP frequencies are 80% and 65%, respectively. Electron ESP events were detected in 19% of RQ shocks and 39% of RL shocks. In addition, we find that (1) ESP events in RQ shocks are less intense than those in RL shocks; (2) RQ shocks with ESP events are predominately quasi-perpendicular shocks; (3) their solar sources are located slightly to the east of the central meridian; and (4) ESP event sizes show a modest positive correlation with the CME and shock speeds. The observation that RL shocks tend to produce more frequently ESP events with larger particle flux increases than RQ shocks emphasizes the importance of type II bursts in identifying solar events prone to producing high particle fluxes in the near-Earth space. However, the trend is not definitive. If there is no type II emission, an ESP event is less likely but not absent. The variability in the probability and size of ESP events most likely reflects differences in the shock formation in the low corona and changes in the properties of the shocks as they propagate through interplanetary space and the escape efficiency of accelerated particles from the shock front.

SEPs and CMEs during cycle 23
Pertti **Mäkelä**, Nat Gopalswamy, Seiji Yashiro, Sachiko Akiyama, Hong Xie and Eino Valtonen
Proceedings of the International Astronomical Union / Volume 4 / Symposium S257, pp 475 – 477, Published online: 16 Март **2009**
http://journals.cambridge.org/action/displayIssue?iid=4866212
We present a study of solar energetic particles (SEPs) in association with coronal mass ejections (CMEs) and type II radio bursts. The particle and CME observations cover the years 1996–2007. We find that heavy-ion events in association with type II bursts and proton events are produced in more western and most energetic CMEs. In addition, the source distribution of type II associated proton events with heavy ions reminds the source distribution

expected for events with flare particles. Therefore, the estimation of relative contributions by flares and shocks in SEP events and separation of suggested different particle acceleration models is complicated.

The HESPERIA REleASE+ Solar Particle Event forecasting system is now publicly available!!

Olga E. **Malandraki**

Email 16 Jul and 27 Sep **2024**

During the last decade the HESPERIA Relativistic Electron Alert System for Exploration or REleASE has been providing real-time forecasts of hazardous solar proton events for the Earth-Moon system, resulting in approximately one-hour average lead times of 30-50 MeV protons.
Its predictions rely on relativistic and near-relativistic electron measurements by the SOHO/EPHIN and ACE/EPAM experiments, without the necessity of a direct view of the solar eruption and thus issuing forecasts also in the case of backside flares not handled well by most other forecasting methods.
We announce the public availability of a considerable update of the system: HESPERIA REleASE+. The new system attempts to improve forecasting accuracy with independent evidence of particle escape from the Sun with the addition of a novel radio module. This automatic recognition module identifies and qualifies Type III radio bursts in real-time STEREO A/SWAVES beacon data. Type IIIs are associated with electron beams accelerated in solar eruptive events and prove a timely and reliable proxy of particle escape from the Sun onto open field lines. The pairing of HESPERIA REleASE with relevant radio information is expected to eliminate existing sources of false alarms of the original system and thus could significantly improve the reliability of proton events forecasting.
The HESPERIA REleASE+ implementation, real-time forecasts and the option to sign up for real-time alerts are now publicly available via the HESPERIA portal at the National Observatory of Athens, Greece:
https://hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/release-plus
https://hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/release-alert-plus

The HESPERIA HORIZON 2020 Project and Book on Solar Particle Radiation Storms Forecasting and Analysis

Olga E. **Malandraki** , Norma B. Crosby

Space Weather Volume16, Issue6 June **2018** Pages 591-592

http://sci-hub.tw/https://onlinelibrary.wiley.com/doi/abs/10.1029/2018SW001950

This article presents the High Energy Solar Particle Events forecasting and Analysis (HESPERIA) project, supported by the HORIZON 2020 programme of the European Union (Project 637324) as well as the resultant recently published book entitled Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond, edited by Malandraki and Crosby, Springer, Astrophysics and Space Sciences Library, 2018, ISBN 978-3-319-60051-2. The book reviews the results of the HESPERIA project as well as our current understanding of solar energetic particle physics.

See https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/swq.18

Solar Energetic Particles and Space Weather: Science and Applications **Review**

Olga E. **Malandraki** and Norma B. Crosby

In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 1, **2018**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf

File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf

This chapter provides an overview on solar energetic particles (SEPs) and their association to space weather, both from the scientific as well as from the applications perspective. A historical overview is presented on how SEPs were discovered in the 1940s and how our understanding has increased and evolved since then. Current state-of-the-art based on unique measurements obtained in the 3-dimensional heliosphere (e.g. by the Ulysses, ACE, STEREO spacecraft) and their analysis is also presented. Key open questions on SEP research expected to be answered in view of future missions that will explore the solar corona and inner heliosphere are highlighted. This is followed by an introduction to why SEPs are studied, describing the risks that SEP events pose on technology and human health. Mitigation strategies for solar radiation storms as well as examples of current SEP forecasting systems are reviewed, in context of the two novel real-time SEP forecasting tools developed within the EU H2020 HESPERIA project.

Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond – New Book Review

Olga E. **Malandraki** and Norma B. Crosby (Eds.)

Astrophysics and Space Science Library No. 444 **2018 File**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
- Explains why it is important to understand the effects of solar energetic particles (SEPs) and be able to predict them from a modern society perspective
- Presents most recent state-of-the-art scientific results on SEPs
- Provides the reader with basic textbook type chapters on SEP origin, SEP acceleration and propagation, SEP interpretation, and SEP forecasting
- Can be used both as background course material to complement other textbook material, as well as a reference book for more senior scientists

Novel prediction tools for SEP events

Olga E. **Malandraki**

Research*eu MAGAZINE No. 62 May **2017**

https://cordis.europa.eu/result/rcn/198644_en.html

HESPERIA (High Energy Solar Particle Events foRecastIng and Analysis) had three core objectives: building new forecasting tools based on empirical forecasting models UMASEP and REleASE; advancing scientific understanding of the physical mechanisms leading to SEPs; and exploring the possibility of incorporating its results into future space weather services.

Scientific Analysis within SEPServer – New Perspectives in Solar Energetic Particle Research: The Case Study of the 13 July 2005 Event

O. E. **Malandraki**, N. Agueda, A. Papaioannou, K.-L. Klein, E. Valtonen, B. Heber, W. Dröge, H. Aurass, A. Nindos, N. Vilmer, B. Sanahuja, A. Kouloumvakos, S. Braune, P. Preka-Papadema, K. Tziotziou, C. Hamadache, J. Kiener, V. Tatischeff, E. Riihonen, Y. Kartavykh, R. Rodríguez-Gasén, R. Vainio

Solar Physics, November **2012**, Volume 281, Issue 1, pp 333-352

Solar energetic particle (SEP) events are a key ingredient of solar–terrestrial physics both for fundamental research and space weather applications. Multi-satellite observations are an important and incompletely exploited tool for studying the acceleration and the coronal and interplanetary propagation of the particles. While STEREO uses for this diagnostic two identical sets of instrumentation, there are many earlier observations carried out with different spacecraft. It is the aim of the **SEPServer project** to make these data and analysis tools available to a broad user community. The consortium will carry out data-driven analysis and simulation-based data analysis capable of deconvolving the effects of interplanetary transport and solar injection from SEP observations, and will compare the results with the electromagnetic signatures. The tools and results will be provided on the web server of the project in order to facilitate further analysis by the research community. This paper describes the data products and analysis strategies with one specific event, the case study of **13 July 2005**. The release time of protons and electrons are derived using data-driven and simulation-based analyses, and compared with hard X-ray and radio signatures. The interconnection of the experimental and the simulation-based results are discussed in detail.

ENERGETIC PARTICLE OBSERVATIONS AND PROPAGATION IN THE THREE-DIMENSIONAL HELIOSPHERE DURING THE 2006 DECEMBER EVENTS

O. E. **Malandraki**[1,2], R. G. Marsden[2], D. Lario[3], C. Tranquille[2], B. Heber[4], R. A. Mewaldt[5], C. M. S. Cohen[5], L. J. Lanzerotti[6,7], R. J. Forsyth[8], H. A. Elliott[9], I. I. Vogiatzis[10], and A. Geranios[11]

Astrophysical Journal, 704:469–476, **2009** October

We report observations of solar energetic particles obtained by the HI-SCALE and COSPIN/LET instruments onboard *Ulysses* during the period of isolated but intense solar activity in 2006 December, in the declining phase of the solar activity cycle. We present measurements of particle intensities and also discuss observations of particle anisotropies and composition in selected energy ranges. Active Region 10930 produced a series of major solar flares with the strongest one (X9.0) recorded on December 5 after it rotated into view on the solar east limb. Located over the South Pole of the Sun, at >72◦S heliographic latitude and 2.8 AU radial distance, *Ulysses* provided unique measurements for assessing the nature of particle propagation to high latitudes under near-minimum solar activity conditions, in a relatively undisturbed heliosphere. The observations seem to exclude the possibility that magnetic field lines originating at low latitudes reached *Ulysses*, suggesting either that the energetic particles observed as large solar energetic particle (SEP) events over the South Pole of the Sun in 2006 December were released when propagating coronal waves reached high-latitude field lines connected to *Ulysses*, or underwent perpendicular diffusion. We also discuss comparisons with energetic particle data acquired by the *STEREO* and *Advanced Composition Explorer* in the ecliptic plane near 1 AU during this period.

Particle Observations and Propagation in the Three-Dimensional Heliosphere
O.E. **Malandraki**, R.G. Marsden, T.R. Sanderson, C. Tranquille, R.J. Forsyth, H.A. Elliott, L.J. Lanzerotti, A. Geranios, E.T. Sarris, B. Heber and R. Mueller-Mellin
BBSO, #1336, **2007**
Ulysses, Dec 2006

Energetic particle dynamics in a simplified model of a solar wind magnetic switchback
F. **Malara**1,2, S. Perri1,2, J. Giacalone3 and G. Zimbardo1,2
A&A 677, A69 (**2023**)
https://www.aanda.org/articles/aa/pdf/2023/09/aa46990-23.pdf
Context. Recent spacecraft observations in the inner heliosphere have revealed the presence of local Alfvénic reversals of the magnetic field, while the field magnitude remains almost constant. These are called magnetic switchbacks (SBs) and are very common in the plasma environment close to the Sun explored by the Parker Solar Probe satellite.
Aims. A simple numerical model of a magnetic field reversal with constant magnitude is used in order to explore the influence of SBs on the propagation of energetic particles within a range of energy typical of solar energetic particles.
Methods. We model the reversal as a region of space of adjustable size bounded by two rotational discontinuities. By means of test particle simulations, beams of mono-energetic particles can be injected upstream of the SB with various initial pitch- and gyro-phase angles. In each simulation, the particle energy may also be changed.
Results. Particle dynamics is highly affected by the ratio between the particle gyroradius and the size of the SB, with multiple pitch-angle scatterings occurring when the particle gyroradius is of the order of the SB size. Further, particle motion is extremely sensitive to the initial conditions, implying a transition to chaos; for some parameters of the system, a large share of particles is reflected backwards upstream as they interact with the SB. These results could have a profound impact on our understanding of solar energetic particle transport in the inner heliosphere, and therefore possible comparisons with in situ spacecraft data are discussed.

Predicting solar energetic proton events (E > 10 MeV)
Marlon Núñez
SPACE WEATHER, VOL. 9, S07003, 28 PP., **2011**
A high level of proton radiation exposure can be dangerous to astronauts, satellite equipment, and air passengers/crew flying along polar routes. The presented solar energetic proton (SEP) event forecaster is based on a dual-model approach for predicting the time interval within which the integral proton flux is expected to meet or surpass the Space Weather Prediction Center threshold of J (E > 10 MeV) = 10 pr cm^{-2} sr^{-1} s^{-1} and the intensity of the first hours of well- and poorly connected SEP events. This forecaster analyzes flare and near-Earth space environment data (soft X-ray, differential and integral proton fluxes). The purpose of the first model is to identify precursors of well-connected events by empirically estimating the magnetic connectivity from the associated CME/flare process zone to the near-Earth environment and identifying the flare temporally associated with the phenomenon. The goal of the second model is to identify precursors of poorly connected events by using a regression model that checks whether the differential proton flux behavior is similar to that in the beginning phases of previous historically poorly connected SEP events and thus deduce similar consequences. An additional module applies a higher-level analysis for inferring additional information about the situation by filtering out inconsistent preliminary forecasts and estimating the intensity of the first hours of the predicted SEP events. The high-level module periodically retrieves solar data and, in the case of well-connected events, automatically identifies the associated flare and active region. For the events of solar cycles 22 and 23 of the NOAA/SWPC SEP list, the presented dual-model system, called UMASEP, has a probability of detection of all well- and poorly connected events of 80.72% (134/166) and a false alarm rate of 33.99% (69/203), which outperforms current automatic forecasters in predicting >10 MeV SEP events. The presented forecaster has an average warning time of 5 h 10 min for the successfully predicted events, 1 h 5 min for well-connected events and 8 h 28 min for poorly connected events, with a maximum warning time of 24 h for very gradual SEP events.

Galactic cosmic ray hydrogen spectra and radial gradients in the inner heliosphere measured by the HELIOS Experiment 6
J. **Marquardt** and B. Heber
A&A 625, A153 (**2019**)
https://doi.org/10.1051/0004-6361/201935413
Context. The HELIOS solar observation probes provide unique data regarding their orbit and operation time. One of the onboard instruments, the Experiment 6 (E6), is capable of measuring ions from 4 to several hundred MeV $nucleon^{-1}$.

Aims. In this paper we aim to demonstrate the relevance of the E6 data for the calculation of galactic cosmic ray (GCR), anomalous cosmic ray (ACR), and solar energetic particle (SEP) fluxes for different distances from the sun and time periods.
Methods. Several corrections have been applied to the raw data: determination of the Quenching factor of the scintillator, correction of the temperature dependent electronics, degradation of the scintillator as well as the effects on the edge of semi-conductor detectors.
Results. Fluxes measured by the E6 are in accordance with the force field solution for the GCR and match models of the anomalous cosmic ray propagation. GCR radial gradients in the inner heliosphere show a different behaviour than in the outer heliosphere.

SOLAR ENERGETIC PARTICLES AND RADIO-SILENT FAST CORONAL MASS EJECTIONS

C. **Marque**, A. Posner and K.-L. Klein

The Astrophysical Journal, 642:1222–1235, **2006, File**

https://iopscience.iop.org/article/10.1086/501157/pdf

Both solar flares and shock waves driven by fast coronal mass ejections (CMEs) can accelerate charged particles in the solar corona and create transient enhancements of solar energetic particle fluxes in interplanetary space (SEP events). Fast CMEs and flares often occur together, which makes it difficult to directly identify the actual source of SEP events detected near Earth orbit. In this paper, we attempt to single out fast CMEs without any signature of particle acceleration related to a flare.We choose meter-wave radio emission from energetic electrons as a tracer of flare-related particle acceleration. In truly radio-silent fast CMEs, the only source of SEP acceleration should be the CME shock. The SOHO LASCO catalog by St. Cyr et al. contains 24 fast CMEs (V > 900 km $s_{\_1}$) located above the western solar limb that occurred between 1996 July and 1998 June. Of these, only three are radio-silent. Comparison of their speeds with the fastmagnetosonic speed in the corona shows that these three CMEs very likely drive coronal shock waves. Their properties do not depart significantly from a reference set of SEP-associated fast CMEs, except for their smaller angular width. Although one, possibly two of these three CMEs are accompanied by weak enhancements of the electron and proton fluxes (E_p < 20 MeV; SOHO COSTEP and ACE EPAM), none produces a conspicuous SEP event. This suggests that eitherCMEshocks accelerate particles over much smaller angular ranges than generally believed or that they are less efficient accelerators at energies above _10 MeV than often thought.

Determination of GLE of Solar Energetic Particles by Means of Spectral Analysis

Juan C. **Márquez-Adame**1, Jorge Pérez-Peraza1, and Victor Velasco-Herrera1

2019 ApJ 878 154

sci-hub.se/10.3847/1538-4357/ab22a1

Using three nonstationary solar series, the solar flare index (FS), the sunspots index (SS), and the solar flux (F10.7) index, we apply the Morlet wavelet analysis to determine the most dominant harmonics of solar activity, 1.73, 3.27, 4.9, 10.4, and 11 yr. The periodicities obtained are processed by the fuzzy logic method, which allows us to reproduce the occurrence dates of ground level enhancements (GLE), since 1942–2006, which we use as a training baseline of these spectral techniques to determine the occurrence of solar particle enhancements in solar cycles. Then, the result of fuzzy logic is extended to periods later than the training period so as to cover the end of cycle 24 and the beginning of cycle 25. In addition to the forecastable aspect of this work, the obtained results are of high interest in view of the recent controversy that has arisen in relation to the occurrence of small GLE (namely sub-GLE), during cycle 24.

Statistical Study of the Correlation between Solar Energetic Particles and Properties of Active Regions

Russell D. **Marroquin**, Viacheslav Sadykov, Alexander Kosovichev, Irina N. Kitiashvili, Vincent Oria, Gelu M. Nita, Egor Illarionov, Patrick M. O'Keefe, Fraila Francis, Chun-Jie Chong, Paul Kosovich

ApJ **2023**

https://arxiv.org/pdf/2303.06100.pdf

The flux of energetic particles originating from the Sun fluctuates during the solar cycles. It depends on the number and properties of Active Regions (ARs) present in a single day and associated solar activities, such as solar flares and coronal mass ejections (CMEs). Observational records of the Space Weather Prediction Center (SWPC NOAA) enable the creation of time-indexed databases containing information about ARs and particle flux enhancements, most widely known as Solar Energetic Particle events (SEPs). In this work, we utilize the data available for Solar Cycles 21-24, and the initial phase of Cycle 25 to perform a statistical analysis of the correlation between SEPs and properties of ARs inferred from the McIntosh and Hale classifications. We find that the complexity of the magnetic field, longitudinal location, area, and penumbra type of the largest sunspot of ARs are most correlated with the production of SEPs. It is found that most SEPs (≈60\%, or 108 out of 181 considered events) were generated from an AR classified with the 'k' McIntosh subclass as the second component, and some of these ARs are more likely to produce SEPs if they fall in a Hale class with δ component. It is confirmed that ARs located in the western hemisphere produced the most SEPs recorded on the Earth's orbit. The resulting database containing information about SEP events and ARs is publicly available and can be used for the development of Machine Learning (ML) models to predict the occurrence of SEPs.

SPARX: a modelling system for Solar Energetic Particle Radiation Space Weather forecasting

M. S. **Marsh**, S. Dalla, M. Dierckxsens, T. Laitinen, N. B. Crosby
Space Weather, Volume 13, Issue 6 June **2015** Pages 386–394
http://arxiv.org/pdf/1409.6368v1.pdf
http://onlinelibrary.wiley.com/doi/10.1002/2014SW001120/full
The capability to predict the parameters of an SEP event such as its onset, peak flux, and duration is critical to assessing any potential space weather impact. We present a new operational modelling system simulating the propagation of Solar Energetic Particles (SEPs) from locations near the Sun to any given location in the heliosphere. The model is based on the test particle approach and is spatially 3D, thus allowing for the possibility of transport in the direction perpendicular to the magnetic field. The model naturally includes the effects of perpendicular propagation due to drifts and drift-induced deceleration. The modelling framework and the way in which parameters of relevance for Space Weather are obtained within a forecasting context are described. The first results from the modelling system are presented. These results demonstrate that corotation and drift of SEP streams play an essential role in shaping SEP flux profiles.

Drift-induced perpendicular transport of Solar Energetic Particles

M. S. **Marsh**, S. Dalla, J. Kelly, and T. Laitinen
E-print, July **2013**, **2013** ApJ 774 4
Drifts are known to play a role in galactic cosmic ray transport within the heliosphere and are a standard component of cosmic ray propagation models. However, the current paradigm of Solar Energetic Particle (SEP) propagation holds the effects of drifts to be negligible, and they are not accounted for in most current SEP modelling efforts. We present full-orbit test particle simulations of SEP propagation in a Parker spiral interplanetary magnetic field which demonstrate that high energy particle drifts cause significant asymmetric propagation perpendicular to the interplanetary magnetic field. Thus in many cases the assumption of field aligned propagation of SEPs may not be valid. We show that SEP drifts have dependencies on energy, heliographic latitude, and charge to mass ratio, that are capable of transporting energetic particles perpendicular to the field over significant distances within interplanetary space, e.g. protons of initial energy 100 MeV propagate distances across the field on the order of 1 AU, over timescales typical of a gradual SEP event. Our results demonstrate the need for current models of SEP events to include the effects of particle drift. We show that the drift is considerably stronger for heavy ion SEPs due to their larger mass to charge ratio. This paradigm shift has important consequences for the modelling of SEP events and is crucial to the understanding and interpretation of in-situ observations.

First ground-level enhancement of solar cycle 25 as seen by the High-Energy Particle Detector (HEPD-01) on board the CSES-01 satellite

Matteo **Martucci**, Monica Laurenza, Simone Benella, Francesco Berrilli, +++++
Space Weather e2022SW003191 **Volume21, Issue1** **2023** **File**
https://doi.org/10.1029/2022SW003191
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003191
In this work we present the HEPD-01 observations of proton fluxes from space during the October 28, 2021 solar energetic particle event, which produced a ground level enhancement on Earth. The event was associated with the major, long-duration X1-class flare and the concomitant coronal mass ejection that erupted from the Active Region 12887. This is the first direct measurement from space of particles emitted during the current solar cycle, recorded by a single instrument in the energy range from ~50 MeV/n up to ~250 MeV/n. We have performed a Weibull-modeled spectral analysis of the energy spectrum in the wide energy range 300 keV - 250 MeV, obtained from combination of HEPD-01 proton measurements with the ones from ACE/ULEIS, SOHO/EPHIN and SOHO/ERNE. The good agreement between data and model, also corroborated by a comparison with other spectral shapes commonly used in these studies, suggests that particles could have possibly been accelerated out from the ambient corona through the contribution of stochastic acceleration at the CME driven shock, even if the presence of seed populations influencing spectral shape could not be excluded. Finally, a Solar Proton Release (SPR) time of 1601±13 UTC and a magnetic path-length of L = 1.32±0.24 AU have been obtained, in agreement with previous results for this event. We remark that new and precise data on protons in the tens/hundreds MeV energy range - like

the one provided by HEPD-01 - could shed more light on particle acceleration as well as provide a reliable parametrization of SEP spectrum for Space Weather purposes. **October 28, 2021**

Proton Fluxes Measured by the PAMELA Experiment from the Minimum to the Maximum Solar Activity for Solar Cycle 24

M. **Martucci**1,2, R. Munini3, M. Boezio3, V. Di Felice4,5, O. Adriani6,7, G. C. Barbarino8,9,G. A. Bazilevskaya …

2018 ApJL 854 L2

http://sci-hub.tw/10.3847/2041-8213/aaa9b2

Precise measurements of the time-dependent intensity of the low-energy (<50 GeV) galactic cosmic rays (GCRs) are fundamental to test and improve the models that describe their propagation inside the heliosphere. In particular, data spanning different solar activity periods, i.e., from minimum to maximum, are needed to achieve comprehensive understanding of such physical phenomena. The minimum phase between solar cycles 23 and 24 was peculiarly long, extending up to the beginning of 2010 and followed by the maximum phase, reached during early 2014. In this Letter, we present proton differential spectra measured from 2010 January to 2014 February by the PAMELA experiment. For the first time the GCR proton intensity was studied over a wide energy range (0.08–50 GeV) by a single apparatus from a minimum to a maximum period of solar activity. The large statistics allowed the time variation to be investigated on a nearly monthly basis. Data were compared and interpreted in the context of a state-of-the-art three-dimensional model describing the GCRs propagation through the heliosphere.

3He and Fe Spectral Properties in 3He-rich Solar Energetic Particle Events

G. M. **Mason**1, A. Kouloumvakos1, G. C. Ho2, R. C. Allen2, R. Gómez-Herrero3, R. F. Wimmer-Schweingruber4, and J. Rodríguez-Pacheco3

2024 ApJ 974 54

https://iopscience.iop.org/article/10.3847/1538-4357/ad6ddc/pdf

We have surveyed 3He-rich events on the Solar Orbiter mission from 2020 April to 2024 April, selecting isolated injections whose rollover 3He spectral shape is presumed to represent the initial acceleration state, unprocessed by subsequent activity such as coronal mass ejections or jets. A main goal has been to find relationships between the spectra of 3He and heavy ions C–Fe, in order to explore a common acceleration mechanism in spite of the fact that these events show 3He enrichments of up to ∼104, while the heavy-ion enrichment is rarely larger than ∼10. Selecting 34 3He injections, we find that heavy ions are always present, and arrive at the same time as the 3He signaling a common origin. Concentrating on Fe since it is a minor ion but with higher abundance than many others, we find its spectral shape and intensity is similar to 3He. In ∼two-thirds of the cases, if the 3He spectrum is shifted to lower energy by a factor 3.0 ± 1.3, it nearly coincides with the Fe spectrum, illustrating their close connection. Several plasma wave turbulence models have calculated spectra that also show the ion rollovers around 1 MeV nucleon−1. The unique mass-to-charge ratio of 3He allows it to interact more efficiently with the turbulence, thereby gaining several times more energy per nucleon than the other heavy ions. In the spectral rollover region this can lead to the observed enormous enhancements of 3He. The acceleration appears to be associated with magnetic reconnection in emerging flux regions on the Sun. **2021 December 31**

Table 1 Event Properties 2020-2024

Heavy-ion Acceleration in 3He-rich Solar Energetic Particle Events: New Insights from Solar Orbiter

G. M. **Mason**, I. Roth, N. V. Nitta, R. Bučík, D. Lario, G. C. Ho, R. C. Allen, A. Kouloumvakos, R. F. Wimmer-Schweingruber, and J. Rodriguez-Pacheco

2023 ApJ 957 112

https://iopscience.iop.org/article/10.3847/1538-4357/acf31b/pdf

We present Solar Orbiter energetic particle observations of two 3He-rich events with features more clearly observed than in prior studies. The event of **2022 November 9** observed from 0.59 au contained hundreds of ultraheavy (UH; mass >78 amu) ions whereas previous observations at 1 au have shown only an occasional count or two. The event of **2023 April 8** observed from 0.29 au fortuitously had very low ambient activity, making it possible to observe spectra from the 3He acceleration mechanism without contamination, revealing extremely low H and 4He intensities arriving simultaneously with other ions observed in typical 3He-rich events. Taken together with previous studies, we believe these data show that 3He-rich events have a single acceleration mechanism that is responsible for the unique abundance features of 3He, heavy ions, and UH ions. Considering the acceleration model of Roth & Temerin that heats the ions over a broad range of gyrofrequencies away from those damped by H and 4He, we calculate reasonable fits to the observed abundances O–Fe. A key result is that high values of, e.g., Fe/O typical of such events is not due to preferential Fe heating, but on the contrary is due mainly to the depletion of O, which at elevated temperatures has a charge-to-mass ratio in the region of the waves damped by 4He. The model also naturally incorporates features of high-ionization states and neutron-rich isotope enhancements that have been long-standing puzzles in observations of this type of flare.

The 18–19 March 2022 series of 3He-rich events observed by Solar Orbiter at 0.36 au compared with EUV, X-ray, and radio observations.

Mason, G. M. et al.

Astron & Astrophys 669, L16 (**2023**).

https://www.aanda.org/articles/aa/pdf/2023/01/aa45576-22.pdf

Context. During the first close perihelion pass of Solar Orbiter, a series of impulsive 3He-rich solar particle events was observed on **18–19 March 2022** from a distance of 0.36 au. In addition to the energetic particle, radio, and X-ray data from Solar Orbiter, the events were observed in radio and/or extreme ultraviolet by STEREO-A, SDO, Wind, and Parker Solar Probe. Aims. Observations of the event series along with remote sensing of flaring and radio emission with only small timing delays due to the close distance allow the association with energetic particles to be determined with much higher accuracy than previously possible from 1 au. Methods. By comparing the onsets of type-III bursts with the arrival of electrons of tens of keV at Solar Orbiter only a few minutes later, it can be seen that, overall, each of the more intense type-III bursts was associated with an electron and ion injection. Extreme ultraviolet data show that the times of the type-III bursts coincide with emission from a small (approximately Earth-sized) loop to the west of a nearby active region. Results. The energetic particle spectra and abundances show typical properties of impulsive 3He-rich flares and, when combined with the remote sensing observations, establish that the particle-accelerating mechanism in this series of events operates near the solar surface in association with magnetic loops, and in the absence of other phenomena such as jets and small coronal mass ejections.

3HE-RICH SOLAR ENERGETIC PARTICLE EVENTS OBSERVED CLOSE TO THE SUN ON SOLAR ORBITER

G. M. **Mason**, R. Bučik2, and the Solar Orbiter/EPD team

Solar Orbiter nugget #12 **2023**

https://www.cosmos.esa.int/web/solar-orbiter/-/3he-rich-solar-energetic-particle-events-observed-close-to-the-sun-on-solar-orbiter

Solar energetic particle (SEP) events are studied intensively since they can fill the inner solar system with ionizing radiation and are the most energetic particle accelerators in the solar system. The Solar Orbiter mission [1] is providing opportunities for better understanding of how these events accelerate and release particles into the interplanetary space, and how they are transported in the solar system. The most abundant SEP events are small “impulsive” events that take place by the thousands in active periods, and show unique properties such as high electron abundances, radio bursts, and ions with abundance mixtures greatly modified from solar material [2, 3]. **3-7 Mar 2022, March 18-19 2022**

Energetic Neutral Hydrogen from Large Solar Flares

Glenn **MASON**

RHESSI Science Nuggets №435   **2022**

https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Energetic_Neutral_Hydrogen_from_Large_Solar_Flares

5 Dec 2006

Evidence for Energetic Neutral Hydrogen Emission from Solar Particle Events

G. M. **Mason**1, M. E. Greenspan7,2, S. G. Kanekal3, R. A. Leske4, M. D. Looper5, J. E. Mazur6, and R. A. Mewaldt4

2021 ApJ 923 195

https://iopscience.iop.org/article/10.3847/1538-4357/ac2fa2/pdf

https://doi.org/10.3847/1538-4357/ac2fa2

We report the probable detection of energetic neutral hydrogen atoms (ENAs) at >0.8 MeV in several large solar energetic particle events observed between 1997 and 2004. The low Earth orbiting SAMPEX satellite detected transient increases of quasi-trapped equatorial protons beginning typically ∼3 hr after the X-ray flare and lasting for up to several hours. Since the magnetic cutoff rigidity is >10 GV at the magnetic latitude where the particles were observed, we interpret the signal as due to ENAs that penetrate Earth's magnetic field and charge exchange in the upper atmosphere, whereupon the charged particles may become trapped. One event outside our survey period (2006 December 5) had previously reported solar flare ENAs, the only example of this phenomenon of which we are aware. Although the statistics are limited, the events we report suggest that the ENAs are produced as the flare-associated coronal mass wjection moves through the corona, as concluded previously for the **2006 December 5** event. The finding of ENAs emitted in conjunction with large solar flares opens a new avenue to understanding these events. **6 Nov 1997, 24 Aug 1998, 10 Apr 2001, 15 Aug 2001, 24 Sep 2001, 2001 November 4, 20 Jul 2002, 15 Jun 2003, 28 Oct 2003**

Table 1 Solar and Interplanetary Properties (1997-2006)

3He-rich solar energetic particle events observed on the first perihelion pass of Solar Orbiter

G. M. **Mason1**, G. C. Ho1, R. C. Allen1, J. Rodríguez-Pacheco2, et al.
A&A 656, L1 (**2021**)
https://www.aanda.org/articles/aa/pdf/2021/12/aa39752-20.pdf
https://doi.org/10.1051/0004-6361/202039752

We report observations of five impulsive solar energetic particle (SEP) events observed inside 1 au during the first perihelion pass of the Solar Orbiter mission, which was launched in February 2020. These small events were all reasonably associated with active regions observed from Earth but which had rotated out of view by the time of the Solar Orbiter observations. Even though most of the events were small, their spectral forms, 3He content, and association with type III bursts convincingly identifies them as 3He-rich impulsive SEP events with properties similar to those previously observed at 1 au. Three of the events showed fast ion rise times, and two of them had long-lasting anisotropies consistent with the Compton-Getting effect**. 2020: 18 Jun., 11 Jul., 20 Jul., 5 Aug., 17 Sep.**

Table 1. 3He-rich solar energetic particle event properties.

A Possible Mechanism for Enriching Heavy Ions in 3He-rich Solar Energetic Particle Events

Glenn M. **Mason**1 and Berndt Klecker2
2018 ApJ 862 7
http://iopscience.iop.org/article/10.3847/1538-4357/aac94c/pdf

We investigate a mechanism to produce a seed population enriched in heavy ions, such as those observed in 3He-rich solar energetic particle events. It is shown that if an initial particle population following a power law in energy nucleon−1 passes through a small amount of material, at energies below the dE/dx Bragg peak, the greater affinity of heavier ions for electron pick-up results in their penetrating the material more easily. This results in an enhancement of heavy ions in the particle population that just barely penetrates the material. The bulk of the seed particles fall in the energy range of 10 s of keV nucleon−1. It is supposed that some further process then energizes this seed population to produce the particles observed in interplanetary space. We find a broad range of parameters that produces enhancements comparable to Fe/O ~ 8 commonly observed.

EVIDENCE FOR A COMMON ACCELERATION MECHANISM FOR ENRICHMENTS OF 3He AND HEAVY IONS IN IMPULSIVE SEP EVENTS

Glenn M. **Mason**1, Nariaki V. Nitta2, Mark E. Wiedenbeck3, and Davina E. Innes
2016 ApJ 823 138

We have surveyed the period 1997–2015 for a rare type of 3He-rich solar energetic particle (SEP) event, with enormously enhanced values of the S/O ratio, that differs from the majority of 3He-rich events, which show enhancements of heavy ions increasing smoothly with mass. Sixteen events were found, most of them small but with solar source characteristics similar to other 3He-rich SEP events. A single event on **2014 May 16** had higher intensities than the others, and curved Si and S spectra that crossed the O spectrum above ~200 keV nucleon−1. Such crossings of heavy-ion spectra have never previously been reported. The dual enhancement of Si and S suggests that element Q/M ratio is critical to the enhancement since this pair of elements uniquely has very similar Q/M ratios over a wide range of temperatures. Besides 3He, Si, and S, in this same event the C, N, and Fe spectra also showed curved shape and enhanced abundances compared to O. The spectral similarities suggest that all have been produced from the same mechanism that enhances 3He. The enhancements are large only in the high-energy portion of the spectrum, and so affect only a small fraction of the ions. The observations suggest that the accelerated plasma was initially cool (~0.4 MK) and was then heated to a few million kelvin to generate the preferred Q/M ratio in the range C–Fe. The temperature profile may be the distinct feature of these events that produces the unusual abundance signature.

INTERPLANETARY PROPAGATION OF SOLAR ENERGETIC PARTICLE HEAVY IONS OBSERVED AT 1 AU AND THE ROLE OF ENERGY SCALING

G. M. **Mason**1, G. Li2, C. M. S. Cohen3, M. I. Desai4, D. K. Haggerty1, R. A. Leske3, R. A. Mewaldt3, and G. P. Zank
2012 ApJ 761 104

We have studied ~0.3 to >100 MeV nucleon–1 H, He, O, and Fe in 17 large western hemisphere solar energetic particle events (SEP) to examine whether the often observed decrease of Fe/O during the rise phase is due to mixing of separate SEP particle populations, or is an interplanetary transport effect. Our earlier study showed that the decrease in Fe/O nearly disappeared if Fe and O were compared at energies where the two species interplanetary diffusion coefficient were equal, and therefore their kinetic energy nucleon–1 was different by typically a factor ~2 ("energy scaling"). Using an interplanetary transport model that includes effects of focusing, convection, adiabatic deceleration, and pitch angle scattering we have fit the particle spectral forms and intensity profiles over a broad range of conditions where the 1 AU intensities were reasonably well connected to the source and not obviously dominated by local shock effects. The transport parameters we derive are similar to earlier studies. Our model follows individual particles with a Monte Carlo calculation, making it possible to determine many properties and effects of the transport. We find that the energy scaling feature is preserved, and that the model is reasonably successful at fitting the magnitude and duration of the Fe/O ratio decrease. This along with successfully fitting the observed decrease of the O/He ratio leads us to conclude that this feature is best understood as a transport effect. Although the effects of transport, in particular adiabatic deceleration, are very significant below a few MeV nucleon–1, the spectral break observed in these events at 1 AU is only somewhat modified by transport, and so the commonly observed spectral breaks must be present at injection. For scattering mean free paths of the order of 0.1 AU adiabatic deceleration is so large below ~200 keV nucleon–1 that ions starting with such energies at injection are cooled sufficiently as to be unobservable at 1 AU. Because of the complicating factors of different spectral break energies for different elements, it appears that SEP abundances determined below the break are least susceptible to systematic distortions.

SOLAR ENERGETIC PARTICLE 3He-RICH EVENTS FROM THE NEARLY QUIET SUN IN 2007–2008

G. M. **Mason**[1], N. V. Nitta[2], C. M. S. Cohen[3], and M. E. Wiedenbeck[4]

Astrophysical Journal, 700:L56–L59, **2009** July

We have used *Advanced Composition Explorer* instruments to survey the period 2007 March through the end of 2008 for ^{3}He-rich solar energetic particle (SEP) events occurring during near solar minimum conditions. Four events were found, all associated with single solar active regions in the western hemisphere. They all show ^{3}He:^{4}He ratios of a few percent (i.e., _100 times solar system abundances), low intensities, and spectra extending up to at least 1 MeV nucleon^{-1}. Two events, on 2008 February 4 and 2008 June 16, were devoid of signatures associated with ^{3}He-rich SEPs, namely they lacked associations with energetic electrons and type-III bursts. In addition, there were no clear coronal mass ejections and X-ray flare activity was very low or absent. We take this as evidence that the irreducible requirement for ^{3}He-rich SEPs is a western hemisphere solar active region where magnetic and plasma processes preferentially energize ^{3}He and heavy ions.

Escape of Flare-accelerated Particles in Solar Eruptive Events

S. **Masson**1, S. K. Antiochos2, and C. R. DeVore

2019 ApJ 884 143

https://doi.org/10.3847/1538-4357/ab4515

https://arxiv.org/pdf/1909.13578.pdf

Impulsive solar energetic particle events are widely believed to be due to the prompt escape into the interplanetary medium of flare-accelerated particles produced by solar eruptive events. According to the standard model for such events, however, particles accelerated by the flare reconnection should remain trapped in the flux rope comprising the coronal mass ejection. The particles should reach the Earth only much later, along with the bulk ejecta. To resolve this paradox, we have extended our previous axisymmetric model for the escape of flare-accelerated particles to fully three-dimensional (3D) geometries. We report the results of magnetohydrodynamic simulations of a coronal system that consists of a bipolar active region embedded in a background global dipole field structured by solar wind. Our simulations show that multiple magnetic reconnection episodes occur prior to and during the coronal mass ejection (CME) eruption and its interplanetary propagation. In addition to the episodes that build up the flux rope, reconnection between the open field and the CME couples the closed corona to the open interplanetary field. Flare-accelerated particles initially trapped in the CME thereby gain access to the open interplanetary field along a trail blazed by magnetic reconnection. A key difference between these 3D results and our previous calculations is that the interchange reconnection allows accelerated particles to escape from deep within the CME flux rope. We estimate the spatial extent of the particle-escape channels. The relative timings between flare acceleration and release of the energetic particles through CME/open-field coupling are also determined. All our results compare favorably with observations.

A MODEL FOR THE ESCAPE OF SOLAR-FLARE-ACCELERATED PARTICLES

S. **Masson**1, S. K. Antiochos1, and C. R. DeVore

2013 ApJ 771 82; **File**

We address the problem of how particles are accelerated by solar flares can escape into the heliosphere on timescales of an hour or less. Impulsive solar energetic particle (SEP) bursts are generally observed in association with so-called eruptive flares consisting of a coronal mass ejection (CME) and a flare. These fast SEPs are believed to be accelerated directly by the flare, rather than by the CME shock. However, the precise mechanism by which the particles are accelerated remains controversial. Regardless of the origin of the acceleration, the particles should remain trapped in the closed magnetic fields of the coronal flare loops and the ejected flux rope, given the magnetic geometry of the standard eruptive-flare model. In this case, the particles would reach the Earth only after a delay of many hours to a few days (coincident with the bulk ejecta arriving at Earth). We propose that the external magnetic reconnection intrinsic to the breakout model for CME initiation can naturally account for the prompt escape of flare-accelerated energetic particles onto open interplanetary magnetic flux tubes. We present detailed 2.5-dimensional magnetohydrodynamic simulations of a breakout CME/flare event with a background isothermal solar wind. Our calculations demonstrate that if the event occurs sufficiently near a coronal-hole boundary, interchange reconnection between open and closed fields can occur. This process allows particles from deep inside the ejected flux rope to access solar wind field lines soon after eruption. We compare these results to standard observations of impulsive SEPs and discuss the implications of the model on further observations and calculations.

The interplanetary magnetic structure that guides solar relativistic particles

S. **Masson**, P. Démoulin1, S. Dasso2 and K.-L. Klein

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Context. Relating in-situ measurements of relativistic solar particles to their parent activity in the corona requires understanding the magnetic structures that guide them from their acceleration site to the Earth. Relativistic particle events are observed at times of high solar activity, when transient magnetic structures such as interplanetary coronal mass ejections (ICMEs) often shape the interplanetary magnetic field (IMF). They may introduce interplanetary paths that are longer than nominal, and magnetic connections rooted far from the nominal Parker spiral.
Aims. We present a detailed study of the IMF configurations during ten relativistic solar particle events of the 23rd activity cycle to elucidate the actual IMF configuration that guides the particles to the Earth, where they are measured by neutron monitors.
Methods. We used magnetic field (MAG) and plasma parameter measurements (SWEPAM) from the ACE spacecraft and determined the interplanetary path lengths of energetic particles through a modified version of the velocity dispersion analysis based on energetic particle measurements with SoHO/ERNE.
Results. We find that the majority (7/10) of the events is detected in the vicinity of an ICME. Their interplanetary path lengths are found to be longer (1.5–2.6 AU) than those of the two events propagating in the slow solar wind (1.3 AU). The longest apparent path length is found in an event within the fast solar wind, probably caused by enhanced pitch angle scattering. The derived path lengths imply that the first energetic and relativistic protons are released at the Sun at the same time as electron beam emitting type III radio bursts.
Conclusions. The timing of the first high-energy particle arrival on Earth is mainly determined by the type of IMF in which the particles propagate. Initial arrival times are as expected from Parker's model in the slow solar wind, and significantly longer in or near transient structures such as ICMEs.

14 Jul. 00, 15 Apr. 01, 18 Apr. 01, 26 Dec. 01, 24 Aug. 02, 28 Oct. 03, 29 Oct. 03, 02 Nov. 03, 20 Jan. 05, 13 Dec. 06

Interchange Slip-Running Reconnection and Sweeping SEP Beams

S. **Masson**, G. Aulanier, E. Pariat and K.-L. Klein

Solar Physics, Volume 276, Numbers 1-2, 199-217, **2012, File**

We present a new model to explain how particles (solar energetic particles; SEPs), accelerated at a reconnection site that is not magnetically connected to the Earth, could eventually propagate along the well-connected open flux tube. Our model is based on the results of a low-β resistive magnetohydrodynamics simulation of a three-dimensional line-tied and initially current-free bipole, which is embedded in a non-uniform open potential field. The topology of this configuration is that of an asymmetric coronal null point, with a closed fan surface and an open outer spine. When driven by slow photospheric shearing motions, field lines, initially fully anchored below the fan dome, reconnect at the null point, and jump to the open magnetic domain. This is the standard interchange mode as sketched and calculated in 2D. The key result in 3D is that reconnected open field lines located in the vicinity of the outer spine keep reconnecting continuously, across an open quasi-separatrix layer, as previously identified for non-open-null-point reconnection. The apparent slipping motion of these field lines leads to formation of an extended narrow magnetic flux tube at high altitude. Because of the slip-running reconnection, we conjecture that if energetic particles would be traveling through, or be accelerated inside, the diffusion region, they would be successively injected along continuously reconnecting field lines that are connected farther and farther from the spine. At the scale of the full Sun, owing to the super-radial expansion of field lines below 3 $R_\odot$, such energetic particles could easily be injected in field lines slipping over significant distances, and could eventually reach the distant flux tube that is well-connected to the Earth.

Acceleration of Relativistic Protons During the 20 January 2005 Flare and CME

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Solar Phys (**2009**) 257: 305–322; **File**, DOI 10.1007/s11207-009-9377-y

The origin of relativistic solar protons during large flare/CME events has not been uniquely identified so far. We perform a detailed comparative analysis of the time profiles of relativistic protons detected by the worldwide network of neutron monitors at Earth with electromagnetic signatures of particle acceleration in the solar corona during the large particle event of 20 January 2005. The intensity – time profile of the relativistic protons derived from the neutron monitor data indicates two successive peaks. We show that microwave, hard X-ray, and γ -ray emissions display several episodes of particle acceleration within the impulsive flare phase. The first relativistic protons detected at Earth are accelerated together with relativistic electrons and with protons that produce pion-decay γ rays during the second episode. The second peak in the relativistic proton profile at Earth is accompanied by new signatures of particle acceleration in the corona within ≈1R_ above the photosphere, revealed by hard X-ray and microwave emissions of low intensity and by the renewed radio emission of electron beams and of a coronal shock wave. We discuss the observations in terms of different scenarios of particle acceleration in the corona.

CME-related particle acceleration regions during a simple eruptive event near solar minimum

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CESRA **2016** p.65

http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v3.pdf

An intriguing feature of many solar energetic particle (SEP) events is the detection of particles over a very extended range of longitudes in the Heliosphere. This may be due to peculiarities of the magnetic field in the corona, to a broad accelerator, to cross-field transport of the particles, or to a combination of these processes. The eruptive flare of the **26th of April 2008** offered an opportunity to study relevant processes under particularly favorable conditions, since it occurred in a very quiet solar and interplanetary environment. This allowed us to investigate the physical link between a single well-identified Coronal Mass Ejection (CME), electron acceleration as traced by radio emission, and the production of SEPs. We conduct a detailed analysis combining radio observations (Nan¸cay Radioheliograph and Decameter Array, Wind/WAVES spectrograph) with remote-sensing observations of the corona in extreme ultraviolet (EUV) and white light as well as in-situ measurements of energetic particles near 1AU (SoHO and STEREO spacecraft). By combining images taken from multiple vantage points we were able to derive the time-dependent evolution of the 3-D pressure front developing around the erupting CME. Magnetic reconnection in the post-CME current sheet accelerated electrons that remained confined in closed magnetic fields in the corona, while the acceleration of escaping particles can be attributed to the pressure front generated ahead of the expanding CME. The CME accelerated electrons remotely from the parent active region, due to the interaction of its laterally expanding flank, traced by an EUV wave, with the ambient corona. SEPs detected at one STEREO spacecraft and SoHO were accelerated later, when the frontal shock of the CME intercepted the spacecraft-connected interplanetary magnetic field line. The injection regions into the Heliosphere inferred from the radio and SEP observations are separated in longitude by about 140 . The observations for this event show that it is misleading to interpret multi-spacecraft SEP measurements in terms of one acceleration region in the corona. The different acceleration regions are linked to different vantage points in the interplanetary space.

The Solar Particle Event on 10–13 September 2017: Spectral Reconstruction and Calculation of the Radiation Exposure in Aviation and Space

Daniel **Matthiä**, Matthias M. Meier, Thomas Berger

Space Weather **2018**

http://sci-hub.tw/10.1029/2018SW001921

The solar energetic particle event on 10 September 2017 and on the following days was the strongest event in recent years. It was recorded as ground level enhancement 72 by neutron monitor stations on Earth and measured by a number of instruments in space. One aspect of such a space weather event is the potentially increased radiation exposure in aviation and space. Numerical simulations can help estimate the elevated dose rates during such an event; a critical aspect in these simulations is the description of the primary particle spectrum. In this work, we present 1-hr averaged proton spectra during the event derived from Geostationary Operational Environmental Satellite measurements and described by two different analytic functions. The derived proton spectra are used to calculate the radiation exposure in aviation and different space scenarios: low-Earth orbit, interplanetary space, and Mars surface, and the results are discussed in the context of available experimental data. While the results indicate that in most of these scenarios in aviation and space the event was of little significance compared to the total exposure from galactic cosmic radiation, the skin dose in a lightly shielded environment in interplanetary space may have reached about 30% to 60% of the NASA 30-day dose limit.

Temporal and spatial evolution of the solar energetic particle event on 20 January 2005

and resulting radiation doses in aviation

Matthia, D.; Heber, B.; Reitz, G.; Meier, M.; Sihver, L.; Berger, T.; Herbst, K.

J. Geophys. Res., Vol. 114, No. A8, A08104, **2009**

The solar energetic particle event on 20 January 2005 was one of the largest ground level events ever observed. Neutron monitor stations in the Antarctic recorded count rate increases of several thousand percent caused by secondary energetic particles, and it took more than 36 h to return to background level. Such huge increases in high energetic solar cosmic radiation on the ground are obviously accompanied by considerable changes in the radiation environment at aviation altitudes. Measurements of 28 neutron monitor stations were used in this work to numerically approximate the primary solar proton spectra during the first 12 h of the event by minimizing the differences between measurements and the results of Monte-Carlo calculated count rate increases. The primary spectrum of solar energetic protons was approximated by a power law in rigidity and a linear angular distribution. The incoming direction of the solar energetic particles was determined and compared to the interplanetary magnetic field direction during the event. The effects on the radiation exposure at altitudes of about 12 km during that time were estimated to range from none at low latitudes up to almost 2 mSv/h for a very short time in the Antarctic region and about 0.1 mSv/h at high latitudes on the Northern Hemisphere. After 12 h, dose rates were still increased by 50% at latitudes above 60° whereas no increases at all occurred at latitudes below 40° during the whole event.

Real-time detection of the Ground Level Enhancement on 10 September 2017 by A.Ne.Mo.S.: System Report

H. **Mavromichalaki**, M. Gerontidou, P. Paschalis, E. Paouris, A. Tezari, C. Sgouropoulos, N. Crosby, M. Dierckxsens

Space Weather **2018**

sci-hub.tw/10.1029/2018SW001992

On **10 September 2017**, a ground level enhancement (GLE) of cosmic ray intensity, identified as GLE72, was recorded by several stations of the worldwide neutron monitor network provided by the high-resolution Neutron Monitor Database (NMDB). The solar proton event that resulted in this GLE was associated with active region AR2673 which produced an X8.2 flare on the solar west limb. Protons were measured by the GOES satellites with energies above 10, 50 and 100 MeV, while particles at higher energies above 500 MeV were registered by ground-based neutron monitors. This GLE event was successfully detected in real-time by the GLE Alert plus System of the Athens Neutron Monitor Station (A.Ne.Mo.S.). In this work an overview of the GLE72 event is given, and a detailed analysis of the evolution of the GLE Alert signal issued by the GLE Alert plus System as well as a post-event summary are presented.

Long-Term Cosmic Ray Variability and the CME-Index

Helen **Mavromichalaki** and Evangelos Paouris

Advances in Astronomy, Volume 2012 (**2012**), Article ID 607172, 8 pages

http://www.hindawi.com/journals/aa/2012/607172/

The cosmic ray modulation in relation to solar activity indices and heliospheric parameters during the period January 1996–October 2011, covering the solar cycle 23 and the ascending phase of solar cycle 24, is studied. The new perspective of this contribution is that the CME-index, obtained from only the CMEs with angular width greater than 30 degrees, gives much better results than in previous works. The proposed model for the calculation of the modulated cosmic ray intensity obtained from the combination of solar indices and heliospheric parameters gives a very satisfactory value of the standard deviation. The best reproduction of the cosmic ray intensity is obtained by taking into account solar and interplanetary indices such as sunspot number, interplanetary magnetic field, CME-index, and heliospheric current sheet tilt. The standard deviation between the observed and calculated values is about 6.63% for the solar cycle 23 and 4.13% for the ascending part of solar cycle 24.

Applications and usage of the real-time Neutron Monitor Database

Mavromichalaki, H.; Papaioannou, A.; Plainaki, C.; Sarlanis, C.; Souvatzoglou, G.; Gerontidou, M.; Papailiou, M.; Eroshenko, E.; Belov, A.; Yanke, V.;and 24 coauthors

Advances in Space Research, Volume 47, Issue 12, p. 2210-2222. **2011**

https://ac.els-cdn.com/S0273117710001249/1-s2.0-S0273117710001249-main.pdf?_tid=55156ffa-1ae0-11e8-af73-00000aacb35e&acdnat=1519641324_cf025aa5b7ce3d48c40e9bddb06eb3ff

https://www.sciencedirect.com/science/article/pii/S0273117710001249?via%3Dihub

A high-time resolution Neutron Monitor Database (NMDB) has started to be realized in the frame of the Seventh Framework Programme of the European Commission. This database will include cosmic ray data from at least 18 neutron monitors distributed around the world and operated in real-time. The implementation of the NMDB will provide the opportunity for several research applications most of which will be realized in real-time mode. An important one will be the establishment of an Alert signal when dangerous solar cosmic ray particles are heading to the Earth, resulting into ground level enhancements effects registered by neutron monitors. Furthermore, on the basis of these events analysis, the mapping of all ground level enhancement features in near real-time mode will provide an overall picture of these phenomena and will be used as an input for the calculation of the ionization of the atmosphere. The latter will be useful together with other contributions to radiation dose calculations within the atmosphere at several altitudes and will reveal the absorbed doses during flights. Moreover, special algorithms for anisotropy and pitch angle distribution of solar cosmic rays, which have been developed over the years, will also be set online offering the advantage to give information about the conditions of the interplanetary space. All of the applications will serve the needs of the modern world which relies at space environment and will use the extensive network of neutron monitors as a multi-directional spectrographic detector. On top of which, the decreases of the cosmic ray intensity - known as Forbush decreases - will also be analyzed and a number of important parameters such as galactic cosmic ray anisotropy will be made available to the users of NMDB. A part of the NMDB project is also dedicated to the creation of a public outreach website with the scope to inform about cosmic rays and their possible effects on humans, technological systems and space-terrestrial environment. Therefore, NMDB will also stand as an informative gate on space research through neutron monitor's data usage.

Interplanetary magnetic field line mixing deduced from impulsive solar flare particles.

Mazur JE, Mason GM, Dwyer JR, Giacalone J, Jokipii JR, Stone EC

(**2000**) Astrophys J 532:L79–L82. doi:10.1086/ 312561

https://iopscience.iop.org/article/10.1086/312561/pdf

We have studied fine-scale temporal variations in the arrival profiles of ~20 keV nucleon to ~2 MeV 21 nucleon ions from impulsive solar flares using instrumentation on board the Advanced Composition Explorer 21 spacecraft at 1 AU between 1997 November and 1999 July. The particle events often had short-timescale (~3 hr) variations in their intensity that occurred simultaneously across all energies and were generally not in coincidence with any local magnetic field or plasma signature. These features appear to be caused by the convection of magnetic flux tubes past the observer that are alternately filled and devoid of flare ions even though they had a common flare source at the Sun. Thus, we have used the particles to study the mixing of the interplanetary magnetic field that is due to random walk. We deduce an average timescale of 3.2 hr for these features, which corresponds to a length of ~0.03 AU.

1999 January 9, 1999 June 4

Probing the energetic particle environment near the Sun

D. J. **McComas**, E. R. Christian, […] A. P. Rouillard

Nature volume 576, pages223–227 (2019)

https://www.nature.com/articles/s41586-019-1811-1.pdf

NASA's Parker Solar Probe mission1 recently plunged through the inner heliosphere of the Sun to its perihelia, about 24 million kilometres from the Sun. Previous studies farther from the Sun (performed mostly at a distance of 1 astronomical unit) indicate that solar energetic particles are accelerated from a few kiloelectronvolts up to near-relativistic energies via at least two processes: 'impulsive' events, which are usually associated with magnetic reconnection in solar flares and are typically enriched in electrons, helium-3 and heavier ions2, and 'gradual' events3,4, which are typically associated with large coronal-mass-ejection-driven shocks and compressions moving through the corona and inner solar wind and are the dominant source of protons with energies between 1 and 10 megaelectronvolts. However, some events show aspects of both processes and the electron–proton ratio is not bimodally distributed, as would be expected if there were only two possible processes5. These processes have been very difficult to resolve from prior observations, owing to the various transport effects that affect the energetic particle population en route to more distant spacecraft6. Here we report observations of the near-Sun energetic particle radiation environment over the first two orbits of the probe. We find a variety of energetic particle events accelerated both locally and remotely including by corotating interaction regions, impulsive events driven by acceleration near the Sun, and an event related to a coronal mass ejection. We provide direct observations of the energetic particle radiation environment in the region just above the corona of the Sun and directly explore the physics of particle acceleration and transport.

Integrated Science Investigation of the Sun (ISIS): Design of the Energetic Particle Investigation

D. J. **McComas**, N. Alexander, N. Angold, S. Bale, C. Beebe, B. Birdwell, M. Boyle, J. M. Burgum, J. A. Burnham, E. R. Christian, … show all 51

Space Science Reviews, Volume 204, Issue 1, pp 187–256 **2016**

http://link.springer.com/journal/11214/204/1?wt_mc=alerts.TOCjournals

The Integrated Science Investigation of the Sun (ISIS) is a complete science investigation on the Solar Probe Plus (SPP) mission, which flies to within nine solar radii of the Sun's surface. ISIS comprises a two-instrument suite to measure energetic particles over a very broad energy range, as well as coordinated management, science operations, data processing, and scientific analysis. Together, ISIS observations allow us to explore the mechanisms of energetic particles dynamics, including their: (1) Origins—defining the seed populations and physical conditions necessary for energetic particle acceleration; (2) Acceleration—determining the roles of shocks, reconnection, waves, and turbulence in accelerating energetic particles; and (3) Transport—revealing how energetic particles propagate from the corona out into the heliosphere. The two ISIS Energetic Particle Instruments measure lower (EPI-Lo) and higher (EPI-Hi) energy particles. EPI-Lo measures ions and ion composition from ∼20 keV/nucleon–15 MeV total energy and electrons from ∼25–1000 keV. EPI-Hi measures ions from ∼1–200 MeV/nucleon and electrons from ∼0.5–6 MeV. EPI-Lo comprises 80 tiny apertures with fields-of-view (FOVs) that sample over nearly a complete hemisphere, while EPI-Hi combines three telescopes that together provide five large-FOV apertures. ISIS observes continuously inside of 0.25 AU with a high data collection rate and burst data (EPI-Lo) coordinated with the rest of the SPP payload; outside of 0.25 AU, ISIS runs in low-rate science mode whenever feasible to capture as complete a record as possible of the solar energetic particle environment and provide calibration and continuity for measurements closer in to the Sun. The ISIS Science Operations Center plans and executes commanding, receives and analyzes all ISIS data, and coordinates science observations and analyses with the rest of the SPP science investigations. Together, ISIS' unique observations on SPP will enable the discovery, untangling, and understanding of the important physical processes that govern energetic particles in the innermost regions of our heliosphere, for the first time. This paper summarizes the ISIS investigation at the time of the SPP mission Preliminary Design Review in January 2014.

A high time-resolution analysis of the Ground-Level Enhancement (GLE) of 23 February 1956 in terms of the CSHKP standard flare model

McCracken, K. G.; Shea, M. A.; Smart, D. F.

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https://www.sciencedirect.com/journal/advances-in-space-research/vol/72/issue/8
https://www.sciencedirect.com/science/article/pii/S0273117723005082/pdfft?md5=3bd51f14d811e0a0110a075a721c3edc&pid=1-s2.0-S0273117723005082-main.pdf

The original real-time analog heritage data from the Huancayo recording ionization chamber is differentiated to yield 15-60 s reso-lution of the first 15 min of the cosmic ray Ground-Level Event (GLE) of **23 February 1956**. The initial High-Energy Impulsive (HEI) event of >12.5-20 GeV solar cosmic rays has a rise time of 2 min 15 s with an exponential rise time constant of 49 s, a fluctuating peak pulse of duration 5-7 min, followed by an abrupt decrease of <1 min duration to-33% of the peak flux. Detailed analysis of these data shows close consistency with the Carmichael-Sturrock-Hirayama-Kopp-Pneuman (CSHKP) standard flare model. The <49-second acceleration time to >12.5 GeV is explicable in terms of any one of three separate mechanisms: super-Dreier electric acceleration, sta-tistical (Fermi first order), and shock acceleration deep in the corona. The fluctuating solar cosmic ray flux, the abrupt cessation, and the strong cosmic ray anisotropy on arrival at Earth are consistent with the acceleration event consisting of a sequence of short-lived reconnection events within the parent active center. In addition, the HEI event had a duration and time domain profile similar to the gyro-synchrotron emission from electrons associated with the initial acceleration event in the CSHKP model, and the observation of a white light flare towards the end of the microwave pulse. The properties of the **GLE-5** HEI event are similar to those accompanying ten other previously studied large GLEs to the west of 240 West on the solar disk. We conclude that the historic high-resolution data from the GLE on 23 February 1956 demonstrate previously unknown properties of the HEI event that are all consistent with cosmic ray acceleration to 25 GeV by the CSHKP and similar flare magnetic reconnection models. A slowly varying and smaller increase com-menced 6 min after the commencement of the HEI event and rose steadily to a maximum-40 min later. This is consistent with several models of acceleration in association with the coronal mass ejection generated by the flare. 20 Jan 2005 GLE-59

The Annual Cosmic-Radiation Intensities 1391 – 2014; The Annual Heliospheric Magnetic Field Strengths 1391 – 1983, and Identification of Solar Cosmic-Ray Events in the Cosmogenic Record 1800 – 1983

K. G. **McCracken** , J. Beer

Solar Phys. **201**5

The annual cosmogenic 10Be ice-core data from Dye 3 and the North Greenland Ice-core Project (NGRIP), and neutron-monitor data, 1951 – 2014, are combined to yield a record of the annual cosmic-ray intensity, 1391 – 2014. These data were then used to estimate the intensity of the heliospheric magnetic field (HMF), 1391 – 1983. All of these annual data are provided in the Electronic Supplementary Material. Analysis of these annual data shows that there were significant impulsive increases in 10Be production in the year following the very large solar cosmic-ray events of 1942, 1949, and 1956. There was an additional enhancement that we attribute to six high-altitude nuclear explosions in 1962. All of these enhancements result in underestimates of the strength of the HMF. An identification process is defined, resulting in a total of seven impulsive 10Be events in the interval 1800 – 1942 prior to the first detection of a solar cosmic-ray event using ionization chambers. Excision of the 10Be impulsive enhancements yields a new estimate of the HMF, designated B(PCR-2). Five of the seven 10Be enhancements prior to 1941 are well correlated with the occurrence of very great geomagnetic storms. It is shown that a solar cosmic-ray

event similar to that of 25 July 1946, and occurring in the middle of the second or third year of the solar cycle, may merge with the initial decreasing phase of the 11-year cycle in cosmic-ray intensity and be unlikely to be detected in the 10Be data. It is concluded that the occurrence rate for solar energetic-particle (SEP) events such as that on 23 February 1956 is about seven per century, and that there is an upper limit to the size of solar cosmic-ray events.

THE HIGH-ENERGY IMPULSIVE GROUND-LEVEL ENHANCEMENT

K. G. **McCracken**1, H. Moraal2, and M. A. Shea

2012 ApJ 761 101, **File**

https://ui.adsabs.harvard.edu/link_gateway/2012ApJ...761..101M/PUB_PDF

We have studied short-lived (21 minute average duration), highly anisotropic pulses of cosmic rays that constitute the first phase of 10 large ground-level enhancements (GLEs), and which extend to rigidities in the range 5-20 GV. We provide a set of constraints that must be met by any putative acceleration mechanism for this type of solar-energetic-particle (SEP) event. The pulses usually have very short rise-times (three to five minutes) at all rigidities, and exhibit the remarkable feature that the intensity drops precipitously by 50% to 70% from the maximum within another three to five minutes. Both the rising and falling phases exhibit velocity dispersion, which indicates that there are particles with rigidities in the range 1 < P (GV) < 3 in the beam, and the evidence is that there is little scattering en route from the Sun. We name these events the high-energy impulsive ground-level enhancement (HEI GLE). We argue that the time-dependence observed at Earth at ~5 GV is a close approximation to that of the SEP pulse injected into the open heliospheric magnetic field in the vicinity of the Sun. We conclude that the temporal characteristics of the HEI GLE impose nine constraints on any putative acceleration process. Two of the HEI GLEs are preceded by short-lived, fast-rising neutron and >90 MeV gamma-ray bursts, indicating that freshly accelerated SEPs had impinged on higher-density matter in the chromosphere prior to the departure of the SEP pulse for Earth. This study was based on an updated archive of the 71 GLEs in the historic record, which is now available for public use. **1960 May 4. 1989 October 22., 1990 May 24., 2005 January 20**

Table 1 Ground-level Enhancements >10% Observed by Neutron Monitors

Investigation of the multiple-component structure of the 20 January 2005 cosmic ray ground level enhancement

K. G. **McCracken**, H. Moraal, P. H. Stoker

JGR, VOL. 113, A12101, doi:10.1029/2007JA012829, **2008; File**

Worldwide observations of the cosmic ray ground level enhancement (GLE) of 20 January 2005 are used to investigate a commonly observed but poorly understood feature of this class of event. It is argued that the GLE comprised two distinctly different cosmic ray populations. The first resulted in an impulsive, highly anisotropic, field-aligned pulse with a relatively hard rigidity spectrum and significant velocity dispersion. The characteristics of the anisotropy were almost identical to those for similar impulsive increases observed during GLEs in 1960, 1978, and 1989. The π 0 γ ray observations from the RHESSI and CORONAS-F spacecraft and Type III radio emissions yield a path length of 1.76 ± 0.1 AU to Earth for the first pulse. After the highest energies in the initial anisotropic pulse had passed Earth, another field-aligned but mildly anisotropic cosmic ray pulse developed slowly worldwide, exhibiting the characteristics of the conventional GLE. The risetime and anisotropy of this second population indicate substantial scattering, apparently at variance to the essentially scatter-free nature of the initial pulse. We show that the coexisting scatter-free initial impulsive increase and the diffusive character of the second pulse are consistent with the standard quasi-linear theory of pitch angle diffusion. Throughout the GLE, the anisotropy remained field-aligned, and a third maximum, seen by some stations, is shown to be due to changes in the direction of the heliospheric magnetic field (HMF). Examination of 22 large (>20%) GLEs in the historical record shows that the impulsive pulse never occurs after the commencement of the P2 pulse, indicating that the impulsive-gradual combination is not due to a chance sampling of differing scattering regions of the HMF. It is further shown that impulsive pulses, or their equivalents, have been observed in 13 out of the 15 GLEs associated with solar activity in the solar longitude range 24°–98°W, leading us to propose that the event of 20 January 2005 should be regarded as the defining example of the GLE. ***The observations lead us to propose two separate acceleration episodes in the typical GLE: (1) acceleration directly associated with the flare itself and located in the lower corona and (2) acceleration by a supercritical shock driven by the associated coronal mass ejection, located at ∼3–5 solar radii and farther in the upper corona.*** A one-to-one association with so-called impulsive and gradual solar energetic particle events at lower energies is proposed. On the basis of these observations, a generic model for the GLE is proposed.

The Signal of Solar Storms Embedded in Cosmogenic Radionuclides: Detectability and Uncertainties

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The threat that solar storms pose to our ever-modernizing society has gathered significant interest in the recent past. This is partly due to the discoveries of large peaks in the content of cosmogenic radionuclides such as radiocarbon (14C) in tree rings and beryllium-10 (10Be) and chlorine-36 (36Cl) in ice cores that were linked to extreme solar storms dated to the past millennia. To better assess the threat that they represent, we need to better quantify the relationship between their energy spectrum and their magnitude with respect to the content of the radionuclides that we measure in environmental archives such as ice cores. Here, we model the global production rate that the 59 largest particle storms coming from the Sun have induced for 10Be, 14C, and 36Cl during the past 70 years. We also consider the deposition flux in 10Be and 36Cl over the high latitudes where all Greenland ice cores are located. Our analysis shows that it is unlikely that any recent solar particle event can be detected in 10Be from ice cores. By relating these values to empirical data from ice cores, we are able to quantify different detection limits and uncertainties for 10Be and 36Cl. Due to different sensitivities to solar energetic particles, we assess that 10Be may only be suitable to detect a limited number of extreme solar storms, while 36Cl is suitable to detect any extreme particle event. This implies that the occurrence-rate estimates of extreme solar storms, based mainly on 14C and 10Be, relate to a small population of potential events.
Table 1951-2016

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Extreme Relativistic Electron Fluxes in GPS Orbit: Analysis of NS41 BDD-IIR Data
Nigel P. **Meredith**, Thomas E. Cayton, Michael D. Cayton, Richard B. Horne
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https://doi.org/10.1029/2023SW003436
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003436
Relativistic electrons in the Earth's outer radiation belt are a significant space weather hazard. Satellites in GPS-type orbits pass through the heart of the outer radiation belt where they may be exposed to large fluxes of relativistic electrons. In this study we conduct an extreme value analysis of the daily average relativistic electron flux in Global Positioning System orbit as a function of energy and L using data from the US NS41 satellite from 10 December 2000 to 25 July 2020. The 1 in 10 year flux at L = 4.5, in the heart of the outer radiation belt, decreases with increasing energy ranging from 8.2 × 106 cm−2s−1sr−1 MeV−1 at E = 0.6 MeV to 33 cm−2s−1sr−1 MeV−1 at E = 8.0 MeV. The 1 in 100 year is a factor of 1.1–1.7 larger than the corresponding 1 in 10 year event. The 1 in 10 year flux at L = 6.5, on field lines which map to the vicinity of geostationary orbit, decrease with increasing energy ranging from 6.2 × 105 cm−2s−1sr−1 MeV−1 at E = 0.6 MeV to 0.48 cm−2s−1sr−1 MeV−1 at E = 8.0 MeV. Here, the 1 in 100 year event is a factor of 1.1–13 times larger than the corresponding 1 in 10 year event, with the value of the factor increasing with increasing energy. Our analysis suggests that the fluxes of relativistic electrons with energies in the range 0.6 ≤ E ≤ 2.0 MeV in the region 4.25 ≤ L ≤ 4.75 have an upper bound. In contrast, further out and at higher energies the fluxes of relativistic electrons are largely unbounded.

Extreme relativistic electron fluxes at geosynchronous orbit: Analysis of GOES E > 2 MeV electrons
Nigel P. **Meredith**, Richard B. Horne, John D. Isles, Juan V. Rodriguez
Space Weather Volume 13, Issue 3 March **2015** Pages 170–184
Relativistic electrons (E > 1 MeV) cause internal charging on satellites and are an important space weather hazard. A key requirement in space weather research concerns extreme events and knowledge of the largest flux expected to be encountered over the lifetime of a satellite mission. This is interesting both from scientific and practical points of view since satellite operators, engineers, and the insurance industry need this information to better evaluate the effects of extreme events on their spacecraft. Here we conduct an extreme value analysis of daily averaged E > 2 MeV electron fluxes from the Geostationary Operational Environmental Satellites (GOES) during the 19.5 year

period from 1 January 1995 to 30 June 2014. We find that the daily averaged flux measured at GOES West is typically a factor of about 2.5 higher than that measured at GOES East, and we conduct independent analyses for these two locations. The 1 in 10, 1 in 50, and 1 in 100 year daily averaged E > 2 MeV electron fluxes at GOES West are 1.84 ×105, 5.00 ×105, and 7.68 ×105 cm−2 s−1 sr−1, respectively. The corresponding fluxes at GOES East are 6.53 ×104, 1.98 ×105, and 3.25 ×105 cm−2 s−1 sr−1, respectively. The largest fluxes seen during the 19.5 year period on 29 July 2004 were particularly extreme and were seen by satellites at GOES West and GOES East. The extreme value analysis suggests that this event was a 1 in 50 year event.

Metcalf, T.R., Alexander, D.: 1999, Coronal trapping of energetic are particles: Yohkoh/HXT observations. *Astrophys. J.* **522**, 1108. DOI. ADS.

The Large Energetic Storm Particle Event of September 18, 2017 Observed by STEREO-A R. **Mewaldt**, C. Cohen, G. Li, J. Hu, D. Lario and E. Christian
PoS(ICRC2019) id. 1120 **2019**
https://pos.sissa.it/358/1120/pdf
Solar Cycle 24 solar activity ended during September 2017 with a series of "bangs" that included four X-Class flares, a record-breaking 3000 km/s CME, and a large ground-level event, all recorded by Earth-based observers. Less well known is the eruption of a far-side CME from the same active region on September 17, which resulted in a spectacular energetic storm particle (ESP) event observed on September 18-19 at STEREOWe report the time history, energy spectra, and composition of ~0.1 to 100 MeV/nucleon ions and 0.1 to 4 MeV electrons measured during this period by the SEPT, LET and HET instruments on STEREO-A. We also compare this event with the intense **July 23, 2012** ESP event also observed by STEREO-A. The composition of ESP ions will be compared with possible seed-particle sources. Finally, these observations will serve as a basis for a modeling effort to be reported by Hu et al. at this conference.

Investigating the Causes of Solar-Cycle Variations in Solar Energetic Particle Fluences and Composition
Mewaldt, Richard; Cohen, Christina; Mason, Glenn M.; von Rosenvinge, Tycho; Li, Gang; Smith, Charles; Vourlidas, Angelos
Joint American Astronomical Society/American Geophysical Union Triennial Earth-Sun Summit, meeting #1, #401.06, 04/**2015**
Measurements with ACE, STEREO, and GOES show that the number of large Solar Energetic Particle (SEP) events in solar cycle 24 is reduced by a factor of ~2 compared to this point of cycle 23, while the fluences of >10 MeV/nuc ions from H to Fe are reduced by factors ranging from ~4 to ~10. We investigate the origin of these cycle-to-cycle differences by evaluating possible factors that include properties of the associated CMEs, seed particle densities, and the interplanetary magnetic field strength and turbulence levels. These properties will be evaluated in the context of existing SEP acceleration models.

Solar energetic particles and their variability from the sun and beyond
Mewaldt, R. A.; Cohen, C. M. S.; Mason, G. M.; von Rosenvinge, T. T.; Leske, R. A.; Luhmann, J. G.; Odstrcil, D.; Vourlidas, A.
SOLAR WIND 13: Proceedings of the Thirteenth International Solar Wind Conference. AIP Conference Proceedings, Volume 1539, pp. 116-121 (**2013**).
With the onset of solar cycle 24 activity STEREO and near-Earth spacecraft are now measuring many multi-spacecraft solar particle events. We present examples of time-intensity distributions, energy spectra, fits to longitude distributions, a combined imaging/in-situ study, and MHD modeling of one event. Implications of these new results are discussed.

Cosmic Rays in the Heliosphere: Requirements for Future Observations **Review**
R. A. **Mewaldt**
Space Science Reviews, online first **2012**, **File**
Since the publication of Cosmic Rays in the Heliosphere in 1998 there has been great progress in understanding how and why cosmic rays vary in space and time. This paper discusses measurements that are needed to continue advances in relating cosmic ray variations to changes in solar and interplanetary activity and variations in the local interstellar environment. Cosmic ray acceleration and transport is an important discipline in space physics and astrophysics, but it also plays a critical role in defining the radiation environment for humans and hardware in space, and is critical to efforts to unravel the history of solar activity. Cosmic rays are measured directly by balloon-borne and space instruments, and indirectly by ground-based neutron, muon and neutrino detectors, and by measurements of cosmogenic isotopes in ice cores, tree-rings, sediments, and meteorites. The topics covered here include: what we can learn from the deep 2008–2009 solar minimum, when cosmic rays reached the highest intensities of the space

era; the implications of 10Be and 14C isotope archives for past and future solar activity; the effects of variations in the size of the heliosphere; opportunities provided by the Voyagers for discovering the origin of anomalous cosmic rays and measuring cosmic-ray spectra in interstellar space; and future space missions that can continue the exciting exploration of the heliosphere that has occurred over the past 50 years.

Energy Spectra, Composition, and Other Properties of Ground-Level Events During Solar Cycle 23

R. A. **Mewaldt**, M. D. Looper, C. M. S. Cohen, D. K. Haggerty, A. W. Labrador, R. A. Leske, G. M. Mason, J. E. Mazur and T. T. von Rosenvinge

Space Science Reviews, 171, Numbers 1-4, 97-120, **2012**, DOI: 10.1007/s11214-012-9884-2 **File**

sci-hub.se/10.1007/s11214-012-9884-2

https://link.springer.com/content/pdf/10.1007/s11214-012-9884-2.pdf

We report spacecraft measurements of the energy spectra of solar protons and other solar energetic particle properties during the 16 Ground Level Events (GLEs) of Solar Cycle 23. The measurements were made by eight instruments on the ACE, GOES, SAMPEX, and STEREO spacecraft and extend from ~0.1 to ~500–700 MeV. All of the proton spectra exhibit spectral breaks at energies ranging from ~2 to ~46 MeV and all are well fit by a double power-law shape. A comparison of GLE events with a larger sample of other solar energetic particle (SEP) events shows that the typical spectral indices are harder in GLE events, with a mean slope of −3.18 at >40 MeV/nuc. In the energy range 45 to 80 MeV/nucleon about ~50 % of GLE events have properties in common with impulsive 3He-rich SEP events, including enrichments in Ne/O, Fe/O, 22Ne/20Ne, and elevated mean charge states of Fe. These 3He-rich events contribute to the seed population accelerated by CME-driven shocks. An analysis is presented of whether highly-ionized Fe ions observed in five events could be due to electron stripping during shock acceleration in the low corona. Making use of stripping calculations by others and a coronal density model, we can account for events with mean Fe charge states of ⟨Q Fe⟩≈+20 if the acceleration starts at ~1.24–1.6 solar radii, consistent with recent comparisons of CME trajectories and type-II radio bursts. In addition, we suggest that gradual stripping of remnant ions from earlier large SEP events may also contribute a highly-ionized suprathermal seed population. We also discuss how observed SEP spectral slopes relate to the energetics of particle acceleration in GLE and other large SEP events. **6-11-1997, 2-5-1998, 6-5-1998, 24-8-1998, 14-7-2000, 15-4-2001, 18-4-2001, 4-11-2001, 26-12-2001, 24-08-2002, 28-10-2003, 29-10-2003, 2-11-2003, 17-01-2005, 20-01-2005, 13-12-2006,**

STEREO OBSERVATIONS OF ENERGETIC NEUTRAL HYDROGEN ATOMS DURING THE 2006 DECEMBER 5 SOLAR FLARE

R. A. **Mewaldt**, R. A. Leske, E. C. Stone, A. F. Barghouty, A. W. Labrador, C. M. S. Cohen, A. C. Cummings, A. J. Davis, T. T. von Rosenvinge, and M. E. Wiedenbeck

ApJL 693 L11-L15, **2009**

http://www.iop.org/EJ/abstract/1538-4357/693/1/L11

We report the discovery of energetic neutral hydrogen atoms (ENAs) emitted during the X9 solar event of **2006 December 5.** Beginning ~1 hr following the onset of this E79 flare, the Low Energy Telescopes (LETs) on both the STEREO A and B spacecraft observed a sudden burst of 1.6-15 MeV protons beginning hours before the onset of the main solar energetic particle event at Earth. More than 70% of these particles arrived from a longitude within ±10° of the Sun, consistent with the measurement resolution. The derived emission profile at the Sun had onset and peak times remarkably similar to the GOES soft X-ray profile and continued for more than an hour. The observed arrival directions and energy spectrum argue strongly that the particle events < 5 MeV were due to ENAs. To our knowledge, this is the first reported observation of ENA emission from a solar flare/coronal mass ejection. Possible origins for the production of ENAs in a large solar event are considered. We conclude that the observed ENAs were most likely produced in the high corona and that charge-transfer reactions between accelerated protons and partially stripped coronal ions are an important source of ENAs in solar events.

On the Differences in Composition between Solar Energetic Particles and SolarWind

R.A. **Mewaldt** · C.M.S. Cohen · G.M. Mason · A.C. Cummings · M.I. Desai · R.A. Leske · J. Raines · E.C. Stone · M.E. Wiedenbeck · T.T. von Rosenvinge · T.H. Zurbuchen

Space Sci Rev (**2007**) 130: 207–219

http://www.springerlink.com/content/p054752525607622/fulltext.pdf

Although the average composition of solar energetic particles (SEPs) and the bulk solar wind are similar in a number of ways, there are key differences which imply that solar wind is not the principal seed population for SEPs accelerated by coronal mass ejection (CME) driven shocks. This paper reviews these composition differences and considers the composition of other possible seed populations, including coronal material, impulsive flare material, and interplanetary CME material.

Solar Energetic Particle Composition, Energy Spectra, and Space Weather
R. A. **Mewaldt**
Space Science Reviews (**2006**) 124: 303–316
http://www.springerlink.com/content/v031701353m13161/
Recent progress in measuring the composition and energy spectra of solar energetic particles (SEPs) accelerated by CME-driven shocks is reviewed, including a comparison of the observed charge-to-mass dependence of breaks in SEP spectra with model predictions. Also discussed is a comparison of SEP and CME kinetic energies in seventeen large SEP events, and estimates of the SEP radiation dose that astronauts would be subject to once they venture outside the protective cover of Earth's magnetosphere.

Small Size Ground Level Enhancements During Solar Cycle 24
Leonty I. **Miroshnichenko**, Chuan Li & Victor G. Yanke
Solar Physics volume 295, Article number: 102 (**2020**)
https://link.springer.com/content/pdf/10.1007/s11207-020-01659-3.pdf
We continue the systematical empirical search for small size ground level enhancements (GLEs) (also called "hidden" or sub-GLEs) using data from ground-based instruments for Solar Cycle 24. The starting point of this research is the hypothesis that small size GLEs may be indicative of the acceleration of solar energetic particles (SEPs) by shocks driven by coronal mass ejections (CMEs). A crucial parameter for solving the problem seems to be the SEP energy spectrum at the Earth's orbit measured by spacecraft detectors and ground-based neutron monitors (NMs). We try to recover the SEP spectrum in a wide range of energies – from GOES non-relativistic energy channels to the relativistic range from NM data, as well as from relevant measurements of some ground-based non-standard (mainly muon) cosmic ray detectors. The main factors that determine the SEP intensity and spectrum shape near the Earth are the source power, location, and/or shock strength. Every "suspected" small GLE is analyzed separately. Finally, we compile the list of statistically confirmed small GLEs and give our interpretation within the frame of the above hypothesis. The three considered models of shock wave acceleration are not suitable to physically and unambiguously explain some features of the observed solar cosmic ray (SCR) spectra. The results emphasize the importance of studying the GLEs of low intensity (hidden GLEs) for better understanding the SEP spectrum formation, especially in the range of relativistic energies. The GLE events from behind-the-limb sources are of special interest. **7 Mar 2011, 23 Jan 2012, 27–28 January 2012, 07 Mar 2012, 13 Mar 2012, 17 May 2012, 23 Jul 2012, 22 May 2013, 19 Nov 2013, 06 Jan 2014. 07(09) Jan 2014, 07 Jun 2015, 22 Jun 2015, 29 Oct 2015, 10 Sep 2017**
Table 1 Observed, predicted, and identified weak GLEs of SC 24.

Retrospective analysis of GLEs and estimates of radiation risks **Review**
Leonty I. **Miroshnichenko**
J. Space Weather Space Clim. **2018**, 8, A52
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170020.pdf
sci-hub.ru/10.1051/swsc/2018042
28 February 2017 marked 75 years since the first confident registration of solar cosmic rays (SCRs), i.e., accelerated solar particles with energies from about 106 to ~1010 ÷ 1011 eV. Modern state of the problems related to the studies of Ground Level Enhancements (GLEs) of relativistic SCRs is critically analyzed based on available direct and proxy data. We are also taking into account extremely large fluxes of non-relativistic solar energetic particles (SEPs). Both kinds of SCR events are of great astrophysical and geo-scientific (geophysical) interests. A number of the GLE properties (total statistics, occurrence rate, longitude distribution, ranking of GLEs, a number of specific GLEs – so-called "rogue" SEP events etc.) are discussed in some detail. We note also the problems of GLE identification (definition) by ground-based observations, the difficulties in the studies of weak ("hidden", or sub-) GLEs etc. One of serious challenges to the problem of radiation hazard in space is a lack of a clear, unambiguous relation between the fluxes (fluences) of relativistic SCR and non-relativistic SEPs. Special attention is paid to the recent debate on the validity, origin and properties of the "ancient" events AD775, AD994, AD1859 (Carrington event) and BC3372. We demonstrate that, in spite of existing uncertainties in proton fluences above 30 MeV, all of them are fitted well by a unique distribution function, at least, with the present level of solar activity. Extremely large SEP events are shown to obey a probabilistic distribution on their fluences with a sharp break in the range of large fluences (or low probabilities). The studies of this kind may be extended for periods with different levels of solar activity in the past and/or in the future. Dose rates at aircraft altitudes are also demonstrated during some GLEs. Several examples of using the SCR data and GLE properties in radiation prediction schemes are considered.

Size Distributions of Solar Proton Events: Methodological and Physical Restrictions
L. I. **Miroshnichenko**, V. G. Yanke
Solar Phys. Volume 291, Issue 12, pp 3685–3704 **2016**
http://link.springer.com/article/10.1007/s11207-016-1002-2
Based on the new catalogue of solar proton events (SPEs) for the period of 1997 – 2009 (Solar Cycle 23) we revisit the long-studied problem of the event-size distributions in the context of those constructed for other solar-flare parameters. Recent results on the problem of size distributions of solar flares and proton events are briefly reviewed. Even a cursory acquaintance with this research field reveals a rather mixed and controversial picture. We concentrate on three main issues: i) SPE size distribution for >10 MeV protons in Solar Cycle 23; ii) size distribution of >1 GV proton events in 1942 – 2014; iii) variations of annual numbers for >10 MeV proton events on long time scales (1955 – 2015). Different results are critically compared; most of the studies in this field are shown to suffer from vastly different input datasets as well as from insufficient knowledge of underlying physical processes in the SPEs under consideration. New studies in this field should be made on more distinct physical and methodological bases. It is important to note the evident similarity in size distributions of solar flares and superflares in Sun-like stars.

Solar Cosmic Rays **Book**
Fundamentals and Applications
Series: Astrophysics and Space Science Library, Vol. 405
Miroshnichenko, Leonty
2nd ed. **2015**, XV, 521 p. 162 illus., 17 illus. in color.
http://link.springer.com/book/10.1007%2F978-3-319-09429-8

Extreme fluxes in solar energetic particle events: Methodological and physical limitations
L.I. **Miroshnichenko**, R.A. Nymmik
Radiation Measurements 61 (**2014**) 6-15
http://www.sciencedirect.com/science/article/pii/S1350448713003806
In this study, all available data on the largest solar proton events (SPEs), or extreme solar energetic particle (SEP) events, for the period from 1561 up to now are analyzed. Under consideration are the observational, methodological and physical problems of energy-spectrum presentation for SEP fluxes (fluences) near the Earth's orbit. Special attention is paid to the study of the distribution function for extreme fluences of SEPs by their sizes. The authors present advances in at least three aspects: 1) a form of the distribution function that was previously obtained from the data for three cycles of solar activity has been completely confirmed by the data for 41 solar cycles; 2) early estimates of extremely large fluences in the past have been critically revised, and their values were found to be overestimated; and 3) extremely large SEP fluxes are shown to obey a probabilistic distribution, so the concept of an "upper limit flux" does not carry any strict physical sense although it serves as an important empirical restriction. SEP fluxes may only be characterized by the relative probabilities of their appearance, and there is a sharp break in the spectrum in the range of large fluences (or low probabilities). It is emphasized that modern observational data and methods of investigation do not allow, for the present, the precise resolution of the problem of the spectrum break or the estimation of the maximum potentialities of solar accelerator(s). This limitation considerably restricts the extrapolation of the obtained results to the past and future for application to the epochs with different levels of solar activity.

Solar Cosmic Rays: 70 Years of Ground-Based Observations **Review**
L. I. **Miroshnichenko***a*, *b*, E. V. Vashenyuk*c*, and J. A. Perez_Peraza*d*
Geomagnetism and Aeronomy, ***2013***, *Vol. 53, No. 5, pp. 541–560.* ***File***
Geomagnetizm i Aeronomiya, ***2013***, *Vol. 53, No. 5, pp. 579–600.* ***File***
The main data have been summarized, and the results, achieved using data from the worldwide network during the entire period of ground-based observations of solar cosmic rays (SCRs) from February 28, 1942, when they were discovered, have been generalized. The methods and equipment for registering SCRs have been described. The physical, methodical, and applied aspects, related to the SCR generation, as well as the SCR interaction with the solar atmosphere, transport in the IMF, motion in the Earth's magnetosphere, and the affect on the Earth's atmosphere, have been discussed. It has been indicated that the fundamental results were achieved in this field of space physics during 70 years of studies. Special attention has been paid to up_to_date models and concepts of ground_level enhancement (GLE). The most promising tendencies in the development and application of this effective method of solar–terrestrial physics have been outlined.

ASTROPHYSICAL ASPECTS IN THE STUDIES OF SOLAR COSMIC RAYS
L. I. **MIROSHNICHENKO** and J. A. PEREZ-PERAZA

International Journal of Modern Physics A, Vol. 23, No. 1 (**2008**) 1–141, **File**

This **review** paper comprises main concepts, available observational data and recent theoretical results related to astrophysical aspects of particle acceleration at/near the Sun and extreme capacities of the solar accelerator(s). We summarize underground and ground-based observations of solar cosmic rays (SCR) accumulated since 1942, direct spacecraft measurements of solar energetic particles (SEP) near the Earth's orbit, indirect information on the SCR variations in the past, and other relevant astrophysical, solar and geophysical data. The list of the problems under discussion includes: upper limit spectrum (ULS) for solar cosmic rays; maximum energy (rigidity), *Em* (*Rm*), of particles accelerated at/near the Sun; production of the flare neutrinos; energetics of SCR and solar flares; production of flare neutrons and gamma rays; charge states and elemental abundances of accelerated solar ions; coronal mass ejections (CME's) and extended coronal structures in acceleration models; magnetic reconnection in acceleration scenarios; size (frequency) distributions of solar proton events (SPE) and stellar flares; occurrence probability of giant flares; archaeology of solar cosmic rays. The discussion allows us to outline a series of interesting conceptual and physical associations of SCR generation with the high-energy processes at other stars. The most reliable estimates of various parameters are given in each of research fields mentioned above; a set of promising lines of future studies is highlighted. A great importance of SCR data for resolving some general astrophysical problems is emphasized.

Spectra and Anisotropy of Solar Energetic Protons During GLE #65 on 28 October, 2003 and GLE #66 on 29 October, 2003.

Mishev, A.L., Koldobskiy, S.A., Larsen, N., Ilya G. Usoskin1,2

Sol Phys 299, 24 (**2024**).

https://doi.org/10.1007/s11207-024-02269-z

https://link.springer.com/content/pdf/10.1007/s11207-024-02269-z.pdf

Solar Cycle 23 was the most active in ground-level enhancements (GLEs) with 16 events registered by the global neutron monitor network. In this paper, we study a very active period in October–November, 2003, which revealed an intense solar activity burst that led to several eruptive processes and produced a sequence of three GLEs. By applying state-of-the-art modelling to records from the global neutron monitor network as well as space-borne data, we derived the spectral and anisotropy characteristics of accelerated solar protons during the **GLE #65 event on 28 October, 2003 and GLE #66 on 29 October, 2003**. The spectra and the pitch angle distributions are obtained with a 5-min time resolution, providing their dynamical evolution throughout the event. The spectra are parameterised with a modified power-law rigidity spectrum, whilst the angular distribution with a Gaussian. The constraints and uncertainties of the derived characteristics are evaluated by corresponding modelling.

Spectra and anisotropy during GLE # 4 on 19 November 1949 derived using historical records

A. **Mishev**, H. Hayakawa, I. Usoskin, K. McCraken, M. Shea and D. Smart

PoS(ICRC2023)1234 pdf **2023**

https://pos.sissa.it/444/1234/pdf

A methodological study of solar energetic particles provides the necessary basis to understand the mechanisms of their acceleration and propagation in interplanetary space. According to the current paradigm, following solar eruptive processes, such as solar flares and/or coronal mass ejections, solar ions can be accelerated to high energies. In most cases, the energy of the accelerated solar ions is several tens of MeV/n, yet in some cases, it exceeds 100 MeV/n and occasionally reaches the GeV/n range. In the latter case, the energy is sufficient for solar ions to generate an atmospheric cascade in the Earth's atmosphere with secondary particles reaching the ground and registered by ground-based detectors. This particular class of events is known as ground-level enhancements (GLEs). At present, 73 GLEs in total have been detected, starting with the Forbush first observations in 1942. The first three events were registered only by ionization chambers; the fourth event was recorded by ionization chambers, muon telescopes, and a non-standard neutron monitor. Using the historical records of ionization chambers, namely their count-rate increases, and a state-of-the-art model, we assessed the spectra of GLE # 4 that occurred on 19 November 1949. We employed a method adapted from neutron monitor data analysis, that is, modelling the ionization chamber responses and other detectors and optimization over the experimental count rate increases. Hence, we assessed the GLE # 4 spectra, hgere presenting preliminary results.

The Easter GLE on 15 April 2001, spectra and angular distribution- new revised results and related space weather effects

A. **Mishev** and N.P. Larsen

PoS(ICRC2023)1235 pdf **2023**

https://pos.sissa.it/444/1235/pdf

A specific interest represents solar protons possessing energy enough to induce an atmospheric cascade in the Earth's atmosphere, whose secondary particles reach the ground, eventually registered by ground-based detectors e.g. neutron monitors. This class of events is known as ground-level enhancements (GLEs). The solar cycle 23 provided several strong GLEs, the first observed on 14 July 2000 (the Bastille day event), while the last was observed on 13 December 2006. The systematic study of relativistic SEPs provides an important basis to understand their acceleration and propagation in interplanetary space, as well as to quantify the related space weather effects such as radiation dose at flight altitudes. The Easter event on 15 April 2001 is among the strongest and accordingly, it is the focus of this study. Here we performed a precise analysis of neutron monitor records and derived the spectral and angular characteristics of the solar energetic particles during this event. We modeled the particle propagation in the Earth's magnetosphere and atmosphere using a newly computed and verified NM yield function computed at several altitudes above sea level. The solar protons spectra and pitch angle distributions were obtained in their dynamical development throughout the event. We assessed the radiation dose at flight altitude and compared the results with experimental measurements performed with the Liulin gamma probe

High-Resolution Spectral and Anisotropy Characteristics of Solar Protons During the GLE N∘73 on 28 October 2021 Derived with Neutron-Monitor Data Analysis

Alexander L. **Mishev**, Leon G. Kocharov, Sergey A. Koldobskiy, Nicholas Larsen, Esa Riihonen, Rami Vainio & Ilya G. Usoskin

Solar Physics volume 297, Article number: 88 (**2022**)

https://link.springer.com/content/pdf/10.1007/s11207-022-02026-0.pdf

https://doi.org/10.1007/s11207-022-02026-0

The first ground-level enhancement of the current Solar Cycle 25 occurred on 28 October 2021. It was observed by several space-borne and ground-based instruments, specifically neutron monitors. A moderate count-rate increase over the background was observed by high-altitude polar stations on the South Pole and Dome C stations at the Antarctic plateau. Most of the neutron monitors registered only marginal count-rate increases. Using detrended records and employing a method verified by direct space-borne measurements, we derive the rigidity spectra and angular distributions of the incoming solar protons in the vicinity of Earth. For the analysis, we employed a newly computed and parameterized neutron-monitor yield function. The rigidity spectra and anisotropy of solar protons were obtained in their time evolution throughout the event. A comparison with the Solar and Heliospheric Observatory/Energetic and Relativistic Nuclei and Electron (SOHO/ENRE) experiment data is also performed. We briefly discuss the results derived from our analysis.

About the Altitude Profile of the Atmospheric Cut-Off of Cosmic Rays: New Revised Assessment

Alexander **Mishev** & Stepan Poluianov

Solar Physics volume 296, Article number: 129 (**2021**)

https://link.springer.com/content/pdf/10.1007/s11207-021-01875-5.pdf

https://doi.org/10.1007/s11207-021-01875-5

Cosmic rays, high-energy subatomic particles of extraterrestrial origin, are systematically measured by space-borne and ground-based instruments. A specific interest is paid to high-energy ions accelerated during solar eruptions, so-called solar energetic particles. In order to build a comprehensive picture of their nature, it is important to fill the gap and inter-calibrate ground-based and space-borne instruments. Here, we focus on ground-based detectors, specifically neutron monitors, which form a global network and provide continuous recording of cosmic ray intensity and its variability, used also to register relativistic solar energetic particles. The count rate of each neutron monitor is determined by the geomagnetic and atmospheric cut-offs, both being functions of the location. Here, on the basis of Monte Carlo simulations with the PLANETOCOSMICS code and by the employment of a new verified neutron monitor yield function, we assessed the atmospheric cut-off as a function of the altitude, as well as for specific stations located in the polar region. The assessed in this study altitude profile of the atmospheric cut-off for primary cosmic rays builds the basis for the joint analysis of strong solar proton events with different instruments and allows one to clarify recent definitions and related discussions about the new sub-class of events, so-called sub-ground-level enhancements (sub-GLEs).

GLE # 67 Event on 2 November 2003: An Analysis of the Spectral and Anisotropy Characteristics Using Verified Yield Function and Detrended Neutron Monitor Data

Alexander L. **Mishev**, Sergey A. Koldobskiy, Leon G. Kocharov & Ilya G. Usoskin

Solar Physics volume 296, Article number: 79 (**2021**)

https://link.springer.com/content/pdf/10.1007/s11207-021-01832-2.pdf

https://doi.org/10.1007/s11207-021-01832-2

During Solar Cycle 23 16 ground-level enhancement events were registered by the global neutron monitor network. In this work we focus on the period with increased solar activity during late October – early November 2003 producing a sequence of three events, specifically on ground-level enhancement GLE 67 on 2 November 2003. On the basis of an analysis of neutron monitor and space-borne data we derived the spectra and pitch-angle distribution of high-energy solar particles with their dynamical evolution throughout the event. According to our analysis, the best fit of the spectral and angular properties of solar particles was obtained by a modified power-law rigidity spectrum and a double Gaussian, respectively. The derived angular distribution is consistent with the observations where an early count rate increase at Oulu neutron monitor with asymptotic viewing direction in the anti-Sun direction was registered. The quality of the fit and model constraints were assessed by a forward modeling. The event integrated particle fluence was derived using two different methods. The derived results are briefly discussed.

Application of the verified neutron monitor yield function for an extended analysis of the ground level enhancement GLE # 71 on May 17, 2012

A. L. **Mishev** , S. A. Koldobskiy , I. G. Usoskin , L. G. Kocharov , G. A. Kovaltsov
Space Weather **Volume19, Issue2** e2020SW002626 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020SW002626
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020SW002626

Intense solar activity was observed in May 2012. A notable ground level enhancement (GLE) was registered on May, 17, 2012 by several space-borne instruments as well as on ground by neutron monitors (NMs). This event is known as GLE # 71. Here, we derived the spectral and angular characteristics, and apparent source position of the solar protons during the GLE # 71, employing verified newly computed neutron monitor yield function and sophisticated unfolding procedure. We considerably improved the previously derived information about the spectra and angular distribution, namely the precision, time span, and time resolution of the derived characteristics, specifically during the event onset and late phase. A comparison with direct measurements, with the PAMELA experiment, of the particle fluence was performed and good agreement between NM and direct space-borne data analysis was achieved. Subsequently, we computed the effective dose rates in the polar region at several altitudes during the event using the derived rigidity spectra of the solar protons as a reliable input for the corresponding radiation model. The contribution of the galactic cosmic rays and solar protons to the exposure is explicitly considered. We computed the integrated exposure during the event and discussed the exposure of crew members/passengers to radiation at several altitudes.

Current status and possible extension of the global neutron monitor network **Review**

Alexander **Mishev**2* and Ilya Usoskin2
J. Space Weather Space Clim. **2020**, 10, 17
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200007.pdf

The global neutron monitor network has been successfully used over several decades to study cosmic ray variations and fluxes of energetic solar particles. Nowadays, it is used also for space weather purposes, e.g. alerts and assessment of the exposure to radiation. Here, we present the current status of the global neutron monitor network. We discuss the ability of the global neutron monitor network to study solar energetic particles, specifically during large ground level enhancements. We demonstrate as an example, the derived solar proton characteristics during ground level enhancements GLE #5 and the resulting effective dose over the globe at a typical commercial jet flight altitude of 40 kft (≈12,200 m) above sea level. We present a plan for improvement of space weather services and applications of the global neutron monitor network, specifically for studies related to solar energetic particles, namely an extension of the existing network with several new monitors. We discuss the ability of the optimized global neutron monitor network to study various populations of solar energetic particles and to provide reliable space weather services. **GLE#5 23 Feb 1956**

Updated Neutron-Monitor Yield Function: Bridging Between In Situ and Ground-Based Cosmic Ray Measurements

Alexander L. **Mishev** , Sergey A. Koldobskiy, Gennady A. Kovaltsov, Agnieszka Gil, Ilya G. Usoskin
JGR Volume125, Issue2 February **2020** e2019JA027433
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019JA027433

An updated yield function for a standard NM64 neutron monitor (NM) is computed and extended to different atmospheric depths from sea level to 500 g/cm ^{2} (~5.7 km altitude) and is presented as lookup tables and a full parametrization. The yield function was validated using the cosmic ray spectra directly measured in space by the AMS-02 experiment during the period May 2011 through May 2017 and confronted with count rates of all NM64-type NMs being in operation during this period. Using this approach, stability of all the selected NMs was analyzed for the period 2011–2017. Most of NMs appear very stable and suitable for studies of long-term solar modulation of cosmic rays. However, some NMs suffer from instabilities like trends, apparent jumps, or strong seasonal waves in the count rates.

Preface to measurement, specification and forecasting of the Solar Energetic Particle (SEP) environment and Ground Level Enhancements (GLEs) **Review**

Alexander **Mishev**1,2* and Piers Jiggens3
J. Space Weather Space Clim. **2019**, 9, E1
https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180076.pdf
The Sun emits energetic particles following eruptive events such as solar flares and Coronal Mass Ejections (CMEs). Solar Energetic Particles (SEPs) arrive in bursts known as Solar Particle Events (SPEs), which penetrate into the Earth's magnetosphere. SEPs with large enough energy induce a complicated atmospheric cascade, which secondary particles lead to an enhancement of count rate of ground-based detectors e.g. Neutron Monitors (NMs). This class of SEPs is therefore referred as Ground Level Enhancements (GLEs). The characterisation of the high-energy SEPs environment with corresponding space weather effects is important for space flights, aviation, and satellite industry. In this topical issue recent developments, addressing important user needs in the space radiation environment domain are published. Some articles are relevant to the specification of the SEP environment whilst others focus on space weather prediction of SEP fluxes. Catalogues based on measurement and processing of SEPs including ground-based data, and modelling of aircrew radiation exposure during major events are also presented.

Assessment of the Radiation Environment at Commercial Jet-Flight Altitudes During GLE 72 on 10 September 2017 Using Neutron Monitor Data

A. L. **Mishev** , I. G. Usoskin
Space Weather Volume 16, Issue 12, pp. 1921-1929 **2018**
sci-hub.tw/10.1029/2018SW001946
As a result of intense solar activity during the first 10 days of September, a ground level enhancement occurred on 10 September 2017. Here we computed the effective dose rates in the polar region at several altitudes during the event using the derived rigidity spectra of the energetic solar protons. The contribution of different populations of energetic particles, namely, galactic cosmic rays and solar protons, to the exposure is explicitly considered and compared. We also assessed the exposure of a crew members/passengers to radiation at different locations and at several cruise flight altitudes and calculated the received doses for two typical intercontinental flights. The estimated received dose during a high latitude, 40 kft, ∼10-hr flight is ∼100 μSv.

First Analysis of Ground-Level Enhancement (GLE) 72 on 10 September 2017: Spectral and Anisotropy Characteristics

A. **Mishev**, I. Usoskin, O. Raukunen, M. Paassilta, E. Valtonen, L. Kocharov, R. Vainio
Solar Physics October **2018**, 293:136
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1354-x.pdf
sci-hub.tw/10.1007/s11207-018-1354-x
https://arxiv.org/pdf/1810.10536.pdf
Using data obtained with neutron monitors and space-borne instruments, we analyzed the second ground-level enhancement (GLE) of Solar Cycle 24, namely the event of 10 September 2017 (GLE 72), and derived the spectral and angular characteristics of associated GLE particles. We employed a new neutron-monitor yield function and a recently proposed model based on an optimization procedure. The method consists of simulating particle propagation in a model magnetosphere in order to derive the cutoff rigidity and neutron-monitor asymptotic directions. Subsequently, the rigidity spectrum and anisotropy of GLE particles are obtained in their dynamical evolution during the event on the basis of an inverse-problem solution. The derived angular distribution and spectra are discussed briefly.

Assessment of spectral and angular characteristics of sub-GLE events using the global neutron monitor network

Alexander **Mishev**1*, Stepan Poluianov1,2 and Ilya Usoskin1,2
J. Space Weather Space Clim. **2017**, 7, A28
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170026.pdf
New recently installed high-altitude polar neutron monitors (NMs) have made the worldwide NM network more sensitive to strong solar energetic particle (SEP) events, registered at ground level, namely ground-level enhancement (GLE) events. The DOMC/B and South Pole NMs in addition to marginal cut-off rigidity also possess lower atmospheric cut-off compared to the sea level. As a result, the two high-altitude polar NM stations are able to detect lower energy SEP events, which most likely would not be registered by the other (near sea level) NMs. Here, we consider several candidates for such type of events called sub-GLEs. Using the worldwide NM database (NMDB) records and an optimization procedure combined with simulation of the global NM network response, we assess the spectral and angular characteristics of sub-GLE particles. With the estimated spectral characteristics as an input, we evaluate the effective dose rate in polar and sub-polar regions at typical commercial flight altitude. Hence, we demonstrate that the global NM network is a useful tool to estimate important space weather effects, e.g., the aircrew exposure due to cosmic rays of galactic and/or solar origins. **07/03/2012, 06/01/2014, 29/10/2015**

Table 1. Derived spectral and angular characteristics of sub-GLE events

Analysis of the Ground-Level Enhancements on 14 July 2000 and 13 December 2006 Using Neutron Monitor Data

Alexander **Mishev**1* and Ilya Usoskin

Solar Phys. Volume 291, Issue 4, pp 1225-1239 **2016**

http://arxiv.org/pdf/1603.08918.pdf

On the basis of neutron monitor data, we estimate the energy spectrum, anisotropy axis direction, and pitch-angle distribution of solar energetic particles during two major ground-level enhancements (GLE 59 on **14 July 2000** and GLE 70 on **13 December 2006**). For the analysis we used a newly computed neutron monitor yield function. The method consists of several consecutive steps: definition of the asymptotic viewing cones of neutron monitor stations considered for the data analysis by computing the cosmic ray particle propagation in a model magnetosphere with the MAGNETOCOSMICS code, computing the neutron monitor model responses, and deriving the solar energetic particle characteristics on the basis of inverse problem solution. The pitch-angle distribution and rigidity spectrum of high-energy protons are obtained as a function of time in the course of ground-level enhancements. A comparison with previously reported results is performed and reasonable agreement is achieved. A discussion of the obtained results is included.

Erratum that is related to the presentation of Figure 6, 2016, Volume 291, Issue 5, pp 1579–1580

Numerical model for computation of effective and ambient dose equivalent at flight altitudes
Application for dose assessment during GLEs

Alexander **Mishev**1* and Ilya Usoskin

J. Space Weather Space Clim., 5, A10 (**2015**)

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140051.pdf

A numerical model for assessment of the effective dose and ambient dose equivalent produced by secondary cosmic ray particles of galactic and solar origin at commercial aircraft altitudes is presented. The model represents a full chain analysis based on ground-based measurements of cosmic rays, from particle spectral and angular characteristics to dose estimation. The model is based on newly numerically computed yield functions and realistic propagation of cosmic ray in the Earth magnetosphere. The yield functions are computed using a straightforward full Monte Carlo simulation of the atmospheric cascade induced by primary protons and α-particles and subsequent conversion of secondary particle fluence (neutrons, protons, gammas, electrons, positrons, muons and charged pions) to effective dose or the ambient dose equivalent. The ambient dose equivalent is compared with reference data at various conditions such as rigidity cut-off and level of solar activity. The method is applied for computation of the effective dose rate at flight altitude during the ground level enhancement of **13 December 2006**. The solar proton spectra are derived using neutron monitor data. The computation of the effective dose rate during the event explicitly considers the derived anisotropy i.e. the pitch angle distribution as well as the propagation of the solar protons in the magnetosphere of the Earth.

Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71

A.L. **Mishev**, F. Adibpourb, I.G. Usoskinc, d, E. Felsbergerb

Advances in Space Research, Volume 55, Issue 1, 1 January **2015**, Pages 354–362

http://www.sciencedirect.com/science/article/pii/S0273117714003822

A new numerical model of estimating and monitoring the exposure of personnel due to secondary cosmic radiation onboard aircraft, in accordance with radiation safety standards as well as European and national regulations, has been developed. The model aims to calculate the effective dose at flight altitude (39,000 ft) due to secondary cosmic radiation of galactic and solar origin. In addition, the model allows the estimation of ambient dose equivalent at typical commercial airline altitudes in order to provide comparison with reference data. The basics, structure and function of the model are described. The model is based on a straightforward full Monte Carlo simulation of the cosmic ray induced atmospheric cascade. The cascade simulation is performed with the PLANETOCOSMICS code. The flux of secondary particles, namely neutrons, protons, gammas, electrons, positrons, muons and charged pions is calculated. A subsequent conversion of the particle fluence into the effective dose or ambient dose equivalent is performed as well as a comparison with reference data. An application of the model is demonstrated, using a computation of the effective dose rate at flight altitude during the ground level enhancements of 20 January 2005, 13 December 2006 and 17 May 2012.

Analysis of the ground level enhancement on 17 May 2012 using data from the global neutron monitor network

A. L. **Mishev**, L. G. Kocharov and I. G. Usoskin
JGR, Volume 119, Issue 2, pages 670–679, February **2014**
http://onlinelibrary.wiley.com/doi/10.1002/2013JA019253/pdf
http://onlinelibrary.wiley.com/doi/10.1002/2013JA019253/abstract
We have analyzed the data of the world neutron monitor network for the first ground level enhancement of solar cycle 24, the ground level enhancement (GLE) on **17 May 2012**. A newly computed neutron monitor yield function and an inverse method are applied to estimate the energy spectrum, anisotropy axis direction, and pitch angle distribution of the high-energy solar particles in interplanetary space. The method includes the determination of the asymptotic viewing cones of neutron monitor stations through computations of trajectories of cosmic rays in a model magnetosphere. The cosmic ray particle trajectories are determined with the GEANT-based MAGNETOCOSMICS code using Tsyganenko 1989 and International Geomagnetic Reference Field models. Subsequent calculation of the neutron monitor responses with the model function is carried out, that represents an initial guess of the inverse problem. Derivation of the solar energetic particle characteristics is fulfilled by fitting the data of the global neutron monitor network using the Levenberg-Marquardt method over the nine-dimensional parameter space. The pitch angle distribution and rigidity spectrum of high-energy protons are obtained as function of time in the course of the GLE. The angular distribution appears quite complicated. It comprises a focused beam along the interplanetary magnetic field line from the Sun and a loss-cone feature around the opposite direction, possibly indicative of the particle transport in interplanetary magnetic field structures associated with previous coronal mass ejections.

Likely Common Coronal Source of Solar Wind and 3He-enriched Energetic Particles: Uncoupled Transport from the Low Corona to 0.2 au

D. G. **Mitchell**1, M. E. Hill1, D. J. McComas2, C. M. S. Cohen3, N. A. Schwadron2,4, P. S. Mostafavi1, W. H. Matthaeus5, N. E. Raouafi1, S. T. Al-Nussirat6, D. E. Larson6Show full author list
2024 ApJ 965 54
https://iopscience.iop.org/article/10.3847/1538-4357/ad2467/pdf
Parker Solar Probe (PSP) observations of a small dispersive event on **2022 February 27 and 28** indicate scatter-free propagation as the dominant transport mechanism between the low corona and greater than 35 solar radii. The event occurred during unique orbital conditions that prevailed along specific flux tubes that PSP encountered repeatedly between 25 and 35 Rs during outbound orbit 11. This segment of the PSP orbit exhibits almost stationary angular motion relative to the rotating solar surface, such that in the rotating frame, PSP's motion is essentially radial. The time dispersion often observed in impulsive solar energetic particle (SEP) events continues in this case down to velocities including the core solar-wind ion velocities. Especially at the onset of this event, the 3He content is much larger than the usual SEP abundances seen in the energy range from ∼100 keV to several MeV for helium. Later in the event, iron is enhanced. The compositional signatures suggest this to be an example of an acceleration mechanism for generating the seed energetic particles required by shock (or compression) acceleration models in SEP events to account for the enrichment of various species above solar abundances in such events. A preliminary search of similar orbital conditions over the PSP mission has not revealed additional such events, although favorable conditions (isolated impulsive acceleration and well-ordered magnetic field connection with minimal magnetic field fluctuation) that would be required are infrequently realized, given the small fraction of the PSP trajectory that meets these observation conditions.

A Living Catalog of Parker Solar Probe IS⊙IS Energetic Particle Enhancements

J. G. **Mitchell**7,1, C. M. S. Cohen2, T. J. Eddy3, C. J. Joyce4, J. S. Rankin3, M. M. Shen3, G. A. de Nolfo1, E. R. Christian1, D. J. McComas3, R. L. McNutt Jr.5 +++
2023 ApJS 264 31
https://iopscience.iop.org/article/10.3847/1538-4365/aca4c8/pdf
Energetic charged particles are pervasive throughout the heliosphere with contributions from solar energetic particle events, stream and corotating interaction regions, galactic cosmic rays, anomalous cosmic rays, and suprathermal ions. The Integrated Science Investigation of the Sun (IS⊙IS) on board the Parker Solar Probe is a suite of energetic particle detectors covering the energy range ∼20 keV–200 MeV nuc−1. IS⊙IS measures energetic particles closer to the Sun than any instrument suite in history, providing a singular view of the energetic particle population in a previously unexplored region. To enable the global research community to efficiently use IS⊙IS data, we have developed an online living catalog of energetic particle enhancements observed by the IS⊙IS instruments. Event identification methodology, information on accessing the catalog, highlights of several events, and a summary of the overall trends are presented. Also included is a summary Event Catalog showing many of the key event parameters for IS⊙IS events to the time of writing. **2021 May 28**
Table 1 Summary ISeIS Event Catalog 2018-2022

Energetic Electron Observations by Parker Solar Probe/IS⊙IS during the First Widespread SEP Event of Solar Cycle 25 on 2020 November 29

J. G. **Mitchell**1,2, G. A. De Nolfo2, M. E. Hill3, E. R. Christian2, I. G. Richardson2,4, D. J. McComas5, R. L. McNutt Jr.3, D. G. Mitchell3, N. A. Schwadron6, S. D. Bale7,8,9,10, J. Giacalone11, C. J. Joyce5, J. T. Niehof6, and J. R. Szalay5

2021 ApJ 919 119

https://iopscience.iop.org/article/10.3847/1538-4357/ac110e/pdf

https://doi.org/10.3847/1538-4357/ac110e

At the end of 2020 November, two coronal mass ejections (CMEs) erupted from the Sun and propagated through the interplanetary medium in the direction of Parker Solar Probe while the spacecraft was located at ∼0.81 au. The passage of these interplanetary CMEs (ICMEs) starting on November 29 (DOY 334) produced the largest enhancement of energetic ions and electrons observed by the Integrated Science Investigation of the Sun (IS⊙IS) energetic particle instrument suite on board Parker Solar Probe during the mission's first eight orbits. This was also the first spatially widespread solar energetic particle event observed in solar cycle 25. We investigate several key characteristics of the energetic electron event including the time profile and anisotropy distribution of near-relativistic electrons as measured by IS⊙IS's low-energy Energetic Particle Instrument (EPI-Lo) and compare these observations with contextual data from the Parker Solar Probe Fields Experiment magnetometer. These are the first electron anisotropy measurements from IS⊙IS/EPI-Lo, demonstrating that the instrument can successfully produce these measurements. We find that the electron count rate peaks at the time of the shock driven by the faster of the two ICMEs, implying that the shock parameters of this ICME are conducive to the acceleration of electrons. Additionally, the angular distribution of the electrons during the passage of the magnetic clouds associated with the ICMEs shows significant anisotropy, with electrons moving primarily parallel and antiparallel to the local magnetic field as well as bidirectionally, providing an indication of the ICME's magnetic topology and connectivity to the Sun or magnetic structures in the inner heliosphere.

Small Electron Events Observed by Parker Solar Probe/IS⊙IS during Encounter 2

J. G. **Mitchell1**,2, G. A. de Nolfo2, M. E. Hill3, E. R. Christian2, D. J. McComas4

2020 ApJ 902 20

https://doi.org/10.3847/1538-4357/abb2a4

https://iopscience.iop.org/article/10.3847/1538-4357/abb2a4/pdf

The current understanding of the characteristics of solar and inner heliospheric electron events is inferred almost entirely from observations made by spacecraft located at 1 astronomical unit (au). Previous observations within 1 au of the Sun, by the Helios spacecraft at ~0.3–1 au, indicate the presence of electron events that are not detected at 1 au or may have merged during transport from the Sun. Parker Solar Probe's close proximity to the Sun at perihelion provides an opportunity to make the closest measurements yet of energetic electron events. We present an overview of measurements of electrons with energies between ~17 keV and ~1 MeV made by the Parker Solar Probe Integrated Science Investigation of the Sun (IS⊙IS) instrument suite during Encounter 2 (2019 March 31–April 10 with perihelion of ~0.17 au), including several small electron events. We examine these events in the context of the electromagnetic and solar wind environment measured by the FIELDS and SWEAP instruments on Parker Solar Probe. We find most of these electron enhancements to be associated with type III radio emissions that reach the local plasma frequency and one enhancement that appears to be primarily associated with abrupt changes in the local magnetic field. Together, these associations suggest that these are indeed the first measurements of energetic electron events within 0.2 au. **2019 April 2, 2019 April 5**

CME -Associated Energetic Ions at 0.23 AU -- Consideration of the Auroral Pressure Cooker Mechanism Operating in the Low Corona as a Possible Energization Process

D. G. **Mitchell**, J. Giacalone, R. C. Allen, M. E. Hill, R. L. McNutt, D. J. McComas, J. R. Szalay, N. A. Schwadron,

ApJS 246 59 **2020**

https://arxiv.org/ftp/arxiv/papers/1912/1912.08891.pdf

sci-hub.si/10.3847/1538-4365/ab63cc

We draw a comparison between a solar energetic particle event associated with the release of a slow coronal mass ejection close to the sun, and the energetic particle population produced in high current density field-aligned current structures associated with auroral phenomena in planetary magnetospheres. We suggest that this process is common in CME development and lift-off in the corona, and may account for the electron populations that generate Type III radio bursts, as well as for the prompt energetic ion and electron populations typically observed in interplanetary space. **Nov 2018**

Solar Radio Bursts Associated with In Situ Detected Energetic Electrons in Solar Cycles 23 and 24

Miteva, R., Samwel, S. W., Zabunov, S.:
2022, Universe, 8(5), 275, 20pp.
https://doi.org/10.3390/universe8050275
The first comprehensive analysis between the in situ detected solar energetic electrons (SEEs) from ACE/EPAM satellite and remotely observed radio signatures in solar cycles (SCs) 23 and 24 (1997–2019) is presented. The identified solar origin of the SEEs (in terms of solar flares, SFs, and coronal mass ejections, CMEs) is associated with solar radio emission of types II, III and IV, where possible. Occurrence rates are calculated as a function of the radio wavelength, from the low corona to the interplanetary space near Earth. The tendencies of the different burst appearances with respect to SC, helio-longitude, and SEE intensity are also demonstrated. The corresponding trends of the driver (in terms of median values of the SF class and CME projected speed) are also shown. A comparison with the respective results when using solar energetic protons is presented and discussed.
CESRA #3350 Jul **2022** https://www.astro.gla.ac.uk/users/eduard/cesra/?p=3350

Solar energetic particle catalogs: Assumptions, uncertainties and validity of reports
R.**Miteva** S.W.Samwel M.V.Costa-Duartec
Journal of Atmospheric and Solar-Terrestrial Physics Volume 180, November **2018** *Pages 26-34*
sci-hub.tw/10.1016/j.jastp.2017.05.003
The aim of this work is to summarize the main underlying assumptions, simplifications and uncertainties while studying solar energetic particles (SEPs). In general, numerous definitions are used for the evaluation of a given SEP parameter and these different methods lead to different outcomes for a given particle event. Several catalogs of SEP events from various instruments are currently available; however, each catalog is specific to the adopted data and analysis. We investigate the differences while comparing several SEP catalogs and outline probable reasons. We focus on SEP statistical studies and quantify the influences of the particle intensity, solar origin location and projection effects. We found that different definitions and criteria used for these parameters change the values of the correlation coefficients between the SEPs and their solar origin.

The Wind/EPACT proton event catalog (1996-2016)
Rositsa **Miteva**, Susan W. Samwel, Marcus V. Costa-Duarte
Solar Phys. 293:27 **2018**
https://arxiv.org/pdf/1801.00469.pdf **File**
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1241-5.pdf
We present the finalized catalog of solar energetic proton events detected by Wind/EPACT instrument over the period **1996-2016**. Onset times, peak times, peak proton intensity and onset-to-peak proton fluence are evaluated for the two available energy channels, at about 25 and 50 MeV. We describe the procedure utilized to identify the proton events and to relate them to their solar origin (in terms of flares and coronal mass ejections). The statistical relationships between the energetic protons and their origin (linear and partial correlation analysis) are reported and discussed in view of earlier findings. Finally, the different trends found in the first eight years of solar cycles 23 and 24 are discussed. **2002.09.05, 2013.12.28**
Table 1. List of Wind/EPACT proton events and their solar origin, flares and CMEs, in the period 1996−2016

Solar radio burst emission from proton-producing flares and coronal mass ejections
R. **Miteva** 1 , S.W. Samwel 2 , V. Krupar 3
Proceedings of Ninth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere" Sunny Beach, Bulgaria, May 30 - June 3, **2017**, p. 19-23
http://ws-sozopol.stil.bas.bg/2017Sunny/Proceedings2017_V3.pdf
We present the occurrence trends of radio burst types in relations to the origin of solar energetic proton events – flares and coronal mass ejections (CMEs) – during the ongoing solar cycle 24 (2009÷2016). Namely, we analyze the occurrence of type II, type III and type IV radio bursts in specific frequency ranges, either as a support for the flare-origin when the emission originates from the low corona or for the CME-origin, when the radio bursts originate in the high corona.

Solar energetic particles and radio burst emission
Rositsa **Miteva**, Susan W. Samwel, Vratislav Krupar
Journal of Space Weather and Space Climate 7, A37 **2017**
https://arxiv.org/pdf/1711.09348.pdf **File**
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170028.pdf
We present a statistical study on the observed solar radio burst emission associated with the origin of in situ detected solar energetic particles. Several proton event catalogs in the period 1996−2016 are used. At the time of appearance of the particle origin (flare and coronal mass ejection) we identified radio burst signatures of types II, III and IV by

inspecting dynamic radio spectral plots. The information from observatory reports is also accounted for during the analysis. The occurrence of solar radio burst signatures is evaluated within selected wavelength ranges during the solar cycle 23 and the ongoing 24. Finally, we present the burst occurrence trends with respect to the intensity of the proton events and the location of their solar origin.

THE ORIGIN OF SEP EVENTS: NEW RESEARCH COLLABORATION AND NETWORK ON SPACE WEATHER

Rositsa **Miteva**1, Larisa Kashapova2, Irina Myagkova3, Nataliia Meshalkina2, Nikola Petrov4, Andrey Bogomolov3, Ivan Myshyakov2, Tsvetan Tsvetkov4, Dimitar Danov1, Dmitriy Zhdanov

https://www.researchgate.net/publication/321292236_THE_ORIGIN_OF_SEP_EVENTS_NEW_RESEARCH_COLLABORATION_AND_NETWORK_ON_SPACE_WEATHER?discoverMore=1

2017

A new project on the solar energetic particles (SEPs) and their solar origins (flares and coronal mass ejections) is described here. The main aim of this project is to answer the question – whether the SEPs observed in situ are driven by flares, by CMEs or both accelerators contribute to an extent which varies from event to event – by deducing a quantitative measure of the flare vs. CME contribution, duration and efficiency. New observations (SONG/Koronas-F, Relec/Vernov) and new approaches of analysis will be utilized (e.g., magnetic topology of active regions using 3D extrapolation techniques of detailed case studies together with statistical analysis of the phenomena). In addition, the identification of the uncertainty limits of SEP injection, onset time and testing the validity of assumptions often taken for granted (association procedures, solar activity longitudinal effects, correlation analysis, etc.) are planned. The project outcomes have the capacity to contribute to other research fields for improvement of modeling schemes and forecasting methods of space weather events.

(6) THE ORIGIN OF SEP EVENTS: NEW RESEARCH COLLABORATION AND NETWORK ON SPACE WEATHER. Available from: https://www.researchgate.net/publication/321292236_THE_ORIGIN_OF_SEP_EVENTS_NEW_RESEARCH_COLLABORATION_AND_NETWORK_ON_SPACE_WEATHER?discoverMore=1 [accessed Nov 28 2017].

Solar cycle dependence of Wind/EPACT protons, solar flares and coronal mass ejections.

Miteva, R., S. W. Samwel, M. V. Costa-Duarte, and O. E. Malandraki.

Sun and Geosphere, 12, 11–19, **2017**b.

http://newserver.stil.bas.bg/SUNGEO//00SGArhiv/SG_v12_No1_2017-pp-11-19.pdf

The aim of this work is to compare the occurrence and overall properties of solar energetic particles (SEPs), solar flares and coronal mass ejections (CMEs) over the first seven years in solar cycles (SCs) 23 and 24. For the case of SEP events, we compiled a new proton event catalog using data from the Wind/EPACT instrument. We confirm the previously known reduction of high energy proton events in SC24 compared to the same period in SC23; our analysis shows a decrease of 25–50 MeV protons by about 30%. The similar trend is found for X to C-class solar flares which are less by about 40% and also for faster than 1000 km/s CMEs, which are reduced by about 45%. In contrast, slow CMEs are more numerous in the present solar cycle. We discuss the implications of these results for the population of SEP-productive flares and CMEs. **2013-03-04, 2013-04-11**

Solar energetic particles and radio burst emission

Rositsa **Miteva**, Susan W. Samwel, Vratislav Krupar

Journal of Space Weather and Space Climate **2017**

https://arxiv.org/pdf/1711.09348.pdf **File**

We present a statistical study on the observed solar radio burst emission associated with the origin of in situ detected solar energetic particles. Several proton event catalogs in the period 1996−2016 are used. At the time of appearance of the particle origin (flare and coronal mass ejection) we identified radio burst signatures of types II, III and IV by inspecting dynamic radio spectral plots. The information from observatory reports is also accounted for during the analysis. The occurrence of solar radio burst signatures is evaluated within selected wavelength ranges during the solar cycle 23 and the ongoing 24. Finally, we present the burst occurrence trends with respect to the intensity of the proton events and the location of their solar origin.

On-line catalogues of solar energetic protons at SRTI-BAS

Miteva R., Danov D. .

Proceedings of Ninth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere" Sunny Beach, Bulgaria, May 30 - June 3, **2016**, p. 66-69 **2017**

http://ws-sozopol.stil.bas.bg/2017Sunny/Proceedings2017_V3.pdf

We outline the status of the on-line catalogs of solar energetic particles supported by the Space Climate group at the Space Research and Technology, Bulgarian Academy of Sciences (SRTI-BAS). In addition to the already compiled proton catalog from Wind/EPACT instrument, in the current report we present preliminary results on the high energy SOHO/ERNE proton enhancement identifications as well as comparative analysis with two other proton lists. The future plans for the on-line catalogs are briefly summarized.

Solar energetic particle catalogs: assumptions, uncertainties and validity of reports

R. **Miteva**, S.W. Samwel, M.V. Costa-Duarte
Journal of Atmospheric and Solar-Terrestrial Physics, (**2017**)
https://arxiv.org/pdf/1705.02144.pdf
http://www.sciencedirect.com/science/article/pii/S1364682617302924.

The aim of this work is to summarize the main underlying assumptions, simplifications and uncertainties while studying solar energetic particles (SEPs). In general, numerous definitions are used for the evaluation of a given SEP parameter and these different methods lead to different outcomes for a given particle event. Several catalogs of SEP events from various instruments are currently available; however, each catalog is specific to the adopted data and analysis. We investigate the differences while comparing several SEP catalogs and outline probable reasons. We focus on SEP statistical studies and quantify the influences of the particle intensity magnitude, solar origin location and projection effects. We found that different definitions and criteria used for these parameters change the values of the correlation coefficients between the SEPs and their solar origin.

Radio Signatures of Solar Energetic Particles During the 23rd Solar Cycle

Miteva, R.; Klein, K.-L.; Samwel, S. W.; Nindos, A.; Kouloumvakos, A.; Reid, H.
E-print, Feb **2014, File;** Cent. Eur.Astrophys. Bull. 37 (**2014**)
http://arxiv.org/pdf/1402.6442v1.pdf

We present the association rates between solar energetic particles (SEPs) and the radio emission signatures in the corona and IP space during the entire solar cycle 23. We selected SEPs associated with X and M-class flares from the visible solar hemisphere. All SEP events are also accompanied by coronal mass ejections. Here, we focus on the correlation between the SEP events and the appearance of radio type II, III and IV bursts on dynamic spectra. For this we used the available radio data from ground-based stations and the Wind/WAVES spacecraft. The associations are presented separately for SEP events accompanying activity in the eastern and western solar hemisphere. We find the highest association rate of SEP events to be with type III bursts, followed by types II and IV. Whereas for types III and IV no longitudinal dependence is noticed, these is a tendency for a higher SEP-association rate with type II bursts in the eastern hemisphere. A comparison with reports from previous studies is briefly discussed.

Table II: Solar energetic particle events with origin at western heliolongitudes: visual identification and [observatory reports] of type II, III and IV radio bursts.

Table III: Solar energetic particle events with origin at eastern or uncertain (with superscript 'u') heliolongitudes: visual identification and [observatory reports] of type II, III and IV radio bursts.

Solar Energetic Particles and Associated EIT Disturbances in Solar Cycle 23

R. **Miteva**, K.-L. Klein, I. Kienreich, M. Temmer, A. Veronig, O. E. Malandraki
E-print, Feb **2014**, **File**; Solar Phys., Volume 289, Issue 7, pp 2601-2631, **2014**
http://arxiv.org/pdf/1402.1676v1.pdf

We explore the link between solar energetic particles (SEPs) observed at 1 AU and large-scale disturbances propagating in the solar corona, named after the Extreme ultraviolet Imaging Telescope (EIT) as EIT waves, which trace the lateral expansion of a coronal mass ejection (CME). A comprehensive search for SOHO/EIT waves was carried out for 179 SEP events during Solar Cycle 23 (1997-2006). 87% of the SEP events were found to be accompanied by EIT waves. In order to test if the EIT waves play a role in the SEP acceleration, we compared their extrapolated arrival time at the footpoint of the Parker spiral with the particle onset in the 26 eastern SEP events that had no direct magnetic connection to the Earth. We find that the onset of proton events was generally consistent with this scenario. However, in a number of cases the first near-relativistic electrons were detected too early. Furthermore, the electrons had in general only weakly anisotropic pitch-angle distributions. This poses a problem for the idea that the SEPs were accelerated by the EIT wave or in any other spatially confined region in the low corona. The presence of weak electron anisotropies in SEP events from the eastern hemisphere suggests that transport processes in interplanetary space, including cross-field diffusion, play a role in giving the SEPs access to a broad range of helio-longitudes. 1997-04-01, **1997-09-24, 1998-04-29, 2000-01-18, 2000-02-17, 2000-06-06, 2000-07-10, 2000-10-29, 2000-11-25, 2001-01-20, 2001-06-15, 2001-09-17, 2001-09-24, 2001-10-09, 2001-11-28, 2002-05-20, 2002-08-16, 2003-04-25, 2003-06-15, 2003-07-17, 2003-10-26, 2003-11-18, 2004-11-04, 2005-01-15, 2005-05-13, 2006-11-06,**

Table 1. Solar energetic particle events with origin at western [W] helio-longitudes and associated EIT disturbances, flares and CMEs.
Table 2. Solar energetic particle events with origin at eastern [E] helio-longitudes and associated EIT disturbances, flares and CMEs.
Table 3. Properties of all 29 eastern particle events associated with EIT waves.
Table 4. Properties of 26 eastern EIT waves for which at least two wave fronts could be identified.

Radio signatures of solar energetic particles during the 23rd solar cycle.
Miteva R, Klein KL, Samwel SW, Nindos A, Kouloumvakos A, Reid H.
2013 Cent. Eur. Astrophys. Bull. 37, 541–553.
SEP events, either gradual or impulsive, were found to have the highest association rate with type III radio bursts and a lower association with type II bursts.

Solar Energetic Particle Events in the 23rd Solar Cycle: Interplanetary Magnetic Field Configuration and Statistical Relationship with Flares and CMEs
R. **Miteva**, K.-L. Klein, O. Malandraki, G. Dorrian
Solar Physics, February **2013**, Volume 282, Issue 2, pp 579-613; **File**
http://arxiv.org/pdf/1403.0708v1.pdf
We study the influence of the large-scale interplanetary magnetic field configuration on the solar energetic particles (SEPs) as detected at different satellites near Earth and on the correlation of their peak intensities with the parent solar activity. We selected SEP events associated with X- and M-class flares at western longitudes, in order to ensure good magnetic connection to Earth. These events were classified into two categories according to the global interplanetary magnetic field (IMF) configuration present during the SEP propagation to 1 AU: standard solar wind or interplanetary coronal mass ejections (ICMEs). Our analysis shows that around 20 % of all particle events are detected when the spacecraft is immersed in an ICME. The correlation of the peak particle intensity with the projected speed of the SEP-associated coronal mass ejection is similar in the two IMF categories of proton and electron events, ≈0.6. The SEP events within ICMEs show stronger correlation between the peak proton intensity and the soft X-ray flux of the associated solar flare, with correlation coefficient r=0.67±0.13, compared to the SEP events propagating in the standard solar wind, r=0.36±0.13. The difference is more pronounced for near-relativistic electrons. The main reason for the different correlation behavior seems to be the larger spread of the flare longitude in the SEP sample detected in the solar wind as compared to SEP events within ICMEs. We discuss to what extent observational bias, different physical processes (particle injection, transport, etc.), and the IMF configuration can influence the relationship between SEPs and coronal activity.
Tables

Study of some characteristics of solar energetic particles and associated solar activities during 1996–2016
Nishant **Mittal**, V.K.Verma
New Astronomy Volume 69, May **2019**, Pages 74-87
https://www.sciencedirect.com/science/article/pii/S1384107618302732
Solar energetic particles (SEP) are believed to originate from two different sources, coronal mass ejections (CMEs) and solar flares. In this paper, we have also investigated some statistical properties such as speed, apparent angular width, acceleration, latitude distribution of SEP effective CMEs observed during the period 1996–2016 covering the solar cycle 23 and solar cycle 24. We find that 76% SEP event associated with solar flares originates in the western hemisphere. We also found that SEP associated CMEs are faster and nearly halo in nature. The study shows that mean starting frequency of SEP events associated DH-type II radio burst is 10.9 MHz. We have also investigated the time delay between the flare start/peak time and related SEP, CME and type II burst start time and it is to be found that almost all SEP events occur later than the start time of the flare, CME, m-type II bursts and DH type II radio events.

Proton Penetration Efficiency over a High Altitude Observatory in Mexico
S. **Miyake**, T. Koi, Y. Muraki, Y. Matsubara, S. Masuda, P. Miranda, T. Naito, E. Ortiz, A. Oshima, T. Sakai, T. Sako, S. Shibata, H. Takamaru, M. Tokumaru, J. F. Valdes-Galicia
In the 21st International Symposium on Very High Energy Cosmic Ray Intercations (ISVHE-CRI **2022**)
https://arxiv.org/pdf/2207.01817.pdf
In association with a large solar flare on **November 7, 2004**, the solar neutron detectors located at Mt. Chacaltaya (5,250m) in Bolivia and Mt. Sierra Negra (4,600m) in Mexico recorded very interesting events. In order to explain

these events, we have performed a calculation solving the equation of motion of anti-protons inside the magnetosphere. Based on these results, the Mt. Chacaltaya event may be explained by the detection of solar neutrons, while the Mt. Sierra Negra event may be explained by the first detection of very high energy solar neutron decay protons (SNDPs) around 6 GeV.

Complex Network for Solar Protons and Correlations With Flares

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020JA028868

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We study the properties of the complex network for solar proton flux (SPF) at six integral energy channels (>1, >5, >10, >30, >50, and >100 MeV). We construct a growing visibility network based on the SPF time series for proton for each channel, which observed by Geostationary Operational Environmental Satellites from April 14, 2010 to May 9, 2018. The clustering coefficient values for SPF networks are much larger than those of the equivalent random network. The logarithmic behavior of the characteristic path length refers to the characteristics of the small-world network. The degree distribution of nodes obeys the power-law behavior with certain exponents that reflects the scale-free nature of the networks. For the constructed SPF networks, the average clustering coefficient shows a jump when the large flares occurred. We show that both western solar longitude large flares (X-class, M-class) and flares associated with coronal mass ejections (with speed greater than 500 km s−1) are relatively more related to the peaks (more than the median) of both SPF time series and PageRank of the networks. We conclude that both the PageRank and clustering coefficient of the SPF network are useful indicators to identify the source of SPFs related to flares and flares associated with coronal mass ejections.

Was the cosmic ray burst detected by the GRAPES-3 on 22 June 2015 caused by transient weakening of geomagnetic field or by an interplanetary anisotropy?

P.K. Mohanty, K.P. Arunbabu, T. Aziz, S.R. Dugad, S.K. Gupta, B. Hariharan, P. Jagadeesan, A. Jain, S.D. Morris, P.K. Nayak, P.S. Rakshe, K. Ramesh,B.S. Rao, M. Zuberi, Y. Hayashi, S. Kawakami, P. Subramanian, S. Raha, S. Ahmad, A. Oshima, S. Shibata, H. Kojima

Physical Review D **2018**

https://arxiv.org/pdf/1803.10499.pdf

The GRAPES-3 muon telescope in Ooty, India had claimed detection of a 2 hour (h) high-energy (~20 GeV) burst of galactic cosmic-rays (GCRs) through a >50σ surge in GeV muons, was caused by reconnection of the interplanetary magnetic field (IMF) in the magnetosphere that led to transient weakening of Earth's magnetic shield. This burst had occurred during a G4-class geomagnetic storm (storm) with a delay of 12h relative to the coronal mass ejection (CME) of 22 June 2015 (Mohanty et al., 2016). However, recently a group interpreted the occurrence of the same burst in a subset of 31 neutron monitors (NMs) to have been the result of an anisotropy in interplanetary space (Evenson et al., 2017) in contrast to the claim in (Mohanty et al., 2016). A new analysis of the GRAPES-3 data with a fine 10.6∘ angular segmentation shows the speculation of interplanetary anisotropy to be incorrect, and offers a possible explanation of the NM observations. The observed 28 minutes (min) delay of the burst relative to the CME can be explained by the movement of the reconnection front from the bow shock to the surface of Earth at an average speed of 35 km/s, much lower than the CME speed of 700 km/s. This measurement may provide a more accurate estimate of the start of the storm.

Acceleration of Solar Energetic Particles by the shock of Interplanetary Coronal Mass Ejection

Shanwlee Sow **Mondal**, Aveek Sarkar, Bhargav Vaidya, Andrea Mignone

ApJ **923** 80 **2021**

https://arxiv.org/pdf/2110.01828.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac2c7a/pdf

https://doi.org/10.3847/1538-4357/ac2c7a

Interplanetary Coronal Mass Ejection (ICME) shocks are known to accelerate particles and contribute significantly to Solar Energetic Particle (SEP) events. We have performed Magnetohydrodynamic-Particle in Cell (MHD-PIC) simulations of ICME shocks to understand the acceleration mechanism. These shocks vary in Alfvénic Mach numbers as well as in magnetic field orientations (parallel \& quasi-perpendicular). We find that Diffusive Shock Acceleration (DSA) plays a significant role in accelerating particles in a parallel ICME shock. In contrast, Shock Drift Acceleration (SDA) plays a pivotal role in a quasi-perpendicular shock. High-Mach shocks are seen to accelerate particles more efficiently. Our simulations suggest that background turbulence and local particle velocity distribution around the shock can indirectly hint at the acceleration mechanism. Our results also point towards a few possible \textit{in situ} observations that could validate our understanding of the topic.

The cosmic-ray ground-level enhancements of 29 September 1989 and 20 January 2005
H. **Moraal**, R. A. Caballero-Lopez, K. G. McCracken
Proc. 34rd International Cosmic Ray Conference, 2015 **2016**
https://arxiv.org/pdf/1610.04635v1.pdf
Enhancements of the comic-ray intensity as observed by detectors on the ground have been observed 71 times since 1942. They are due to solar energetic particles accelerated in the regions of solar flares deep in the corona, or in the shock front of coronal mass ejections (CMEs) in the solar wind. The latter is the favoured model for the classical gradual ground level enhancement (GLE). In several papers since the one of McCracken et al. (2008), we pointed out, however, that some GLEs are too impulsive to be accelerated in the CME shocks. This hypothesis, together with other properties of GLEs, is demonstrated graphically in this paper by plotting and comparing the time profiles of GLEs 42 of 29 September 1989 and GLE 69 of 20 January. These two events are respectively the largest examples of gradual and prompt events.

The pulse shape of cosmic-ray ground-level enhancements
H. **Moraal**, K. G. McCracken, R. A. Caballero-Lopez
Proc. 34rd International Cosmic Ray Conference, **2015**
https://arxiv.org/ftp/arxiv/papers/1604/1604.07504.pdf **File**
Enhancements of the comic-ray intensity as observed by detectors on the ground have been observed 71 times since 1942. They are due to solar energetic particles accelerated in the regions of solar flares deep in the corona, or in the shock front of coronal mass ejections (CMEs) in the solar wind. The latter is the favoured model for the classical gradual ground-level enhancement (GLE). In several papers since the one of McCracken et al. (2008), we pointed out, however, that some GLEs are too impulsive to be accelerated in the CME shocks. With this hypothesis in mind we study the time profiles of all the available GLEs. The main results are that there is a continuous range from gradual to impulsive, that the fastest risers are concentrated at heliolongitudes that are magnetically well-connected to Earth, and that the shape of the pulse is a powerful indicator of propagation conditions between Sun and Earth. This ranges from relatively quiet to highly disturbed.

The Cosmic-Ray Ground-level Enhancement of 1989 September 29
H. **Moraal**1 and R. A. Caballero-Lopez
2014 ApJ 790 154
The ground-level enhancement (GLE) of **1989 September 29** is one of the largest of 71 solar energetic particle events observed by neutron monitors on Earth. It was smaller than the record-breaking GLE 5 of 1956 February 23, but by some measures it was larger than GLE 69 of 2005 January 20. It is also the most extensively studied of the 71 GLEs, and it was observed by more than 50 ground-based detectors in the worldwide network. This paper contains another study of the event, with the main difference from previous studies that all the existing observations are employed, instead of the usual selection of stations. An effort is made to represent all the information graphically. This reveals new insight in the event, mainly about its time profile. The main conclusion is that the event is the best example available of a "classical" GLE that has a gradual increase toward peak intensity and does not contain two or more distinct peaks as inferred previously. It does, however, suggest that there were two acceleration or release mechanisms: a prompt, rapid one and a delayed, slower one. This conclusion is based on a detailed comparison with GLE 69 of **2005 January 20**, which is the best-known example of a double-peaked event with a "prompt" component. It is also found that the rigidity spectrum was probably softer than derived in several previous studies, and that the decay phase of the event reveals that the cosmic-ray diffusion coefficient in the neutron monitor range is proportional to rigidity.

The Time Structure of Ground Level Enhancements in Solar Cycle 23 **Review**
H. **Moraal** and K. G. McCracken
Space Science Reviews, 171, Numbers 1-4, 85-95, **2012, File**
In a recent paper McCracken et al. (J. Geophys. Res. 113:A12101, 2008) proposed that the Ground Level Enhancement (GLE) of **20 January 2005** may have been produced by more than one acceleration mechanism, with the first acceleration due to the solar flare and the second one due to the CME associated with that event. They also noted several other GLEs with similar multiple pulse structures. This paper systematically investigates all the GLEs of solar cycle 23, from GLE 55 on 6 November 1997 to GLE 70 on 13 December 2006, to study their morphology and pulse structure, and to determine whether the multiple structures that may be found in these events are qualitatively similar to that of the GLE of 20 January 2005. We use all the data of all NMs that saw each event, to

have as much directional and spectral information as possible. It is shown that three of these 16 events do contain such double-pulse structures, and the properties of these three are discussed in some detail.
15 Apr 2001, 13 Dec 2006,

Pitch-angle Distributions of 0.5–1 GeV Solar Protons Crossing Earth's Orbit: Influence of the Large-scale Turbulent Interplanetary Magnetic Field

Ashraf **Moradi**1 and Joe Giacalone1
2023 ApJ 952 153
https://iopscience.iop.org/article/10.3847/1538-4357/acdbcb/pdf
Using numerical simulations, we analyze the time evolution of the pitch-angle distribution of 500 MeV and 1 GeV solar protons, released impulsively near the Sun, at 1 au. The numerical model solves the equations of motion of an ensemble of particles that move in both the average Parker spiral field and a large-scale turbulent interplanetary magnetic field (IMF). Our model also includes the heliospheric current sheet (HCS). The focus of this study is to determine the effect of the large-scale turbulent IMF on the pitch-angle distribution of GV-rigidity protons and its time variations in terms of understanding variations in ground-level enhancement (GLE) events. Our particular interest is to explain the two distinct opposite-directed fluxes of the unusual event on **1989 October 22** (GLE#44). The results show that by adding the large-scale turbulence to the average Parker IMF, the pitch-angle distribution at 1 au depends strongly on the observer's location relative to the release location of the particles at the Sun. Even a 0.2° displacement in latitude or longitude leads to a significant change in the observed distribution and/or its variation in time. We find that there are some observer locations for which the distinct sunward and antisunward fluxes coexist at certain times of the events. We also find that the HCS has an important effect. For instance, even in locations of poor magnetic connection with the release location at the Sun, but near the HCS, there can be two fluxes moving in different directions at the same time.

The Effect of the Fluctuating Interplanetary Magnetic Field on the Cosmic Ray Intensity Profile of the Ground-level Enhancement (GLE) Events

Ashraf **Moradi**1 and Joe Giacalone1
2022 ApJ 932 73
https://iopscience.iop.org/article/10.3847/1538-4357/ac66e0/pdf
We numerically integrate the equations of motion of a large number of GeV protons, released impulsively near the Sun, in order to study their time–intensity behavior at the location of an observer at 1 au. This is relevant to the interpretation of Ground Level Enhancements (GLEs) detected by neutron monitors on Earth. Generally, the observed time–intensity profiles reveal a single sharp rise, followed by slow decay. However, in the **1989 October 22** GLE event, there was an initial sharp spike followed by a secondary smaller spike in the particle intensity. We consider whether the propagation of the high-energy protons in a large-scale turbulent interplanetary magnetic field (IMF) can lead to this unusual time–intensity profile. The IMF model includes large-scale magnetic turbulence and a heliospheric current sheet. Ad-hoc scattering is used to mimic the effect of smaller-scale fluctuations resulting in pitch-angle scattering. Proton fluxes as a function of time and location for an observer are determined for various turbulence parameters, IMF polarities, and the size of the particle source near the Sun. We find that the fluctuating IMF leads to considerable variation in the arrival location of the particles crossing 1 au, and the time–intensity profile depends significantly on the observer's location and can have multiple peaks. An alternate explanation for the unusual structure in the 1989 October 22 GLE event is provided. Our findings show that the large-scale turbulent IMF enhances the access of the high-energy protons to the HCS at the early time of the event, which leads to efficient cross-field transport.

Propagation of Scatter-free Solar Energetic Electrons in a Meandering Interplanetary Magnetic Field

Ashraf **Moradi** and Gang Li
2019 ApJ 887 102
sci-hub.se/10.3847/1538-4357/ab4f68
We investigate energetic electron transport in a meandering interplanetary magnetic field under the scatter-free regime. The meandering magnetic field is adopted from the Giacalone model in which a single parameter V rms is used to characterize how the interplanetary magnetic field deviates from the Parker field. The trajectories of energetic electrons are followed in this meandering field using test particle simulations. Ten thousand electrons are injected in the ecliptic plane and the path length distributions are obtained at distances 0.2, 0.5, 1.0, 2.0, and 3.0 au from the Sun for five different V rms, 0.3, 0.6, 1.0, 1.5, 2.0, and 2.5 km s^{-1}. By generating 10,000 different realizations of the meandering field line, we also obtain the path length distribution of the field lines. Our simulations show that the path length distributions of the electrons and that of the field lines are different and the difference increases with V rms. When the V rms approaches zero, the field lines approach the Parker field, and the differences between particle path lengths and field path lengths are small but nonzero due to the gradient and

curvature drifts. The path lengths for 1 MeV electrons do not differ much from those for 100 MeV electrons. Our results of the distribution of electron path length can be compared to the observations of Zhao et al. to set constraints on V rms. We also calculate both the longitudinal and latitudinal displacements from the source when electrons arrive at 1 au. This provides some basis for understanding simultaneous observations of impulsive events made at multiple spacecraft.

MEMPSEP III. A machine learning-oriented multivariate data set for forecasting the Occurrence and Properties of Solar Energetic Particle Events using a Multivariate Ensemble Approach

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Space Weather **Volume22, Issue9** September 2024 e2023SW003765

https://arxiv.org/ftp/arxiv/papers/2310/2310.15390.pdf

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003765

We introduce a new multivariate data set that utilizes multiple spacecraft collecting in-situ and remote sensing heliospheric measurements shown to be linked to physical processes responsible for generating solar energetic particles (SEPs). Using the Geostationary Operational Environmental Satellites (GOES) flare event list from Solar Cycle (SC) 23 and part of SC 24 (1998-2013), we identify 252 solar events (flares) that produce SEPs and 17,542 events that do not. For each identified event, we acquire the local plasma properties at 1 au, such as energetic proton and electron data, upstream solar wind conditions, and the interplanetary magnetic field vector quantities using various instruments onboard GOES and the Advanced Composition Explorer (ACE) spacecraft. We also collect remote sensing data from instruments onboard the Solar Dynamic Observatory (SDO), Solar and Heliospheric Observatory (SoHO), and the Wind solar radio instrument WAVES. The data set is designed to allow for variations of the inputs and feature sets for machine learning (ML) in heliophysics and has a specific purpose for forecasting the occurrence of SEP events and their subsequent properties. This paper describes a dataset created from multiple publicly available observation sources that is validated, cleaned, and carefully curated for our machine-learning pipeline. The dataset has been used to drive the newly-developed Multivariate Ensemble of Models for Probabilistic Forecast of Solar Energetic Particles (MEMPSEP; see MEMPSEP I (Chatterjee et al., 2023) and MEMPSEP II (Dayeh et al., 2023) for associated papers). **15-19 Apr 2001, 20-22 Jan 2005**

The low energy magnetic spectrometer on Ulysses and ACE response to near relativistic protons

Bruno **Morgado**1,2, Dalmiro Jorge Filipe Maia2, Louis Lanzerotti3, Patrícia Gonçalves1 and J. Douglas Patterson

A&A 577, A61 (**2015**)

Aims. We show that the Heliosphere Instrument for Spectra Composition and Anisotropy at Low Energies (HISCALE) on board the Ulysses spacecraft and the Electron Proton Alpha Monitor (EPAM) on board the Advance Composition Explorer (ACE) spacecraft can be used to measure properties for ion populations with kinetic energies in excess of 1 GeV. This previously unexplored source of information is valuable for understanding the origin of near relativistic ions of solar origin.

Methods. We model the instrumental response from the low energy magnetic spectrometers from EPAM and HISCALE using a Monte Carlo approach implemented in the Geant4 toolkit to determine the response of different energy channels to energies up to 5 GeV. We compare model results with EPAM observations for **2012 May 17** ground level solar cosmic ray event, including directional fluxes.

Results. For the 2012 May event, all the ion channels in EPAM show an onset more than one hour before ions with the highest nominal energy range (1.8 to 4.8 MeV) were expected to arrive. We show from Monte Carlo simulations that the timing at different channels, the ratio between counts at the different channels, and the directional fluxes within a given channel, are consistent with and can be explained by the arrival of particles with energies from 35 MeV to more than 1 GeV. Onset times for the EPAM penetrating protons are consistent with the rise seen in neutron monitor data, implying that EPAM and ground neutron monitors are seeing overlapping energy ranges and that both are consistent with GeV ions being released from the Sun at 10:38 UT.

Connecting remote and in situ observations of shock-accelerated electrons associated with a coronal mass ejection⋆

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A&A 683, A31 (**2024**)

https://arxiv.org/pdf/2312.07166.pdf

https://www.aanda.org/articles/aa/pdf/2024/03/aa47873-23.pdf
Context. One of the most prominent sources for energetic particles in our Solar System are huge eruptions of magnetised plasma from the Sun, known as coronal mass ejections (CMEs), which usually drive shocks that accelerate charged particles up to relativistic energies. In particular, energetic electron beams can generate radio bursts through the plasma emission mechanism, for example, type II and accompanying herringbone bursts.
Aims. In this work, we investigate the acceleration location, escape, and propagation directions of various electron beams in the solar corona and compare them to the arrival of electrons at spacecraft.
Methods. To track energetic electron beams, we used a synthesis of remote and direct observations combined with coronal modeling. Remote observations include ground-based radio observations from the Nançay Radioheliograph (NRH) combined with space-based extreme-ultraviolet and white-light observations from Solar Dynamics Observatory (SDO), Solar Terrestrial Relations Observatory (STEREO), and Solar Orbiter (SolO). We also used direct observations of energetic electrons from the STEREO and Wind spacecraft. These observations were then combined with a three-dimensional (3D) representation of the electron acceleration locations, including the results of magneto-hydrodynamic models of the solar corona. This representation was subsequently used to investigate the origin of electrons observed remotely at the Sun and their link to in situ electrons.
Results. We observed a type II radio burst followed by herringbone bursts that show single-frequency movement through time in NRH images. The movement of the type II burst and herringbone radio sources seems to be influenced by regions in the corona where the CME is more capable of driving a shock. We found two clear distinct regions where electrons are accelerated in the low corona and we found spectral differences between the radio emission generated in these regions. We also found similar inferred injection times of near-relativistic electrons at spacecraft to the emission time of the type II and herringbone bursts. However, only the herringbone bursts propagate in a direction where the shock encounters open magnetic field lines that are likely to be magnetically connected to the same spacecraft.
Conclusions. Our results indicate that if the in situ electrons are indeed shock-accelerated, the most likely origin of the in situ electrons arriving first is located near the acceleration site of herringbone electrons. This is the only region during the early evolution of the shock where there is clear evidence of electron acceleration and an intersection of the shock with open field lines, which can be directly connected to the observing spacecraft. **March 28, 2022**

Multiple regions of shock-accelerated particles during a solar coronal mass ejection
Morosan, Diana E.; Carley, Eoin P.; Hayes, Laura A.; Murray, Sophie A.; Zucca, Pietro; Fallows, Richard A.; McCauley, Joe; Kilpua, Emilia K. J.; Mann, Gottfried; Vocks, Christian; Gallagher, Peter T.
Nature Astronomy **2019**
sci-hub.se/10.1038/s41550-019-0689-z
The Sun is an active star that can launch large eruptions of magnetized plasma into the heliosphere, known as coronal mass ejections (CMEs). These can drive shocks that accelerate particles to high energies, often resulting in radio emission at low frequencies (<200 MHz). So far, the relationship between the expansion of CMEs, shocks and particle acceleration is not well understood, partly due to the lack of radio imaging at low frequencies during the onset of shock-producing CMEs. Here, we report multi-instrument radio, white-light and ultraviolet imaging of the second largest flare in solar cycle 24 (2008–present) and its associated fast CME (3,038± 288 km s−1). We identify the location of a multitude of radio shock signatures, called herringbones, and find evidence for shock-accelerated electron beams at multiple locations along the expanding CME. These observations support theories of non-uniform, rippled shock fronts driven by an expanding CME in the solar corona.
RHESSI Science Nuggets # 348 Apr **2019**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Multiple_Regions_of_Shock-accelerated_Particles_during_a_Solar_Coronal_Mass_Ejection

Shock Wave Structure in the Presence of Energetic Particles
Parisa **Mostafavi**1,2, Gary P. Zank1,2 and Gary M. Webb
Journal of Physics: Conference Series, Volume 900, Number 1 012016 **2017**
http://iopscience.iop.org/article/10.1088/1742-6596/900/1/012016/pdf
Energetic particles that are not equilibrated with the thermal plasma (such as pickup ions (PUIs), anomalous cosmic rays (ACRs) and solar energetic particles (SEPs)) can modify the structure of collisionless shock waves. This is relevant to the inner and outer heliosphere and the Very Local Interstellar Medium (VLISM) where observations of shock waves in the e.g., the inner heliosphere show that the energetic particle component pressure is greater than the both the magnetic field and thermal gas pressure (Lario et al., 2015). Voyager 2 observations revealed that the heliospheric termination shock (HTS) is very broad and mediated by energetic particles. PUIs and SEPs contribute both a collisionless heat flux and a higher-order viscosity. We show that the incorporation of both effects can completely determine the structure of collisionless shocks mediated by energetic ions. Since the reduced form of the PUI mediated plasma model is structurally identical to the classical cosmic ray two-fluid model (Axford et al.,

(1982)), we note that the presence of viscosity at least formally eliminates the need of a gas sub-shock in the classical two-fluid model, including in that regime where three are possible. By considering parameters upstream of the heliospheric termination shock (HTS), we show that the thermal gas remains relatively cold and the shock is mediated by PUIs. We determine the structure of the weak interstellar shock observed by Voyager 1. We consider the inclusion of the thermal heat flux and viscosity to address the most general form of an energetic particle-thermal plasma two-fluid model.

The issues of reliability of solar energetic proton flux databases and models
D. **Mottl**[a] and R. Nymmik
Advances in Space Research
Volume 39, Issue 8, **2007**, Pages 1355-1361

Long-term Variation of the Solar Diurnal Anisotropy of Galactic Cosmic Rays Observed with the Nagoya Multi-directional Muon Detector

K. **Munakata**1, M. Kozai1, C. Kato1, and J. Kóta
2014 ApJ 791 22
We analyze the three-dimensional anisotropy of the galactic cosmic ray (GCR) intensities observed independently with a muon detector at Nagoya in Japan and neutron monitors over four solar activity cycles. We clearly see the phase of the free-space diurnal anisotropy shifting toward earlier hours around solar activity minima in A > 0 epochs, due to the reduced anisotropy component parallel to the mean magnetic field. This component is consistent with a rigidity-independent spectrum, while the perpendicular anisotropy component increases with GCR rigidity. We suggest that this harder spectrum of the perpendicular component is due to contribution from the drift streaming. We find that the bi-directional latitudinal density gradient is positive in the A > 0 epoch, while it is negative in the A < 0 epoch, in agreement with the drift model prediction. The radial density gradient of GCRs, on the other hand, varies with a ~11 yr cycle with maxima (minima) in solar maximum (minimum) periods, but we find no significant difference between the radial gradients in the A > 0 and A < 0 epochs. The corresponding parallel mean free path is larger in A < 0 than in A > 0. We also find, however, that the parallel mean free path (radial gradient) appears to persistently increase (decrease) in the last three cycles of weakening solar activity. We suggest that simple differences between these parameters in A > 0 and A < 0 epochs are seriously biased by these long-term trends.

Cosmic ray short burst observed with the Global Muon Detector Network (GMDN) on June 22, 2015

K. **Munakata**, M. Kozai, P. Evenson, T. Kuwabara, C. Kato, M. Tokumaru, M. Rockenbach, A. Dal Lago, R. R. S. Mendonca, C. R. Braga, N. J. Schuch,H. K. Al Jassar, M. M. Sharma, M. L. Duldig, J. E. Humble, I. Sabbah, J. Kota
ApJ **2018**
https://arxiv.org/pdf/1806.10601.pdf
We analyze the short cosmic ray intensity increase ("cosmic ray burst": CRB) on **June 22, 2015** utilizing a global network of muon detectors and derive the global anisotropy of cosmic ray intensity and the density (i.e. the omnidirectional intensity) with 10-minute time resolution. We find that the CRB was caused by a local density maximum and an enhanced anisotropy of cosmic rays both of which appeared in association with Earth's crossing of the heliospheric current sheet (HCS). This enhanced anisotropy was normal to the HCS and consistent with a diamagnetic drift arising from the spatial gradient of cosmic ray density, which indicates that cosmic rays were drifting along the HCS from the north of Earth. We also find a significant anisotropy along the HCS, lasting a few hours after the HCS crossing, indicating that cosmic rays penetrated into the inner heliosphere along the HCS. Based on the latest geomagnetic field model, we quantitatively evaluate the reduction of the geomagnetic cut-off rigidity and the variation of the asymptotic viewing direction of cosmic rays due to a major geomagnetic storm which occurred during the CRB and conclude that the CRB is not caused by the geomagnetic storm, but by a rapid change in the cosmic ray anisotropy and density outside the magnetosphere.

Solar Neutron Decay Protons observed in November 7, 2004

Yasushi **Muraki**, Jose F. Valde-Galicia, Ernesto Ortiz, Yutaka Matsubara, Shoichi Shibata, Takashi Sako, Satoshi Masuda, Munetoshi Tokumaru, Tatsumi Koi, Akitoshi Ooshima, Takasuke Sakai, Tsuguya Naito, Pedro Miranda
Earth, Planet and Space **2021**
https://arxiv.org/pdf/2012.15623.pdf
We have found an interesting event registered by the solar neutron telescopes installed at high mountains in Bolivia (5250 m a.s.l.) and Mexico (4600 m a.s.l.). The event was observed November 7th of 2004 in association with a large solar flare of magnitude X2.0. Some features in our registers and in two satellites (GOES 11 and SOHO) reveal the presence of electrons and protons as possible products of neutron decay. Solar neutron decay protons

(sndp) were recorded on board ISEE3 satellite in **June 3rd, 1982** . On **October 19th, 1989**, the ground level detectors installed in Goose Bay and Deep River revealed the registration of solar neutron decay protons (sndp). Therefore this is the second example that such an evidence is registered on the Earth's surface.

Simultaneous Observation of Solar Neutrons from the ISS and High Mountain Observatories in association with a flare on July 8, 2014

Y. **Muraki**, D. Lopez, K. Koga, F. Kakimoto, T. Goka, L.X. Gonzalez, S.Masuda, Y. Matsubara, H. Matsumoto, P. Miranda, O. Okudaira, T. Obara, J. Salinas, T. Sako, S. Shibata, R.Ticona, Y. Tsunesada,J.F. Valdes-Galicia, K. Watanabe, T. Yamamoto

Solar Phys. Volume 291, Issue 4, pp 1241-1265 **2016**

Proceeding of the 34th International Cosmic Ray Conference in Hague in August, 2015, **2015**

http://arxiv.org/ftp/arxiv/papers/1508/1508.04923.pdf

An M6.5-class flare was observed at N12E56 of the solar surface at 16:06 UT **on July 8, 2014**. In association with this flare, solar neutron detectors located on two high mountains, Mt. Sierra Negra and Chacaltaya and at the space station observed enhancements in the neutral channel. The authors analysed these data and a possible scenario of enhancements produced by high-energy protons and neutrons is proposed, using the data from continuous observation of a solar surface by the ultraviolet telescope onboard the Solar Dynamical Observatory (SDO).
An M6.5-class flare was observed at N12E56 on the solar surface at 16:06 UT on July 8, 2014. In association with the flare, two neutron detectors located at high mountains, Mt. Sierra Negra in Mexico and Mt. Chacaltaya in Bolivia, recorded two neutron pulses, separated approximately by 30 min. Moreover, enhancements were also observed by the solar neutron detector onboard the International Space Station. We analyzed these data combined with solar images from Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory. From these we noticed that the production mechanism of neutrons cannot be explained by a single model; at least one of the enhancements may be explained by an electric field generated by the collision of magnetic loops and the other by the shock acceleration mechanism at the front side of the CME.

Measurement by FIB on the ISS: Two Emissions of Solar Neutrons Detected?

Y. **Muraki**,1 K. Koga,2 T. Goka,2,3 H. Matsumoto,2 T. Obara,2,4 O. Okudaira,2 S. Shibata,5 and T. Yamamoto

Advances in Astronomy, Volume 2012 (**2012**), Article ID 379304, 14 pages

http://www.hindawi.com/journals/aa/2012/379304/

A new type of solar neutron detector (FIB) was launched on board the Space Shuttle Endeavour on July 16, 2009, and began collecting data at the International Space Station (ISS) on August 25, 2009. This paper summarizes the three years of observations obtained by the solar neutron detector FIB until the end of July 2012. The solar neutron detector FIB can determine both the energy and arrival direction of neutrons. We measured the energy spectra of background neutrons over the South Atlantic Anomaly (SAA) region and elsewhere and found the typical trigger rates to be 20 and 0.22 counts/sec, respectively. It is possible to identify solar neutrons to within a level of 0.028 counts/sec, provided that directional information is applied. Solar neutrons were possibly observed in association with the M-class solar flares that occurred on **March 7 (M3.7) and June 7 (M2.5) of 2011**. This marked the first time that neutrons had been observed in M-class solar flares. A possible interpretation of the production process is provided.

Detection of high-energy solar neutrons and protons by ground level detectors on April 15, 2001 Original Research Article

Y. **Muraki**, Y. Matsubara, S. Masuda, S. Sakakibara, T. Sako, K. Watanabe, R. Bütikofer, E.O. Flückiger, A. Chilingarian, G. Hovsepyan, F. Kakimoto, T. Terasawa, Y. Tsunesada, H. Tokuno, A. Velarde, P. Evenson, J. Poirier, T. Sakai

Astroparticle Physics, Volume 29, Issue 4, p. 229-242, **2008, File**.

In association with the large solar flare of April 15, 2001, the Chacaltaya neutron monitor observed a 3.6σ enhancement of the counting rate between 13:51 and 14:15 UT. Since the enhancement was observed beginning 11 min before the GLE, solar neutrons must be involved in this enhancement. The integral energy spectrum of solar neutrons can be expressed by a simple power law in energy with the index γ=-3.0±1.0. On the other hand, an integral energy spectrum of solar protons has been obtained in the energy range between 650 MeV and 12 GeV. The spectrum can also be expressed by a power law with the power index γ=-2.75±0.15. The flux of solar protons observed at Chacaltaya (at 12 GeV) was already one order less than the flux of the galactic cosmic rays. It may be the first simultaneous observation of the energy spectra of both high-energy protons and neutrons. Comparing the Yohkoh soft X-ray telescope images with the observed particle time profiles, an interesting picture of the particle acceleration mechanism has been deduced.

Neutron Production in Solar Flares by Reactions of Accelerated 3He

R. J. **Murphy**1 and B. Kozlovsky

2017 ApJ 851 102

Previously, we showed that 3He is enhanced in the ion population accelerated in large solar flares, with a 3He/4He ratio of >0.1; i.e., several orders of magnitude larger than the accepted coronal value. We also showed that when 3He is enhanced, its nuclear reactions with elements of the solar atmosphere can significantly impact both positron production (and the subsequent positron-annihilation line) and the gamma-ray de-excitation-line spectrum. Both the 2.223 MeV neutron-capture line and escaping neutrons are important additional flare observables. Neutron production from reactions of 3He with heavy elements of the solar atmosphere are not currently included in our neutron-production code, and the reliable and consistent analysis of all available solar-flare data requires that neutron-production calculations include these reactions. We evaluate the neutron-production cross sections for these reactions and include them in the code. We then explore how the neutron observables (the escaping-neutron yield and spectrum and the flux of the neutron-capture line) are affected by 3He reactions. We find that neutron production by accelerated 3He reactions with heavy elements is similar to that by accelerated 4He and so will be significant only for accelerated 3He/4He ratios greater than 1.

RHESSI Science Nuggets #338 November **2018**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Neutron_Production_in_Solar_Flares

Neutron-decay Protons from Solar Flares as Seed Particles for CME-shock Acceleration in the Inner Heliosphere

Ronald J. **Murphy**1 and Yuan-Kuen Ko

2017 ApJ 846 53

http://iopscience.iop.org.sci-hub.cc/0004-637X/846/1/53/

The protons in large solar energetic particle events are accelerated in the inner heliosphere by fast shocks produced by coronal mass ejections. Unless there are other sources, the protons these shocks act upon would be those of the solar wind (SW). The efficiency of the acceleration depends on the kinetic energy of the protons. For a 2000 km s−1 shock, the most effective proton energies would be 30–100 keV; i.e., within the suprathermal tail component of the SW. We investigate one possible additional source of such protons: those resulting from the decay of solar-flare-produced neutrons that escape from the Sun into the low corona. The neutrons are produced by interactions of flare-accelerated ions with the solar atmosphere. We discuss the production of low-energy neutrons in flares and their decay on a interplanetary magnetic field line near the Sun. We find that even when the flaring conditions are optimal, the 30–100 keV neutron-decay proton density produced by even a very large solar flare would be only about 10% of that of the 30–100 keV SW suprathermal tail. We discuss the implication of a seed-particle source of more frequent, small flares.

EVIDENCE FOR ENHANCED ^{3}HE IN FLARE-ACCELERATED PARTICLES BASED ON NEW CALCULATIONS OF THE GAMMA-RAY LINE SPECTRUM

R. J. **Murphy**[1], B. Kozlovsky[2], and G. H. Share[3]

2016 *ApJ* **833** 196

The 3He abundance in impulsive solar energetic particle (SEP) events is enhanced up to several orders of magnitude compared to its photospheric value of [3He]/[4He] = 1–3 × 10−4. Interplanetary magnetic field and timing observations suggest that these events are related to solar flares. Observations of 3He in flare-accelerated ions would clarify the relationship between these two phenomena. Energetic 3He interactions in the solar atmosphere produce gamma-ray nuclear-deexcitation lines, both lines that are also produced by protons and α particles and lines that are essentially unique to 3He. Gamma-ray spectroscopy can, therefore, reveal enhanced levels of accelerated 3He. In this paper, we identify all significant deexcitation lines produced by 3He interactions in the solar atmosphere. We evaluate their production cross sections and incorporate them into our nuclear deexcitation-line code. We find that enhanced 3He can affect the entire gamma-ray spectrum. We identify gamma-ray line features for which the yield ratios depend dramatically on the 3He abundance. We determine the accelerated 3He/α ratio by comparing these ratios with flux ratios measured previously from the gamma-ray spectrum obtained by summing the 19 strongest flares observed with the Solar Maximum Mission Gamma-Ray Spectrometer. All six flux ratios investigated show enhanced 3He, confirming earlier suggestions. The 3He/α weighted mean of these new measurements ranges from 0.05 to 0.3 (depending on the assumed accelerated α/proton ratio) and has a <1 × 10−3 probability of being consistent with the photospheric value. With the improved code, we can now exploit the full potential of gamma-ray spectroscopy to establish the relationship between flare-accelerated ions and 3He-rich SEPs.

The time profile of relativistic solar particle events as observed by neutron monitors

Sophie **Musset**1, Karl-Ludwig Klein2*, Nicolas Fuller2, Gaelle Khreich2,3 and Antonin Wargnier2

J. Space Weather Space Clim. **2023**, 13, 15
https://www.swsc-journal.org/articles/swsc/pdf/2023/01/swsc220075.pdf **File**
The most energetic particles accelerated in solar eruptive events are protons and nuclei with energies that may reach a few tens of GeV. They can be detected on the Earth through the secondaries they produce when interacting with the atmosphere. Solar energetic particle events where this happens are called Ground-Level Enhancements (GLEs). Their study is relevant on the one hand because the high particle energies pose particularly strong challenges to the understanding of the acceleration processes. On the other hand, the secondary particles constitute a source of radiation in the atmosphere that may temporarily exceed the permanent dose rate from galactic cosmic rays. This makes the monitoring of radiation doses received by aircrew from GLEs one issue of space weather services for civil aviation. This study addresses the time profiles of GLEs, in the search for commonalities that can be used to constrain models of acceleration and propagation and to forecast the evolution of an ongoing event. We investigate historical GLEs (1971–2012) with the worldwide network of neutron monitors, comparing the rise and the decay as observed by the neutron monitor with the strongest response. The sample comprises 23 events. We evaluate statistical correlations between rise time and decay time inferred from fits to the time profiles and compute a normalised median GLE time profile. An empirical correlation reported in earlier work between the observed rise times and decay times of the neutron monitor count rate profiles is confirmed. We find indications of a statistical relationship between the rise times and the parent eruptive activity. We discuss ideas on the mechanisms behind the correlation of rise and decay times and on its usefulness for space weather services. **1982 Dec 7, 1989 Nov 15, 2000 Jul 14 , 2001 Apr 15**
Table 1. GLEs used in the present study 1971(GLE22) – 2012(GLE71)
Table 2. List of GLEs, in the order of increasing time to maximum, and of parameters of the associated SXR bursts and CMEs

Features of Solar Energetic Particle Events During the 23rd Cycle of Solar Activity and their Relationship with Solar X-ray, Gamma-Emission and Coronal Mass Ejections

Myagkova I.N., Miteva R., Kashapova L., Bogomolov A.V., Danov D.
Proceedings of Eleventh Workshop “Solar Influences on the Magnetosphere, Ionosphere and Atmosphere” Primorsko, Bulgaria, June 3÷7, **2019**, p. 201-206
http://ws-sozopol.stil.bas.bg/2019Primorsko/Proceedings2019.pdf
The study on the relationship of solar cosmic ray events (in particular, the ratio of the maximum between the proton and electron fluxes) with X-ray and gamma radiation from solar flares, as well as with parameters of coronal mass ejections was carried out. It was done on the basis of SOHO/ERNE proton event catalog (http://newserver.stil.bas.bg/SEPcatalog/) and Solar Flares Catalog based on measurements of X- and gamma-emission (>50 keV) detected by SONG (CORONAS-F – Russian solar observatory) from August, 2001 till December, 2003 (http://swx.sinp.msu.ru/apps/solar_flares_cat/index.php). Solar electron flux (> 300 keV) were measured in the polar caps by MKL-instrument on board CORONAS-F satellite.

Prompt emission of relativistic protons up to GeV energies from M6.4-class solar flare on July 17, 2023

Carlos **Navia**, Marcel Oliveira, Andre Nepomuceno
ApJ **2024**
https://arxiv.org/pdf/2401.00002.pdf
We show evidence of *particle acceleration at GEV energies associated directly with protons from the prompt emission of a long-duration M6-class solar flare on **July 17, 2023**, rather than from protons acceleration by shocks from its associated Coronal Mass Ejection (CME),* which erupted with a speed of 1342 km/s. Solar Energetic Particles (SEP) accelerated by the blast have reached Earth, up to an almost S3 (strong) category of a radiation storm on the NOAA scale. Also, we show a temporal correlation between the fast rising of GOES-16 proton and muon excess at ground level in the count rate of the New-Tupi muon detector at the central SAA region. A Monte Carlo spectral analysis based on muon excess at New-Tupi is consistent with *the acceleration of electrons and protons (ions) up to relativistic energies (GeV energy range) in the impulsive phase of the flare*. In addition, we present another two marginal particle excesses (with low confidence) at ground-level detectors in correlation with the solar flare prompt emission.

Characterization of the Early Dynamics of Solar Coronal Bright Fronts

Mohamed **Nedal**, Kamen Kozarev, Rositsa Miteva, Oleg Stepanyuk, Momchil Dechev
Bulgarian Astronomical Journal **2024**
https://arxiv.org/pdf/2404.03396.pdf
We present a comprehensive characterization of 26 CME-driven compressive waves known as Coronal Bright Fronts (CBFs) observed in the low solar corona between 2010 and 2017. These CBFs have been found to be associated with SEP events near Earth, indicating their importance in understanding space weather phenomena. The aim of this study is to analyze and describe the early dynamics of CBFs using a physics-based heliospheric SEP

forecasting system known as the SPREAdFAST framework. This framework utilizes a chain of data-driven analytic and numerical models to predict SEP fluxes at multiple locations in the inner heliosphere by considering their acceleration at CMEs near the Sun and subsequent interplanetary transport. To estimate the time-dependent plasma and compression parameters of the CBFs, we utilized sequences of base-difference images obtained from the AIA instrument on board the SDO satellite, and measurements of the height-time profiles of the CMEs obtained from the LASCO instrument on board the SOHO satellite. We employed kinematic measurements and plasma model results to derive these parameters. The SPREAdFAST framework facilitated the analysis and correlation of these observations with SEP events near Earth. Our analysis yielded statistical relations and distributions for both the shocks and plasma parameters associated with the 26 CBFs investigated. By combining the observations from the AIA and LASCO instruments, as well as the data products from the SPREAdFAST framework, we obtained a comprehensive understanding of the early dynamics of CBFs, including their temporal evolution, plasma properties, and compressional characteristics. These findings contribute to the growing body of knowledge in the field and have implications for space weather forecasting and the study of SEP events. **2011-05-11**
Table 1: List of the CBF events with their associated flares and CMEs 2010-2017

Forecasting Solar Energetic Proton Integral Fluxes with Bi-Directional Long Short-Term Memory Neural Networks

Mohamed **Nedal**, Kamen Kozarev, Nestor Arsenov, Peijin Zhang
Journal of Space Weather and Space Climate **2023**, 13, 26
https://arxiv.org/pdf/2309.11636.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2023/01/swsc230017.pdf

Solar energetic particles are mainly protons and originate from the Sun during solar flares or coronal shock waves. Forecasting the Solar Energetic Protons (SEP) flux is critical for several operational sectors, such as communication and navigation systems, space exploration missions, and aviation flights, as the hazardous radiation may endanger astronauts', aviation crew and passengers' health, the delicate electronic components of satellites, space stations, and ground power stations. Therefore, the prediction of the SEP flux is of high importance to our lives and may help mitigate the negative impacts of one of the serious space weather transient phenomena on the near-Earth space environment. Numerous SEP prediction models are being developed with a variety of approaches, such as empirical models, probabilistic models, physics-based models, and AI-based models. In this work, we use the bi-directional long short-term memory (BiLSTM) neural network model architecture to train SEP forecasting models for 3 standard integral GOES channels (>10 MeV, >30 MeV, and >60 MeV) with 3 forecast windows (1-day, 2-day, and 3-day ahead) based on daily data obtained from the OMNIWeb database from 1976 to 2019. As the SEP variability is modulated by the solar cycle, we select input parameters that capture the short-term, typically within a span of a few hours, and long-term, typically spanning several days, fluctuations in solar activity. We take the F10.7 index, the sunspot number, the time series of logarithm of the x-ray flux, the solar wind speed, and the average strength of the interplanetary magnetic field as input parameters to our model. The results are validated with an out-of-sample testing set and benchmarked with other types of models.
ERRATUM J. Space Weather Space Clim. **2023, 13**, 29 https://www.swsc-journal.org/articles/swsc/pdf/2023/01/swsc230031s.pdf

Energetic Particles, Tangential Discontinuities, and Solar Flux Tubes†

M. **Neugebauer**1,* andJ. Giacalone
JGR **2015**

This study examines the probable sources of sharp changes in the flux of energetic particles (EPs) in the solar wind. Data acquired by the ACE LEMS sensors during 1999 were used to identify EP boundaries that were not located at interplanetary shocks or caused by intermittent connection to the Earth's bow shock. It was found that at least 68%, and probably 80%, of such boundaries occur at significant changes in the plasma and magnetic field in the solar wind. Those changes are consistent with crossing pre-existing tangential discontinuities or flux-tube boundaries rather than by local MHD turbulence or time-dependent bursts of acceleration. Because some of the EP boundaries would not have been detected by Borovsky's [2008] analysis of flux-tube boundaries, it is concluded that such boundaries in the solar wind are at least 30% more prevalent than previously suggested. The result can also be used to explain some observations of localized variations in EP flux both ahead of and behind the interplanetary shocks where particle acceleration occurred without requiring local acceleration.

Comparison of solar X-ray line emission with microwave emission during flares.

Neupert,W..M.:
1968, Astrophys. J. 153, L59 – L64.

SHOCK ACCELERATION OF SOLAR ENERGETIC PROTONS: THE FIRST 10 MINUTES
C. K. **Ng** and D. V. Reames

Astrophysical Journal, 686: L123–L126, **2008** October
http://www.journals.uchicago.edu/doi/pdf/10.1086/592996
Proton acceleration at a parallel coronal shock is modeled with self-consistent Alfve´n wave excitation and shock transmission. 18–50 keV seed protons at 0.1% of plasma proton density are accelerated in 10 minutes to a power-law intensity spectrum rolling over at 300 MeV by a 2500 km s^{-1} shock traveling outward from 3.5 , for typical coronal conditions and low ambient wave intensities. Interaction of high-energy protons of large $r_{,}$ pitch angles with Alfve´n waves amplified by low-energy protons of small pitch angles is key to rapid acceleration. Shock acceleration is not significantly retarded by sunward streaming protons interacting with downstream waves. There is no significant second-order Fermi acceleration.

Cannibals in PARADISE: The Effect of Merging Interplanetary Shocks on Solar Energetic Particle Events

Antonio **Niemela**1,2, Nicolas Wijsen1, Angels Aran3,4, Luciano Rodriguez2, Jasmina Magdalenic1,2, and Stefaan Poedts1,5
2024 ApJL 967 L35
https://iopscience.iop.org/article/10.3847/2041-8213/ad4c70/pdf
Gradual solar energetic particle (SEP) events are associated with shocks driven by coronal mass ejections (CMEs). The merging of two CMEs (so-called cannibalistic CMEs) and the interaction of their associated shocks has been linked to some of the most powerful solar storms ever recorded. Multiple studies have focused on the observational aspects of these SEP events, yet only a handful have focused on modeling similar CME–CME interactions in the heliosphere using advanced magnetohydrodynamic (MHD) models. This work presents, to our knowledge, the first modeling results of a fully time-dependent 3D simulation that captures both the interaction of two CMEs and its effect on the acceleration and transport of SEPs. This is achieved by using an MHD model for the solar wind and CME propagation together with an integrated SEP model. We perform different simulations and compare the behavior of the energetic protons in three different solar wind environments, where a combination of two SEP-accelerating CMEs are modeled. We find that particle acceleration is significantly affected by the presence of both CMEs in the simulation. Initially, less efficient acceleration results in lower-energy particles. However, as the CMEs converge and their shocks eventually merge, particle acceleration is significantly enhanced through multiple acceleration processes between CME-driven shocks, resulting in higher particle intensities and energy levels. **2015-06-25**

Advancing interplanetary magnetohydrodynamic models through solar energetic particle modelling
Insights from the 2013 March 15 SEP event⋆

A. **Niemela**1,2, N. Wijsen3,4, A. Aran5,6, L. Rodriguez2, J. Magdalenic1,2 and S. Poedts1,7
A&A 679, A93 (**2023**)
https://www.aanda.org/articles/aa/pdf/2023/11/aa47116-23.pdf
Aims. This study utilises a modelling approach to investigate the impact of perturbed solar wind conditions caused by multiple interplanetary coronal mass ejections (ICMEs) on the evolution of solar energetic particle (SEP) distributions. Furthermore, we demonstrate the utility of SEP models in evaluating the performance of solar wind and coronal mass ejection (CME) models. To illustrate these concepts, we focussed on modelling the gradual SEP event that occurred on 2023 March 15.
Methods. We utilised the 3D magnetohydrodynamic model EUHFORIA (EUropean Heliospheric FORecasting Information Asset) to simulate the various ICMEs that caused the highly perturbed solar wind conditions observed during the March 15 event. We conducted three separate EUHFORIA simulations, employing both non-magnetised and magnetised models for these ICMEs. To analyse the behaviour of energetic particles in the simulated solar wind environments, we employed the energetic particle transport and acceleration model PARADISE (PArticle Radiation Asset Directed at Interplanetary Space Exploration).
Results. In the vicinity of Earth, the three EUHFORIA simulations exhibit strong similarities and closely match the observed in situ data. Nevertheless, when incorporating these distinct solar wind configurations into PARADISE, notable disparities emerge in the simulated SEP intensities. This discrepancy can be attributed to the different magnetic enhancements and closed magnetic structures introduced by the different CME models within the EUHFORIA simulations. These variations strongly impact the transport mechanisms of SEPs, leading to significant deviations in the particle intensities simulated by PARADISE. Furthermore, our findings highlight the significance of cross-field diffusion even in scenarios with reduced perpendicular mean free path. This effect becomes particularly prominent when SEPs are trapped within the inner heliosphere due to the presence of ICMEs. In these scenarios, the extended duration of confinement allows the slower cross-field diffusion process to become more pronounced and exert a greater influence on the spatial distribution of SEPs, especially near and within the boundaries of ICMEs.

Conclusions. Solar energetic particle models enable us to indirectly validate the accuracy of the underlying solar wind and CME models across significant portions of the heliosphere, rather than solely relying on discrete points where spacecraft are situated. This broader validation provides valuable insights into the reliability and effectiveness of the CME models on a global scale.

Mult-viewpoint Observations of a Widely Distributed Solar Energetic Particle Event: the Role of EUV Waves and Shock Signatures

Alexander **Nindos**∗1 , Athanasios Kouloumvakos1 , Spiros Patsourakos1 , Angelos Vourlidas2 , Anastasios Anastasiadis3 , Alexander Hillaris4 , and Ingmar Sandberg3

CESRA **2016** p.38

http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v3.pdf

On **2012 March 7**, two large eruptive events occurred in the same active region within 1 hr from each other. Each consisted of an X-class flare, a coronal mass ejection (CME), an extreme-ultraviolet (EUV) wave, and a shock wave. The eruptions gave rise to a major solar energetic particle (SEP) event observed at widely separated (˜120◦) points in the heliosphere. From multi-viewpoint energetic proton recordings we determine the proton release times at STEREO B and A (STB, STA) and the first Lagrange point (L1) of the Sun–Earth system. Using EUV and white-light data, we determine the evolution of the EUV waves in the low corona and reconstruct the global structure and kinematics of the first CME's shock, respectively. We compare the energetic proton release time at each spacecraft with the EUV waves' arrival times at the magnetically connected regions and the timing and location of the CME shock. We find that the first flare/CME is responsible for the SEP event at all three locations. The proton release at STB is consistent with arrival of the EUV wave and CME shock at the STB footpoint. The proton release time at L1 was significantly delayed compared to STB. Three-dimensional modeling of the CME shock shows that the particle release at L1 is consistent with the timing and location of the shock's western flank. This indicates that at L1 the proton release did not occur in low corona but farther away from the Sun. However, the extent of the CME shock fails to explain the SEP event observed at STA. A transport process or a significantly distorted interplanetary magnetic field may be responsible.

Solar Activities Associated with 3He-rich Solar Energetic Particle Events Observed by Solar Orbiter

Nariaki **Nitta**, Radoslav Bučík, Radoslav Bučík, Glenn Mason, George Ho, Christina Cohen, Raul Gómez-Herrero, Linghua Wang, and Laura Balmaceda

Front. Astron. Space Sci. 10: 1148467. **2023**

doi: 10.3389/fspas.2023.1148467

https://www.frontiersin.org/articles/10.3389/fspas.2023.1148467/full

https://www.frontiersin.org/articles/10.3389/fspas.2023.1148467/pdf

A series of 3He-rich solar energetic particle (SEP) events was observed by Solar Orbiter in May 2021 at a radial distance of 0.95 AU. An isolated active region AR 12824 was likely the ultimate source of these SEP events. The period of the enhanced flux of 3He was also a period of frequent type III bursts in the decametric-hectometric range, confirming their close relationship. As in past studies, we try to find the solar activities possibly responsible for 3He-rich SEP events, using the type III bursts close to the particle injection times estimated from the velocity dispersion. But this exercise is not as straightforward as in many of the past studies since the region produced many more type III bursts and jet-like eruptions than the SEP injections. We may generalize the solar activities for the 3He-rich SEP events in question as coronal jets, but their appearances do not necessarily conform to classic jets that consist of a footpoint and a spire. Conversely, such jets often did not accompany type III bursts. The areas that produced jet-like eruptions changed within the active region from the first to the second set of 3He-rich SEP events, which may be related to the extended coronal mass ejection that launched stealthily. **21–24 May 2021**

Understanding the Origin of Variable Compositions of Gradual Solar Energetic Particle Events by Combining Observations and Numerical Simulations

Nariaki **Nitta**1, Meng Jin1,2 ,Christina Cohen3

ECU2020 Presentation #21333

15 Apr 2001, 4 Nov 2001, 24 Aug 2002, 2014-02-25, 11 Apr 2013,

Solar Sources of 3He-rich Solar Energetic Particle Events in Solar Cycle 24

Nariaki V. **Nitta**, Glenn M. Mason, Linghua Wang, Christina M. S. Cohen, Mark E. Wiedenbeck

ApJ **806** 235 **2015**

http://arxiv.org/pdf/1505.06804v1.pdf

Using high-cadence extreme-ultraviolet (EUV) images obtained by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory, we investigate the solar sources of 26 3He-rich solar energetic particle

(SEP) events at ≲1 MeV nucleon-1 that were well-observed by the Advanced Composition Explorer during solar cycle 24. Identification of the solar sources is based on the association of 3He-rich events with type III radio bursts and electron events as observed by Wind. The source locations are further verified in EUV images from the Solar and Terrestrial Relations Observatory, which provides information on solar activities in the regions not visible from the Earth. Based on AIA observations, 3He-rich events are not only associated with coronal jets as emphasized in solar cycle 23 studies, but also with more spatially extended eruptions. The properties of the 3He-rich events do not appear to be strongly correlated with those of the source regions. As in the previous studies, the magnetic connection between the source region and the observer is not always reproduced adequately by the simple potential field source surface model combined with the Parker spiral. Instead, we find a broad longitudinal distribution of the source regions extending well beyond the west limb, with the longitude deviating significantly from that expected from the observed solar wind speed.

Table 1 List of 3He-rich SEP Events with Clear Injections and/or Accompanied by Electron Events

Table 2 Various Observations Related to 3He-rich SEP Events

2012 January 13, 2014 May 16,

What Are Special About Ground-Level Events?

Flares, CMEs, Active Regions and Magnetic Field Connection **Review**

N.V. **Nitta**, Y. Liu, M.L. DeRosa, R.W. Nightingale,

Space Sci. Rev. 171, Numbers 1-4, 61-83, **2012**, **File**

https://link.springer.com/content/pdf/10.1007/s11214-012-9877-1.pdf

sci-hub.si/10.1007/s11214-012-9877-1

Ground level events (GLEs) occupy the high-energy end of gradual solar energetic particle (SEP) events. They are associated with coronal mass ejections (CMEs) and solar flares, but we still do not clearly understand the special conditions that produce these rare events. During Solar Cycle 23, a total of 16 GLEs were registered, using ground-based neutron monitor data. We first ask if these GLEs are clearly distinguishable from other SEP events observed from space. Setting aside possible difficulties in identifying all GLEs consistently, we then try to find observables which may unmistakably isolate these GLEs by studying the basic properties of the associated eruptions and the active regions (ARs) that produced them. It is found that neither the magnitudes of the CMEs and flares nor the complexities of the ARs give sufficient conditions for GLEs. It is possible to find CMEs, flares or ARs that are not associated with GLEs but that have more extreme properties than those associated with GLEs. We also try to evaluate the importance of magnetic field connection of the AR with Earth on the detection of GLEs and their onset times. Using the potential field source surface (PFSS) model, a half of the GLEs are found to be well-connected. However, the GLE onset time with respect to the onset of the associated flare and CME does not strongly depend on how well-connected the AR is. The GLE onset behavior may be largely determined by when and where the CME-driven shock develops. We could not relate the shocks responsible for the onsets of past GLEs with features in solar images, but the combined data from the Solar TErrestrial RElations Observatory (STEREO) and the Solar Dynamics Observatory (SDO) have the potential to change this for GLEs that may occur in the rising phase of Solar Cycle 24.

Coronal Jet Observed by Hinode As The Source Of A 3He-rich Solar Energetic Particle Event

Nariaki V. **Nitta**1, Glenn M. Mason2, Mark E. Wiedenbeck3,4, Christina M. S. Cohen4, S¨am Krucker5, Iain G. Hannah5, Masumi Shimojo6 and Kazunari Shibata7

E-print, Feb 2008; ApJL, 675:L125–L128, **2008** March 10

http://www.journals.uchicago.edu/doi/pdf/10.1086/533438

We study the solar source of the 3He-rich solar energetic particle (SEP) event observed on 2006 November 18.

SOLAR SOURCES OF IMPULSIVE SOLAR ENERGETIC PARTICLE EVENTS AND THEIR MAGNETIC FIELD CONNECTION TO THE EARTH

Nariaki V. **Nitta**,1 Donald V. Reames,2 Marc L. DeRosa,1 Yang Liu,3 Seiji Yashiro,4 and Natchimuthuk Gopalswamy5

The Astrophysical Journal, 650:438-450, **2006**

the solar origin of impulsive solar energetic particle (SEP) events, often referred to as 3He-rich flares, type III radio bursts

LOW CORONAL SIGNATURES OF LARGE SOLAR ENERGETIC PARTICLE EVENTS

Nariaki V. **Nitta**,1 Edward W. Cliver,2 and Allan J. Tylka3

Astrophysical Journal, 586:L103–L106, **2003, File**

We report on the low coronal signatures of major solar energetic particle (SEP) events. Because large SEP events are highly associated with both flares and coronal mass ejections, we focused on flare-associated motions in soft X-rays. In a sample of a half-dozen well-observed flares associated with SEP events, we identified two basic types of motions or ejections. For one class of events including those of **2001 November 4 and 1998 April 20**, the ejections occur on active region or larger scales. They have an extended "preeruption" phase in which the involved structures slowly rise or expand on timescales of tens of minutes. For the second class of events, including those on **1997 November 6 and 2001 April 15**, the large-scale preeruption phase is absent. In these events, ejecta appear explosively at the onset of the flare impulsive phase. The observed differences in ejections appear to correlate with spectral/compositional/charge state characteristics of large SEP events, suggesting that flare ejecta are diagnostic of shock properties/environment.

Predicting >10 MeV SEP Events from Solar Flare and Radio Burst Data.

Núñez, M., Paul-Pena, D.,
2020. Universe 6 (10), 161.
https://www.mdpi.com/2218-1997/6/10/161

The prediction of solar energetic particle (SEP) events or solar radiation storms is one of the most important problems in the space weather field. These events may have adverse effects on technology infrastructures and humans in space; they may also irradiate passengers and flight crews in commercial aircraft flying at polar latitudes. This paper explores the use of ≥ M2 solar flares and radio burst observations as proxies for predicting >10 MeV SEP events on Earth. These observations are manifestations of the parent event at the sun associated with the SEP event. As a consequence of processing data at the beginning of the physical process that leads to the radiation storm, the model may provide its predictions with large anticipation. The main advantage of the present approach is that the model analyzes solar data that are updated every 30 min and, as such, it may be operational; however, a disadvantage is that those SEP events associated with strong well-connected flares cannot be predicted. For the period from November 1997 to February 2014, we obtained a probability of detection of 70.2%, a false alarm ratio of 40.2%, and an average anticipation time of 9 h 52 min. In this study, the prediction model was built using decision trees, an interpretable machine learning technique. This approach leads to outputs and results comparable to those derived by the Empirical model for Solar Proton Event Real Time Alert (ESPERTA) model. The obtained decision tree shows that the best criteria to differentiate pre-SEP scenarios and non-pre-SEP scenarios are the peak and integrated flux for soft X-ray flares and the radio type III bursts.

Predicting well-connected SEP events from observations of solar EUVs and energetic protons

Marlon **Núñez**1*, Teresa Nieves-Chinchilla2 and Antti Pulkkinen2
J. Space Weather Space Clim. **2019**, 9, A27
https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180069.pdf

This study shows a quantitative assessment of the use of Extreme Ultraviolet (EUV) observations in the prediction of Solar Energetic Proton (SEP) events. The UMASEP scheme (Space Weather, 9, S07003, 2011; 13, 2015, 807–819) forecasts the occurrence and the intensity of the first hours of SEP events. In order to predict well-connected events, this scheme correlates Solar Soft X-rays (SXR) with differential proton fluxes of the GOES satellites. In this study, we explore the use of the EUV time history from GOES-EUVS and SDO-AIA instruments in the UMASEP scheme. This study presents the results of the prediction of the occurrence of well-connected >10 MeV SEP events, for the period from May 2010 to December 2017, in terms of Probability of Detection (POD), False Alarm Ratio (FAR), Critical Success Index (CSI), and the average and median of the warning times. The UMASEP/EUV-based models were calibrated using GOES and SDO data from May 2010 to October 2014, and validated using out-of-sample SDO data from November 2014 to December 2017. The best results were obtained by those models that used EUV data in the range 50–340 Å. We conclude that the UMASEP/EUV-based models yield similar or better POD results, and similar or worse FAR results, than those of the current real-time UMASEP/SXR-based model. The reason for the higher POD of the UMASEP/EUV-based models in the range 50–340 Å, was due to the high percentage of successful predictions of well-connected SEP events associated with <C4 flares and behind-the-limb flares, which amounted to 25% of all the well-connected events during the period May 2010 to December 2017. By using all the available data (2010–2017), this study also concluded that the simultaneous use of SXRs and EUVs in 94 Å in the UMASEP-10 tool for predicting all >10 MeV SEP events, improves the overall performance, obtaining a POD of 92.9% (39/42) compared with 81% (34/42) of the current tool, and a slightly worse FAR of 31.6% (18/57) compared with 29.2% (14/58) of the current tool. **August 4, 2011, September 30, 2013, June 26, 2015, October 29, 2015**
Table 1. List of prompt SEP events with energies >10 MeV which occurred from May 2010 to December 2017.

Predicting well-connected SEP events from observations of solar soft X-rays and near-relativistic electrons

Marlon **Núñez**
J. Space Weather Space Clim. **2018**, 8, A36

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc180006.pdf
This paper studies the use of electron data from the Electron Proton Alpha Monitor (EPAM) on board the Advanced Composition Explorer (ACE) in the UMASEP (University of Málaga Solar particle Event Predictor) scheme [Núñez, Space Weather 9 (2011) S07003; Núñez, Space Weather 13 (2015)] for predicting well-connected >10 MeV Solar Energetic Proton (SEP) events. In this study, the identification of magnetic connection to a solar particle source is done by correlating Geostationary Operational Environmental Satellites (GOES) Soft X-Ray (SXR) fluxes with ACE EPAM electrons fluxes with energies of 0.175–0.375 MeV. The forecasting performance of this model, called Well-Connected Prediction with electrons (WCP-electrons), was evaluated for a 16-year period from November 2001 to October 2017. This performance is compared with that of the component of current real-time tool UMASEP-10, called here WCP-protons model, which predicts the same type of events by correlating GOES SXR with differential proton fluxes with energies of 9–500 MeV. For the aforementioned period, the WCP-electrons model obtained a Probability of Detection (POD) of 50.0%, a False Alarm Ratio (FAR) of 39% and an Average Warning Time (AWT) of 1 h 44 min. The WCP-protons model obtained a POD of 78.0%, a FAR of 22% and an AWT of 1 h 3 min. These results show that the use of ACE EPAM electron data in the UMASEP scheme obtained a better anticipation time (additional 41 min on average) but a lower performance in terms of POD and FAR. We also analyzed the use of a combined model, composed of WCP-electrons and WCP-protons, working in parallel (i.e. the combined model issues a forecast when any of the individual models emits a forecast). The combined model obtained the best POD (84%), and a FAR and AWT (34.4% and 1 h 34 min, respectively) which is in between those of the individual models. **April 11, 2013**
Table 1. Forecasting results of the WCP-electrons and WCP-protons model for predicting all prompt SEP events with energies >10 MeV which occurred from November 2001 to October 2017

HESPERIA Forecasting Tools: Real-Time and Post-Event **Review**

Marlon **Núñez,** Karl-Ludwig Klein, Bernd Heber, Olga E. Malandraki, Pietro Zucca, Johannes Labrens, Pedro Reyes-Santiago, Patrick Kuehl, and Evgenios Pavlos
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 7, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
Within the HESPERIA Horizon 2020 project, two novel real-time tools to predict Solar Energetic Particle (SEP) events were developed. The HESPERIA UMASEP-500 tool makes real-time predictions using a lag-correlation between the soft X-ray (SXR) flux and high-energy differential proton fluxes of the GOES satellite network. We found that the use of proton data alone allowed this tool to make predictions before any Neutron Monitor (NM) station's alert. The performance of this tool for predicting Ground Level Enhancement (GLE) events for the period 2000–2016 may be summarized as follows: the probability of detection (POD) was 53.8%, the false alarm ratio (FAR) was 30%, and the average warning time (AWT) to the first NM station's alert was 8 min. The developed HESPERIA REleASE tool makes real-time predictions of the proton flux-time profiles of 30–50 MeV protons at L1 and is based on electron intensity measurements of energies from 0.25 to 1 MeV and their intensity changes. The performance was tested by using all historic ACE/EPAM and SOHO/EPHIN data from 2009 until 2016 and has shown that the forecast tools have a low FAR (30%) and a high POD (63%). Furthermore, two methods using historical data were explored for predicting SEP events and compared. The UMASEP-10mw tool was developed for predicting >10 MeV SEP events using microwave data. The time derivative of the soft X-rays (SXR) was replaced by the microwave flux density. It was found that the use of SXRs and microwave data produced the same POD (78%) with the most notable difference being that the use of microwave data does not yield any false alarm. Furthermore, a study was carried out on the possibility for the microwave emissions to be used to predict the spectral hardness of the SEP event and important results were deduced.

Real-time prediction of the occurrence of GLE events

Marlon **Núñez**, Pedro J. Reyes-Santiago, Olga E. Malandraki
Space Weather Volume 15, Issue 7 July **2017** Pages 861–873
http://sci-hub.st/10.1002/2017SW001605
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001605
A tool for predicting the occurrence of Ground Level Enhancement (GLE) events using the UMASEP scheme is presented. This real-time tool, called HESPERIA UMASEP-500, is based on the detection of the magnetic connection, along which protons arrive in the near-Earth environment, by estimating the lag correlation between the time derivatives of 1 min soft X-ray flux (SXR) and 1 min near-Earth proton fluxes observed by the GOES satellites. Unlike current GLE warning systems, this tool can predict GLE events before the detection by any neutron monitor (NM) station. The prediction performance measured for the period from 1986 to 2016 is presented for two consecutive periods, because of their notable difference in performance. For the 2000–2016 period, this

prediction tool obtained a probability of detection (POD) of 53.8% (7 of 13 GLE events), a false alarm ratio (FAR) of 30.0%, and average warning times (AWT) of 8 min with respect to the first NM station's alert and 15 min to the GLE Alert Plus's warning. We have tested the model by replacing the GOES proton data with SOHO/EPHIN proton data, and the results are similar in terms of POD, FAR, and AWT for the same period. The paper also presents a comparison with a GLE warning system. **28 October 2003**,

Table 1. Forecasting results for GLE events from 1986 to 2016

A preliminary assessment of the failed and successful predictions of proton spectral hardness using microwave emission

WP2 Team (OBSPARIS, NOA, UMA) Leader: Marlon **Nunez**

August 26, **2016**

https://www.hesperia.astro.noa.gr/WP2/Hesperia_task_2-2.pdf **File**

Task 2-2 of the HESPERIA project aims at investigating if the hardness or softness of the proton spectrum in interplanetary space can be predicted from the shape of the microwave spectrum. The technique developed by Chertok et al (2009) is to use the ratio of peak microwave flux densities near 9 and 15 GHz as a predictor: hard proton spectra (characterized in Chertok et al (2009) and in the following by the logarithm of the ratio of the proton intensities above 10 MeV and above 100 MeV, δ = log J(E > 10 MeV) J(E > 100 MeV) are predicted when the high-frequency microwave emission is important - that is, when the ratio of the 9 GHz flux density to the 15 GHz flux density is low, whereas steep proton spectra are predicted when this ratio is high. The purpose of the present document is to re-evaluate this tool, and to discuss when it works, when not, and why it fails in certain cases. We also assess if the flux density ratio used by Chertok et al (2009) can be replaced by another parameter, namely the peak frequency of the microwave spectrum.

Real-time prediction of the occurrence and intensity of the first hours of >100 MeV solar energetic proton events

Marlon **Núñez**

Space Weather Volume 13, Issue 11 November **2015** Pages 807–819 DOI: 10.1002/2015SW001256

Space Weather Quarterly Vol. 12, Issue 4, p. 21-34, **2015**

http://onlinelibrary.wiley.com/doi/10.1002/SWQv12i004/epdf

http://sci-hub.cc/10.1002/2015SW001256

A new model for predicting the occurrence of >100 MeV solar energetic proton (SEP) events and the first hours of the >100 MeV integral proton flux is presented. This model uses a novel approach based on the lag correlation between strong positive derivatives of X-ray flux and proton flux. The new model has been validated with data from January 1994 to September 2013, obtaining a probability of detection of all >100 MeV SEP events of 80.85%, a false alarm ratio of 29.62%, and an average warning time of 1 h and 6 min. The model identifies the associated flare and active region. Currently, there is no other automatic empirical or physics-based system able to predict SEP events of energies in the interval of 100 MeV to ~430 MeV (lower GLE cutoff according to Clem and Dorman (2000)). This paper also proposes the combined use of the new prediction model and the existing one for predicting >10 MeV SEP events. The combined SEP prediction models have been developed to improve mitigation of adverse effects on near-Earth and interplanetary missions.

Table 1. Results of the use of the >100 MeV model for prediction of all SEP events in the interval from January 1994 to September 2013

Predicting Solar Energetic Proton Events (E > 10 MeV),

Nu.n˜ ez, M.,

Space Weather, 9, S07003, **2011**.

http://sci-hub.cc/10.1029/2010SW000640

A high level of proton radiation exposure can be dangerous to astronauts, satellite equipment, and air passengers/crew flying along polar routes. The presented solar energetic proton (SEP) event forecaster is based on a dual-model approach for predicting the time interval within which the integral proton flux is expected to meet or surpass the Space Weather Prediction Center threshold of J (E > 10 MeV) = 10 pr cm-2 sr-1 s-1 and the intensity of environment data (soft X-ray, differential and integral proton fluxes). The purpose of the first model is to identify precursors of well-connected events by empirically estimating the magnetic connectivity from the associated CME/flare process zone to the near-Earth environment and identifying the flare temporally associated with the phenomenon. The goal of the second model is to identify precursors of poorly connected events by using a regression model that checks whether the differential proton flux behavior is similar to that in the beginning phases of previous historically poorly connected SEP events and thus deduce similar consequences. An additional module applies a higher-level analysis for inferring additional information about the situation by filtering out inconsistent preliminary forecasts and estimating the intensity of the first hours of the predicted SEP events. The high-level module periodically retrieves solar data and, in the case of well-connected events, automatically identifies the associated flare and active region. For the events of solar cycles 22 and 23 of the NOAA/SWPC SEP list, the presented dual-model system, called UMASEP, has a probability of detection of all well- and poorly connected events of 80.72% (134/166) and a false alarm rate of 33.99% (69/203), which outperforms current automatic forecasters in predicting >10 MeV SEP events. The presented forecaster has an average warning time of 5 h 10 min for the successfully predicted events, 1 h 5 min for well-connected events and 8 h 28 min for poorly connected events, with a maximum warning time of 24 h for very gradual SEP events.

Direct Determination of a Bare Neutron Counter Yield Function

W. **Nuntiyakul**, P.-S. Mangeard, D. Ruffolo, P. Evenson, J. W. Bieber, J. Clem, A. Hallgren et al.

JGR Volume125, Issue4 April **2020** e2019JA027304

https://doi.org/10.1029/2019JA027304

Ground-based neutron counters are a standard tool for detecting atmospheric showers from GeV range primary cosmic rays of either solar or galactic origin. Bare neutron counters, a type of lead-free neutron monitor, function much like standard neutron monitors but have different yield functions primarily because they are more sensitive to neutrons of lower energy. When operated together with standard monitors, the different yield functions allow estimates to be made of the energy spectrum of galactic or solar particles. In 2010 a new array of 12 bare neutron detectors was installed at the South Pole to operate together with the neutron monitor there. Prior to installation, two of the detectors were operated on a ship that traveled from Sweden to Antarctica and back from November 2009 to April 2010. The purpose of this latitude survey was to use Earth's magnetic field as a spectrometer, blocking cosmic rays below the local cutoff rigidity (momentum per unit charge), from which we determined the response function versus rigidity of these bare counters. By comparing that measured response function to direct measurements of the cosmic ray spectrum taken by the PAMELA spacecraft, we were able to make a direct determination of the yield function for these detectors.

On specific features of chemical composition of solar energetic particles<<<

R. A. **Nymmik**

Cosmic Research, Volume 49, Number 3, 240-246, **2011**

(Kosmicheskie Issledovaniya, 2011, Vol. 49, No. 3, pp. 249–255.)

The methodology of analysis and the results of determination of chemical composition of Solar Energetic Particles (SEP) events at energies ≥4 MeV per nucleon are presented. The systematic description of experimental data about chemical composition of SEP is necessary both for better understanding of the processes resulting in generation and propagation of high-energy particles, and for development of a quantitative calculation model of fluxes of SEP particles.

Some problems with developing a standard for determining solar energetic particle fluxes

R.A. **Nymmik**

Advances in Space Research

Volume 47, Issue 4, 15 February **2011**, Pages 622-628

Based on the author's experience in ISO TC20/SC14 Working Group 4, this paper discusses the common problems encountered when developing a standard for solar energetic particle (SEP) fluxes. The problem involving the reliability of the distribution function describing the SEP events and the interpolation of this function into the region of not-yet-observed large events are discussed. The problems with describing the fluences of SEPs over a wide range of energy in the form of energetic spectra are analyzed. Requirements for SEP flux models are formulated. The reliability of some SEP flux models is determined by comparing their predictions with the experimental data.

Solar energetic proton access to the magnetosphere during the 10-14 September 2017 particle event

T. P. **O'Brien**, J. E. Mazur, M. D. Looper

Space Weather 16?, 12, 2022-2037 **2018**

http://sci-hub.tw/10.1029/2018SW001960

We explore the penetration of >60 MeV protons into the magnetosphere during the 10-14 September 2017 solar energetic particle event. Solar energetic particles can cause single event effects and total dose degradation in spacecraft electronics. Therefore, it is important for satellite anomaly analysis to understand how deep into the magnetosphere these particles penetrate. Whereas most studies of geomagnetic cutoffs use low altitude data, we use data from the Relativistic Proton Spectrometer on NASA's Van Allen Probes, which is in a high altitude, elliptical orbit. We determine how the penetration depends on particle energy, location, and direction of incidence. We evaluate multiple published models of the geomagnetic cutoff to determine how well these models constrain the spectrum at the location of a spacecraft inside the magnetosphere given data outside the magnetosphere. We show that, compared to cutoff models, low altitude proton measurements are far superior for near-real-time monitoring of the geomagnetic cutoff in support of high altitude anomaly resolution.

Longitudinal dependence of solar proton peak intensities using the X-ray and proton data in the period of 22-23 cycles

Yu P **Ochelkov**

2013 J. Phys.: Conf. Ser. 409 012183

The calculations of the heliolongitudinal dependence of solar proton peak intensities for protons with energy more than 30 MeV were made. The new method of analysis of a posteriory probability of SPE observations with the proton peak intensities more than the given intensity by condition of observation the associated solar X-ray bursts with peak intensities more than the given intensity was used. It was shown that the heliolongitudinal peak intensity decrease for the event with flares in the western half of solar disk is practically absent, for heliolongitudinal interval from 00 up to 300 E is equal to 30 and for heliolongitudinal interval 300–900 E is equal to100-150.

Signals of solar cosmic ray flux variations inferred from the noise in raw CCD solar images taken by SOHO/EIT†

Suyeon **Oh**1,*, Hyungmin Park2, Yu Yi

JGR, Volume 119, Issue 1, pages 88–96, January **2014**

http://onlinelibrary.wiley.com/doi/10.1002/2013JA019142/pdf

The noise embedded in the raw data in one scientific discipline has sometimes been proven to be a valuable signal for another discipline and there are examples throughout science history. The solar images taken by the CCD detectors of the Sun monitoring satellites such as SOHO, TRACE, STEREO, SDO, and so on, are usually cleaned by removing the traces of cosmic rays on the raw CCD data files. Thus, while applying the method of removing the cosmic ray traces, we may be able to estimate the cosmic ray flux by counting the number of traces. The net cosmic ray flux is the sum of galactic cosmic rays and solar-originating particles. The latter are seen as highly transient flux changes related to solar eruptions such as flares and coronal mass ejections. We can identify this kind of 'cosmic ray' event from the association with phenomena revealed in processed solar images, and we show this using the data of SOHO/EIT. On the other hand, the estimated cosmic ray flux in the steady state is anti-correlated with solar cycle sunspot number. The profiles of estimated solar cosmic ray flux showing significant increase are found to be strongly correlated with the ground neutron monitor Ground Level Enhancements. Additionally, the profile of estimated cosmic ray flux is consistent with that of the GOES P6 channel. It indicates that the particles with energy higher than 80 MeV may mainly produce the tracks on CCD of EIT. In conclusion, the raw solar images are valuable data for estimating both long-term cosmic ray variations and transient solar particles events.

20 February 2002 , 23 August 2005 ,13 December 2006,

South Pole neutron monitor forecasting of solar proton radiation intensity

Oh, S. Y.; Bieber, J. W.; Clem, J.; Evenson, P.; Pyle, R.; Yi, Y.; Kim, Y.-K.

Space Weather, Vol. 10, No. 0, S05004, **2012, File**

http://dx.doi.org/10.1029/2012SW000795

We describe a practical system for forecasting peak intensity and fluence of solar energetic protons in the tens to hundreds of MeV energy range. The system could be useful for forecasting radiation hazard, because peak intensity and fluence are closely related to the medical physics quantities peak dose rate and total dose. The method uses a pair of ground-based detectors located at the South Pole to make a measurement of the solar particle energy spectrum at relativistic (GeV) energies, and it then extrapolates this spectrum downward in energy to make a prediction of the peak intensity and fluence at lower energies. A validation study based upon 12 large solar particle events compared the prediction with measurements made aboard GOES spacecraft. This study shows that useful predictions (logarithmic correlation greater than 50%) can be made down to energies of 40–80 MeV (GOES channel P5) in the case of peak intensity, with the prediction leading the observation by 166 min on average. For higher energy GOES channels, the lead times are shorter, but the correlation coefficients are larger.

Characteristics of solar proton events associated with ground level enhancements

Oh, S. Y.; Yi, Y.; Bieber, J. W.; Evenson, P.; Kim, Y. K.

J. Geophys. Res., Vol. 115, No. A10, A10107, **2010; File**

In certain explosive events, the Sun emits large numbers of protons with energy up to tens of GeV. Particle acceleration processes on the Sun can be understood through the observation of such energetic particles. According to the definition of NOAA Space Environment Services Center, a solar proton event (SPE) is defined as an event with a peak intensity of >10 pfu (particle flux unit; 1 particle cm−2 sr−1 s−1) for >10 MeV protons. Major SPEs are not always associated with ground level enhancements (GLEs), whereas relatively minor SPEs are sometimes associated with GLEs. We examined the peak intensities of 85 SPEs after 1986 using the intensity of proton differential energy channels (P3–P10) from GOES. We identified 31 SPEs associated with GLEs having well-defined profiles with a large increase and clear peak for each proton channel. They have larger peak intensity and fluence and shorter delay time between onset and peak than SPEs without GLEs. Fluences and peak intensities of SPEs have a good correlation with percent increases of GLEs, with the best correlation coefficients obtained for the peak intensities and fluences of channels P8, P9, and P10. For these energy channels (spanning 350–700 MeV), we find that there are threshold values for GOES fluence and peak intensity such that most SPEs above the threshold are associated with GLEs, whereas almost none below the thresholds are.

Table

Statistical reality of globally nonsimultaneous Forbush decrease events

Oh, S. Y.; Yi, Y.

J. Geophys. Res., Vol. 114, No. A11, A11102, **2009**

http://dx.doi.org/10.1029/2009JA014190

The Forbush decrease (FD) event, a sudden decrease of galactic cosmic ray intensity measured by neutron monitor (NM), is known as a globally simultaneous phenomenon. However, some of them do not occur simultaneously in universal time. On the basis of the difference of main phase onset time distributions of two kinds of FD events, Oh et al. (2008) suggested that the global simultaneity of FD events depends on the solar wind physical parameters and propagation direction in three-dimensional heliosphere around the Earth. In order to get the hypothesis approved with a higher confidence level, the FD event data set is extended to 218 events with a longer period from 1971 to 2006 using Oulu, Inuvik, and Magadan station data. In addition, the probability of the same distribution of those two different classes of FD events is calculated in each NM station's view. All three NM stations confirm the probability of different distributions of FD main phase onset times of globally simultaneous and nonsimultaneous with a confidence level of 99%, compared with 94% of previous study. The statistics in this study may support the hypothesis that the simultaneous FD events occur when stronger magnetic barriers pass by the Earth through the central part of the magnetic barriers and in contrast that the nonsimultaneous FD events occur only if the less strong magnetic barriers pass the Earth on the dusk side of the magnetosphere.

Origin of large solar proton events.

Ohki, K.:

2003, Solar Phys. 213, 111 – 120.

Electron Power-Law Spectra in Solar and Space Plasmas **Review**

M. **Oka**, J. Birn, M. Battaglia, C. C. Chaston, S. M. Hatch…

Space Science Reviews August **2018**, 214:82

https://arxiv.org/pdf/1805.09278.pdf

https://link.springer.com/content/pdf/10.1007%2Fs11214-018-0515-4.pdf

Particles are accelerated to very high, non-thermal energies in solar and space plasma environments. While energy spectra of accelerated electrons often exhibit a power law, it remains unclear how electrons are accelerated to high energies and what processes determine the power-law index δδ. Here, we review previous observations of the power-law index δδ in a variety of different plasma environments with a particular focus on sub-relativistic electrons. It appears that in regions more closely related to magnetic reconnection (such as the 'above-the-looptop' solar hard X-ray source and the plasma sheet in Earth's magnetotail), the spectra are typically soft (δ≳4δ≳4). This is in contrast to the typically hard spectra (δ≲4δ≲4) that are observed in coincidence with shocks. The difference implies that shocks are more efficient in producing a larger non-thermal fraction of electron energies when compared to magnetic reconnection. A caveat is that during active times in Earth's magnetotail, δδ values seem spatially uniform in the plasma sheet, while power-law distributions still exist even in quiet times. The role of magnetotail reconnection in the electron power-law formation could therefore be confounded with these background conditions. Because different regions have been studied with different instrumentations and methodologies, we point out a need for more systematic and coordinated studies of power-law distributions for a better understanding of possible scaling laws in particle acceleration as well as their universality.

The Random Hivemind: An Ensemble Deep Learner. A Case Study of Application to Solar Energetic Particle Prediction Problem

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ApJ **2023**

https://arxiv.org/pdf/2303.08092.pdf

Deep learning has become a popular trend in recent years in the machine learning community and has even occasionally become synonymous with machine learning itself thanks to its efficiency, malleability, and ability to operate free of human intervention. However, a series of hyperparameters passed to a conventional neural network (CoNN) may be rather arbitrary, especially if there is no surefire way to decide how to program hyperparameters for a given dataset. The random hivemind (RH) alleviates this concern by having multiple neural network estimators make decisions based on random permutations of features. The learning rate and the number of epochs may be boosted or attenuated depending on how all features of a given estimator determine the class that the numerical feature data belong to, but all other hyperparameters remain the same across estimators. This allows one to quickly see whether consistent decisions on a given dataset can be made by multiple neural networks with the same hyperparameters, with random subsets of data chosen to force variation in how data are predicted by each, placing the quality of the data and hyperparameters into focus. The effectiveness of RH is demonstrated through experimentation in the predictions of dangerous solar energetic particle events (SEPs) by comparing it to that of using both CoNN and the traditional approach used by ensemble deep learning in this application. Our results demonstrate that RH outperforms the CoNN and a committee-based approach, and demonstrates promising results with respect to the ``all-clear'' prediction of SEPs.

Can the solar atmosphere generate very high energy cosmic rays?

Z.N. **Osmanov**, D. Kuridze, S.M. Mahajan
MNRAS **2024**
https://arxiv.org/pdf/2409.17801
The origin and acceleration of high-energy particles in space (cosmic rays), constitute important topics in modern astrophysics. Among the two categories of cosmic rays - galactic and solar cosmic rays - the latter are much less investigated. Primary source of solar cosmic ray particles are impulsive explosions of the magnetized plasma known as solar flares and coronal mass ejections. These particles are characterized by relatively low energies compared to their galactic counterparts. In this work, we explore resonance wave-wave (RWW) interaction between the polarized electromagnetic radiation emitted by the solar active region and the quantum waves associated with high-energy, relativistic electrons generated during solar flares. We find that RWW could accelerate the relativistic electrons to enormous energies even comparable to energies in the galactic cosmic rays.

Solar Energetic Particle Ground-Level Enhancements and the Solar Cycle

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Solar Phys. **297**, Article number: 105 **2022**
https://arxiv.org/pdf/2207.12787.pdf
https://link.springer.com/content/pdf/10.1007/s11207-022-02037-x.pdf
Severe geomagnetic storms appear to be ordered by the solar cycle in a number of ways. They occur more frequently close to solar maximum and declining phase, are more common in larger solar cycles and show different patterns of occurrence in odd- and even-numbered solar cycles. Our knowledge of the most extreme space weather events, however, comes from the spikes in cosmogenic-isotope (14C, 10Be and 36Cl) records that are attributed to significantly larger solar energetic particle (SEP) events than have been observed during the space age. Despite both storms and SEPs being driven by solar eruptive phenomena, the event-by-event correspondence between extreme storms and extreme SEPs is low. Thus it should not be assumed a priori that the solar cycle patterns found for storms also hold for SEPs and the cosmogenic-isotope events. In this study we investigate the solar cycle trends in the timing and magnitude of the 67 SEP ground-level enhancements (GLEs) recorded by neutron monitors since the mid 1950s. Using a number of models of GLE occurrence probability, we show that GLEs are around a factor four more likely around solar maximum than around solar minimum, and that they preferentially occur earlier in even-numbered solar cycles than in odd-numbered cycles. There are insufficient data to conclusively determine whether larger solar cycles produce more GLEs. Implications for putative space-weather events in the cosmogenic-isotope records are discussed. We find that GLEs tend to cluster within a few tens of days, likely due to particularly productive individual active regions, and with approximately 11-year separations, owing to the solar cycle ordering. But these timescales do not explain cosmogenic-isotope spikes which require multiple extreme SEP events over consecutive years.

Catalogue of >55 MeV Wide-longitude Solar Proton Events Observed by SOHO, ACE, and the STEREOs at ≈1 AU During 2009 – 2016

Miikka **Paassilta**, Athanasios Papaioannou, Nina Dresing, Rami Vainio…
Solar Physics April **2018**, 293:70
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1284-7.pdf
Based on energetic particle observations made at ≈1≈1 AU, we present a catalogue of 46 wide-longitude (>45∘>45∘) solar energetic particle (SEP) events detected at multiple locations during 2009 – 2016. The particle kinetic energies of interest were chosen as >55>55 MeV for protons and 0.18 – 0.31 MeV for electrons. We make use of proton data from the Solar and Heliospheric Observatory/Energetic and Relativistic Nuclei and Electron Experiment

(SOHO/ERNE) and the Solar Terrestrial Relations Observatory/High Energy Telescopes (STEREO/HET), together with electron data from the Advanced Composition Explorer/Electron, Proton, and Alpha Monitor (ACE/EPAM) and the STEREO/Solar Electron and Proton Telescopes (SEPT). We consider soft X-ray data from the Geostationary Operational Environmental Satellites(GOES) and coronal mass ejection (CME) observations made with the SOHO/Large Angle and Spectrometric Coronagraph (LASCO) and STEREO/Coronagraphs 1 and 2 (COR1, COR2) to establish the probable associations between SEP events and the related solar phenomena. Event onset times and peak intensities are determined; velocity dispersion analysis (VDA) and time-shifting analysis (TSA) are performed for protons; TSA is performed for electrons. In our event sample, there is a tendency for the highest peak intensities to occur when the observer is magnetically connected to solar regions west of the flare. Our estimates for the mean event width, derived as the standard deviation of a Gaussian curve modelling the SEP intensities (protons ≈44∘≈44∘, electrons ≈50∘≈50∘), largely agree with previous results for lower-energy SEPs. SEP release times with respect to event flares, as well as the event rise times, show no simple dependence on the observer's connection angle, suggesting that the source region extent and dominant particle acceleration and transport mechanisms are important in defining these characteristics of an event. There is no marked difference between the speed distributions of the CMEs related to wide events and the CMEs related to all near-Earth SEP events of similar energy range from the same time period. **26 December 2013, 25 February 2014, 1 September 2014**
Table

Catalogue of 55 – 80 MeV solar proton events extending through Solar Cycles 23 and 24.

Paassilta, M., Raukunen, O., Vainio, R., Valtonen, E., Papaioannou, A., Siipola, R., Riihonen, E., Dierckxsens, M., Crosby, N., Malandraki, O., Heber, B., Klein, K.-L.:
2017, J. Space Weather Space Clim. 7, A14.
https://arxiv.org/pdf/1707.00498.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170003.pdf
We present a new catalogue of solar energetic particle events near the Earth, covering solar cycle 23 and the majority of solar cycle 24 (1996-2016), based on the 55-80 MeV proton intensity data gathered by the Solar and Heliospheric Observatory/the Energetic and Relativistic Nuclei and Electron experiment (SOHO/ERNE). In addition to ERNE proton and heavy ion observations, data from the Advanced Composition Explorer/Electron, Proton and Alpha Monitor (ACE/EPAM) (near-relativistic electrons), SOHO/EPHIN (Electron Proton Helium Instrument) (relativistic electrons), SOHO/LASCO (Large Angle and Spectrometric Coronagraph) (coronal mass ejections, CMEs) and Geostationary Operational Environmental Satellite (GOES) soft X-ray experiments are also considered and the associations between the particle and CME/X-ray events deduced to obtain a better understanding of each event. A total of 176 solar energetic particle (SEP) events have been identified as having occurred during the time period of interest; their onset and solar release times have been estimated using both velocity dispersion analysis (VDA) and time-shifting analysis (TSA) for protons, as well as TSA for near-relativistic electrons. Additionally, a brief statistical analysis was performed on the VDA and TSA results, as well as the X-rays and CMEs associated with the proton/electron events, both to test the viability of the VDA and to investigate possible differences between the two solar cycles. We find, in confirmation of a number of previous studies, that VDA results for protons that yield an apparent path length of $1 \text{ AU} < s \lesssim 3 \text{ AU}$ seem to be useful, but those outside this range are probably unreliable, as evidenced by the anticorrelation between apparent path length and release time estimated from the X-ray activity. It also appears that even the first-arriving energetic protons apparently undergo significant pitch angle scattering in the interplanetary medium, with the resulting apparent path length being on average about twice the length of the spiral magnetic field. The analysis indicates an increase in high-energy SEP events originating from the far-eastern solar hemisphere; for instance, such an event with a well-established associated GOES flare has so far occurred three times during cycle 24 but possibly not at all during cycle 23. The generally lower level of solar activity during cycle 24, as opposed to cycle 23, has probably caused a significant decrease in total ambient pressure in the interplanetary space, leading to a larger proportion of SEP-associated halo-type CMEs. Taken together, these observations point to a qualitative difference between the two solar cycles. **6 November 1997, 17 July 2012**
Table 3. Proton fluxes, selected TSA and VDA parameters, ion fluences, and Fe/O ratios for 55–80 MeV proton events in 1996–2016. https://www.swsc-journal.org/articles/swsc/olm/2017/01/swsc170003/swsc170003-1-olm.pdf

Analysis and modelling of the solar energetic particle radiation environment in the inner heliosphere in preparation for solar orbiter Thesis

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http://hdl. handle.net/10803/667033
https://www.tdx.cat/handle/10803/667033#page=1
The Sun is the main source of all kind of solar energetic particles in the Solar System, electrons, protons and ions with energies from few keV to several GeV. These particles are released from the solar corona and spread through the interplanetary space, the heliosphere, influenced by the interplanetary magnetic field and arriving to the Earth

and interacting with the terrestrial magnetosphere. The effects of SEP interactions with space-based devices, manned missions and the Earth atmosphere are encompassed by what is known as space weather. This thesis describes the work we performed on this field, that can be divided in three parts: i) observational studies of solar energetic particles carried out using data coming from space-based missions such as STEREO and Helios, as well as tools like SEPEM server; ii) the development of tools and particle instrument modelling in order to use of them with pre-existing models to be used in the simulation of solar events; iii) solar energetic particle event simulations making use of transport models, either adapting tools previously developed by our group, as SEPInversion, or creating new software capable of carrying out full inversions of events, that is, taking into account the angular response and the energetic response of the particle instrument. These tools developed during this work have allow us to study and characterise the radiation conditions in the inner heliosphere applying modelling techniques never used done before. We also explore some of the applications of these tools. We developed a study about the radial dependence of electron peak intensities and anisotropy, we simulate observations of EPD/EPT instrument on board Solar Orbiter using Helios data and finally we studied the expected cumulated fluence and the fluence spectra computed using SEPEM for Solar Orbiter mission. In conclusion, the obtained results as well as the developed tools will be very useful for the study and interpretation of the future scientific data coming from Parker Solar Probe, Solar Orbiter and BepiColombo.

Full inversion of solar relativistic electron events measured by the Helios spacecraft

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A&A 624, A3 **2019**

https://arxiv.org/pdf/1902.06602.pdf

sci-hub.se/10.1051/0004-6361/201834520

Context. The Parker Solar Probe and the incoming Solar Orbiter mission will provide measurements of solar energetic particle (SEP) events at close heliocentric distances from the Sun. Up to present, the largest data set of SEP events in the inner heliosphere are the observations by the two Helios spacecraft.

Aims. We re-visit a sample of 15 solar relativistic electron events measured by the Helios mission with the goal of better characterising the injection histories of solar energetic particles and their interplanetary transport conditions at heliocentric distances <1 AU.

Methods. The measurements provided by the E6 instrument on board Helios provide us with the electron directional distributions in eight different sectors that we use to infer the detailed evolution of the electron pitch-angle distributions. The results of a Monte Carlo interplanetary transport model, combined with a full inversion procedure, were used to fit the observed directional intensities in the 300–800 keV nominal energy channel. Unlike previous studies, we have considered both the energy and angular responses of the detector. This method allowed us to infer the electron release time profile at the source and determine the electron interplanetary transport conditions.

Results. We discuss the duration of the release time profiles and the values of the radial mean free path, and compare them with the values reported previously in the literature using earlier approaches. Five of the events show short injection histories (<30 min) at the Sun and ten events show long-lasting (>30 min) injections. The values of mean free path range from 0.02 AU to 0.27 AU.

Conclusions. The inferred injection histories match with the radio and soft X-ray emissions found in literature. We find no dependence of the radial mean free path on the radial distance. In addition, we find no apparent relation between the strength of interplanetary scattering and the size of the solar particle release.

1976 March 21, 1978 January 1, 1980 May 28, 1980 May 29, 1982 June 2

Table 2. Observational characteristics of the selected events (1976-1982).

Interplanetary transport of solar near-relativistic electrons on 2014 August 1 over a narrow range of heliolongitudes

Daniel **Pacheco**, Neus Agueda, Raúl Gómez-Herrero and Angels Aran

J. Space Weather Space Clim. **2017**, 7, A30

https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170022.pdf

We study two consecutive solar near-relativistic (>50 keV) electron events observed on **2014 August 1** by both STEREO spacecraft with a longitudinal separation of only about 35°. The events were unambiguously associated with a solar source location and not accompanied by type II radio bursts or coronal mass ejections. Despite their close location, the two spacecraft were embedded in different solar wind streams and the electron intensities observed by the two STEREOs showed clear differences in onset times, peak intensities and pitch-angle distributions. The apparently better connected spacecraft, STEREO B, observed a smaller and more isotropic intensity increase and a later event onset time than STEREO A. Since the interplanetary transport conditions of solar energetic particles (SEPs) have a direct influence on the characteristics of the observed temporal profiles and the particle anisotropies at the spacecraft location, our aim is to understand if the observations on 2014 August 1 could be explained by different interplanetary transport conditions along each flux tube connecting the spacecraft with the solar source. For that purpose, we use a Monte Carlo interplanetary transport model combined with an inversion procedure to fit the in-situ observations of the two near-relativistic multi-spacecraft electron events. This allows us to obtain the injection profiles at the Sun and infer the transport conditions, which are characterized by the electron radial mean free path, λr. We obtain an almost simultaneous release of electrons for both spacecraft in both events. The release is consistent with the timing and duration of the type III radio burst emission and it is larger for STEREO B, the better connected spacecraft. In addition, we obtain different transport conditions in different solar wind streams. We find that the stream in which STEREO B was embedded was more diffusive (λr = 0.1AU for Event I and λr = 0.06AU for Event II) than the stream in which STEREO A was embedded (λr = 0.31AU for Event I andλr = 0.37AU for Event II). These different transport regimes are sufficient to explain the early onset for the worse connected spacecraft, STEREO A, and the observation of larger and more anisotropic intensities.

Corrugated Features in Coronal-mass-ejection-driven Shocks: A Discussion on the Predisposition to Particle Acceleration

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2019 ApJ 879 122

https://arxiv.org/pdf/1907.07884.pdf

sci-hub.se/10.3847/1538-4357/ab2460

The study of the acceleration of particles is an essential element of research in heliospheric science. Here, we discuss the predisposition to the particle acceleration around shocks driven by coronal mass ejections (CMEs) with corrugated wave-like features. We adopt these attributes on shocks formed from disturbances due to the bimodal solar wind, CME deflection, irregular CME expansion, and the ubiquitous fluctuations in the solar corona. In order to understand the role of a wavy shock in particle acceleration, we define three initial smooth shock morphologies each associated with a fast CME. Using polar Gaussian profiles we model these shocks in the low corona. We establish the corrugated appearance on smooth shock by using combinations of wave-like functions that represent the disturbances from the medium and CME piston. For both shock types, smooth and corrugated, we calculate the shock normal angles between the shock normal and the radial upstream coronal magnetic field in order to classify the quasi-parallel and quasi-perpendicular regions. We consider that corrugated shocks are predisposed to different processes of particle acceleration due to irregular distributions of shock normal angles around the shock. We suggest that disturbances due to CME irregular expansion may be a decisive factor in origin of particle acceleration. Finally, we regard that accepting these features on shocks may be the starting point for investigating some questions regarding the sheath and shock, like downstream jets, instabilities, shock thermalization, shock stability, and injection particle processes.

Exploring the Origin of Solar Energetic Electrons I: Constraining the Properties of the Acceleration Region Plasma Environment

Ross **Pallister**, Natasha L. S. Jeffrey

ApJ **958** 18 **2023**

https://arxiv.org/pdf/2310.04229.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ad0035/pdf

Solar flare electron acceleration is an efficient process, but its properties (mechanism, location) are not well constrained. Via hard X-ray (HXR) emission, we routinely observe energetic electrons at the Sun, and sometimes we detect energetic electrons in interplanetary space. We examine if the plasma properties of an acceleration region (size, temperature, density) can be constrained from in-situ observations, helping to locate the acceleration region in the corona, and infer the relationship between electrons observed in-situ and at the Sun. We model the transport of energetic electrons, accounting for collisional and non-collisional effects, from the corona into the heliosphere (to 1.0 AU). In the corona, electrons are transported through a hot, over-dense region. We test if the properties of this region can be extracted from electron spectra (fluence and peak flux) at different heliospheric locations. We find that cold, dense coronal regions significantly reduce the energy at which we see the peak flux and fluence for distributions measured out to 1.0 AU, the degree of which correlates with the temperature and density of plasma in the region. Where instrument energy resolution is insufficient to differentiate the corresponding peak values, the spectral ratio of [7-10) to [4-7) keV can be more readily identified and demonstrates the same relationship. If flare electrons detected in-situ are produced in, and/or transported through hot, over-dense regions close to HXR-emitting electrons, then this plasma signature should be present in their lower-energy spectra (1-20 keV), observable at varying heliospheric distances with missions such as Solar Orbiter.

RHESSI Nuggets #474 **2024**

https://heliowiki.smce.nasa.gov/wiki/index.php/Simulated_heliospheric_electron_spectra_show_sensitivity_to_plasma_properties_of_a_source_region_in_the_flaring_corona

Proton acceleration at tearing coronal null-point current sheets

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A&A 622, A207 (**2019**)
https://www.aanda.org/articles/aa/pdf/2019/02/aa34284-18.pdf
Context. Non-thermal particle acceleration in the solar corona is thought to constitute a substantial part of the energy budget of explosive events such as solar flares. One well-established mechanism of non-thermal acceleration is directly via fields in current sheets.
Aims. In this paper we study proton acceleration during “spine-fan reconnection” at a 3D magnetic null point. This type of reconnection has recently been implicated in some flares known as circular-ribbon flares. It has also recently been discovered that the reconnecting current sheet may undergo a non-linear tearing-type instability. This tearing leads to the formation of flux ropes and quasi-turbulent dynamics.
Methods. A predictor-corrector test particle code is used to model the trajectories of protons at different stages of sheet tearing: when the sheet is intact, just after the formation of the first major flux rope, and once the non-linear phase of the instability has become more fully developed. The fields for these proton trajectories were taken from snapshots of a 3D magnetohydrodynamics simulation treated as three static field geometries represented by interpolated grids. Acceleration in the intact current sheet is compared to earlier simulations of infinite static current sheets and then used as a control case with which to compare the later snapshots.
Results. Protons are found to be predominantly accelerated along the fan surface, especially in the absence of current sheet tearing. Most of the highest energy protons are accelerated in the main body of the current sheet, along the direction of strongest parallel electric field. A high energy tail is present in the kinetic energy distribution. After tearing commences, this direct acceleration no longer dominates and acceleration in the outflow regions makes a proportionally greater contribution. Sheet tearing appears overall to hinder the acceleration of protons in the fan plane, at least in the absence of time-dependent acceleration mechanisms. Some correlation is found between high energy protons and locations of flux ropes formed by the instability, but the nature of the link remains at present unclear.

On Weibull's Spectrum of Nonrelativistic Energetic Particles at IP Shocks: Observations and Theoretical Interpretation

G. **Pallocchia**, M. Laurenza, and G. Consolini
2017 ApJ 837 158
Some interplanetary shocks are associated with short-term and sharp particle flux enhancements near the shock front. Such intensity enhancements, known as shock-spike events (SSEs), represent a class of relatively energetic phenomena as they may extend to energies of some tens of MeV or even beyond. Here we present an SSE case study in order to shed light on the nature of the particle acceleration involved in this kind of event. Our observations refer to an SSE registered on 2011 October 3 at 22:23 UT, by STEREO B instrumentation when, at a heliocentric distance of 1.08 au, the spacecraft was swept by a perpendicular shock moving away from the Sun. The main finding from the data analysis is that a Weibull distribution represents a good fitting function to the measured particle spectrum over the energy range from 0.1 to 30 MeV. To interpret such an observational result, we provide a theoretical derivation of the Weibull spectrum in the framework of the acceleration by "killed" stochastic processes exhibiting power-law growth in time of the velocity expectation, such as the classical Fermi process. We find an overall coherence between the experimental values of the Weibull spectrum parameters and their physical meaning within the above scenario. Hence, our approach based on the Weibull distribution proves to be useful for understanding SSEs. With regard to the present event, we also provide an alternative explanation of the Weibull spectrum in terms of shock-surfing acceleration.

Improved modelling of SEP event onset within the WSA-Enlil-SEPMOD framework

Erika **Palmerio**, Janet G. Luhmann, M. Leila Mays, Ronald M. Caplan, +++
Journal of Space Weather and Space Climat **14**, 3 **2024**
https://arxiv.org/pdf/2401.05309.pdf
https://doi.org/10.1051/swsc/2024001
https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc230053.pdf
Multi-spacecraft observations of solar energetic particle (SEP) events not only enable a deeper understanding and development of particle acceleration and transport theories, but also provide important constraints for model validation efforts. However, because of computational limitations, a given physics-based SEP model is usually best-suited to capture a particular phase of an SEP event, rather than its whole development from onset through decay. For example, magnetohydrodynamic (MHD) models of the heliosphere often incorporate solar transients only at the outer boundary of their so-called coronal domain -- usually set at a heliocentric distance of 20-30 R⊙. This means that particle acceleration at CME-driven shocks is also computed from this boundary onwards, leading to simulated SEP event onsets that can be many hours later than observed, since shock waves can form much lower in the solar corona. In this work, we aim to improve the modelled onset of SEP events by inserting a "fixed source" of particle injection at the outer boundary of the coronal domain of the coupled WSA-Enlil 3D MHD model of the heliosphere. The SEP model that we employ for this effort is SEPMOD, a physics-based test-particle code based on a field line

tracer and adiabatic invariant conservation. We apply our initial tests and results of SEPMOD's fixed-source option to the **2021 October 9** SEP event, which was detected at five well-separated locations in the inner heliosphere -- Parker Solar Probe, STEREO-A, Solar Orbiter, BepiColombo, and near-Earth spacecraft.

CMEs and SEPs During November-December 2020: A Challenge for Real-Time Space Weather Forecasting

Erika **Palmerio**, Christina O. Lee, M. Leila Mays, Janet G. Luhmann, David Lario, Beatriz Sánchez-Cano, Ian G. Richardson, Rami Vainio, Michael L. Stevens, Christina M. S. Cohen, Konrad Steinvall, Christian Möstl, Andreas J. Weiss, Teresa Nieves-Chinchilla, Yan Li, Davin E. Larson, Daniel Heyner, Stuart D. Bale, Antoinette B. Galvin, Mats Holmström, Yuri V. Khotyaintsev, Milan Maksimovic, Igor G. Mitrofanov

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https://arxiv.org/pdf/2203.16433.pdf
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Predictions of coronal mass ejections (CMEs) and solar energetic particles (SEPs) are a central issue in space weather forecasting. In recent years, interest in space weather predictions has expanded to include impacts at other planets beyond Earth as well as spacecraft scattered throughout the heliosphere. In this sense, the scope of space weather science now encompasses the whole heliospheric system, and multi-point measurements of solar transients can provide useful insights and validations for prediction models. In this work, we aim to analyse the whole inner heliospheric context between two eruptive flares that took place in late 2020, i.e. the M4.4 flare of **November 29** and the C7.4 flare of **December 7**. This period is especially interesting because the STEREO-A spacecraft was located ~60° east of the Sun-Earth line, giving us the opportunity to test the capabilities of "predictions at 360°" using remote-sensing observations from the Lagrange L1 and L5 points as input. We simulate the CMEs that were ejected during our period of interest and the SEPs accelerated by their shocks using the WSA-Enlil-SEPMOD modelling chain and four sets of input parameters, forming a "mini-ensemble". We validate our results using in-situ observations at six locations, including Earth and Mars. We find that, despite some limitations arising from the models' architecture and assumptions, CMEs and shock-accelerated SEPs can be reasonably studied and forecast in real time at least out to several tens of degrees away from the eruption site using the prediction tools employed here.

CME Magnetic Structure and IMF Preconditioning Affecting SEP Transport

Erika **Palmerio** , Emilia K. J. Kilpua , Olivier Witasse ,David Barnes , Beatriz Sánchez-Cano, Andreas J. Weiss , Teresa Nieves-Chinchilla , Christian Möstl , Lan K. Jian , … See all authors

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Coronal mass ejections (CMEs) and solar energetic particles (SEPs) are two phenomena that can cause severe space weather effects throughout the heliosphere. The evolution of CMEs, especially in terms of their magnetic structure, and the configuration of the interplanetary magnetic field (IMF) that influences the transport of SEPs are currently areas of active research. These two aspects are not necessarily independent of each other, especially during solar maximum when multiple eruptive events can occur close in time. Accordingly, we present the analysis of a CME that erupted on **May 11, 2012** (SOL2012-05-11) and an SEP event following an eruption that took place on **May 17, 2012** (SOL2012-05-17). After observing the May 11 CME using remote-sensing data from three viewpoints, we evaluate its propagation through interplanetary space using several models. Then, we analyze in-situ measurements from five predicted impact locations (Venus, Earth, the Spitzer Space Telescope, the Mars Science Laboratory en route to Mars, and Mars) in order to search for CME signatures. We find that all in-situ locations detect signatures of an SEP event, which we trace back to the May 17 eruption. These findings suggest that the May 11 CME provided a direct magnetic connectivity for the efficient transport of SEPs. We discuss the space weather implications of CME evolution, regarding in particular its magnetic structure, and CME-driven IMF preconditioning that facilitates SEP transport. Finally, this work remarks the importance of using data from multiple spacecraft, even those that do not include space weather research as their primary objective.

Solar Energetic Particle Time Series Analysis with Python

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2022
https://arxiv.org/pdf/2210.10432.pdf

Solar Energetic Particles (SEPs) are charged particles accelerated within the solar atmosphere or the interplanetary space by explosive phenomena such as solar flares or Coronal Mass Ejections (CMEs). Once injected into the interplanetary space, they can propagate towards Earth, causing space weather related phenomena. For their analysis, interplanetary in-situ measurements of charged particles are key. The recently expanded spacecraft fleet in the heliosphere not only provides much-needed additional vantage points, but also increases the variety of missions and instruments for which data loading and processing tools are needed. This manuscript introduces a series of Python functions that will enable the scientific community to download, load, and visualize charged particle measurements of the current space missions that are especially relevant to particle research as time series or dynamic spectra. In addition, further analytical functionality is provided that allows the determination of SEP onset times as well as their inferred injection times. The full workflow, which is intended to be run within Jupyter Notebooks and can also be approachable for Python laymen, will be presented with scientific examples. All functions are written in Python, with the source code publicly available at GitHub under a permissive license. Where appropriate, available Python libraries are used, and their application is described. **9 October 2021, 28 October 2021**

Correlation Analyses Between the Characteristic Times of Gradual Solar Energetic Particle Events and the Properties of Associated Coronal Mass Ejections

Z. H. **Pan**, C. B. Wang, Yuming Wang and X. H. Xue
Solar Physics, Volume 270, Number 2, 593-607, **2011**
https://link.springer.com/content/pdf/10.1007/s11207-011-9763-0.pdf
It is generally believed that gradual solar energetic particles (SEPs) are accelerated by shocks associated with coronal mass ejections (CMEs). Using an ice-cream cone model, the radial speed and angular width of 95 CMEs associated with SEP events during 1998 – 2002 are calculated from SOHO/LASCO observations. Then, we investigate the relationships between the kinematic properties of these CMEs and the characteristic times of the intensity-time profile of their accompanied SEP events observed at 1 AU. These characteristic times of SEP are i) the onset time from the accompanying CME eruption at the Sun to the SEP arrival at 1 AU, ii) the rise time from the SEP onset to the time when the SEP intensity is one-half of peak intensity, and iii) the duration over which the SEP intensity is within a factor of two of the peak intensity. It is found that the onset time has neither significant correlation with the radial speed nor with the angular width of the accompanying CME. For events that are poorly connected to the Earth, the SEP rise time and duration have no significant correlation with the radial speed and angular width of the associated CMEs. However, for events that are magnetically well connected to the Earth, the SEP rise time and duration have significantly positive correlations with the radial speed and angular width of the associated CMEs. This indicates that a CME event with wider angular width and higher speed may more easily drive a strong and wide shock near to the Earth-connected interplanetary magnetic field lines, may trap and accelerate particles for a longer time, and may lead to longer rise time and duration of the ensuing SEP event.

Solar flares, CMEs and solar energetic particle events during solar cycle 24

Bimal **Pande**, SeemaPande, RameshChandra, MaheshChandra Mathpal
Advances in Space Research
Volume 61, Issue 2, 15 January **2018**, Pages 777-785
https://ac.els-cdn.com/S0273117717308360/1-s2.0-S0273117717308360-main.pdf?_tid=c852e7fa-f76c-11e7-996f-00000aacb361&acdnat=1515743413_fcc7715b29ddc76611893d377d79bcf6
https://sci-hub.tw/10.1016/j.asr.2017.11.025 **File**
We present here a study of Solar Energetic Particle Events (SEPs) associated with solar flares during 2010–2014 in solar cycle 24. We have selected the flare events (≥GOES M-class), which produced SEPs. The SEPs are classified into three categories i.e. weak (proton intensity ≤ 1 pfu), minor (1 pfu < proton intensity < 10 pfu) and major (proton intensity ≥ 10 pfu). We used the GOES data for the SEP events which have intensity greater than one pfu and SOHO/ERNE data for the SEP event less than one pfu intensity. In addition to the flare and SEP properties, we have also discussed different properties of associated CMEs. **15 February 2011 , 07 June 2011, 03 August 2011**
Table 1 SEPs associated with GOES M class flares during 2010–2014.

Precursor Effects in Different Cases of Forbush Decreases

M. **Papailiou** · H. Mavromichalaki · A. Belov · E. Eroshenko · V. Yanke
Solar Phys (**2012**) 276:337–350, **File**
Over the last few years, the pre-decreases or pre-increases of the cosmic-ray intensity observed before a Forbush decrease, called the precursor effect and registered by the worldwide neutron monitor network, have been investigated for different cases of intense events. The Forbush decreases presented in this particular study were chosen from a list of events that occurred in the time period 1967 – 2006 and were characterized by an enhanced first harmonic of cosmic-ray anisotropy prior to the interplanetary disturbance arrival. The asymptotic longitudinal cosmic-ray distribution diagrams for the events under consideration were studied using the "Ring of Stations" method, and data on solar flares, solar-wind speed, geomagnetic indices, and interplanetary magnetic field were analyzed in detail. The results revealed that the use of this method allowed the selection of a large number of events with well-defined precursors, which could be separated into at least three categories, according to duration and

longitudinal zone. Finally, this analysis showed that the first harmonic of cosmic-ray anisotropy could serve as an adequate tool in the search for precursors and could also be evidence for them.
8 September 1981, 2 October1981, 17 August 2001, 25 September 2001, 25 August 2002, 7 September 2002.

Revisiting Empirical Solar Energetic Particle Scaling Relations II. Coronal Mass Ejections
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A&A 690, A60 **2024**
https://arxiv.org/pdf/2407.16479
https://www.aanda.org/articles/aa/pdf/2024/10/aa50705-24.pdf
Aims. The space radiation environment conditions and the maximum expected coronal mass ejection (CME) speed are being assessed through the investigation of scaling laws between the peak proton flux and fluence of Solar Energetic Particle (SEP) events with the speed of the CMEs. Methods. We utilize a complete catalog of SEP events, covering the last ~25 years of CME observations (i.e. 1997 to 2017). We calculate the peak proton fluxes and integrated event fluences for those events reaching an integral energy of up to E> 100 MeV, covering the period of the last ~25 years of CME observations. For a sample of 38 strong SEP events, we first investigate the statistical relations between the recorded peak proton fluxes (IP) and fluences (FP) at a set of integral energies of E >10 MeV, E>30 MeV, E>60 MeV, and E>100 MeV versus the projected CME speed near the Sun (VCME) obtained by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (SOHO/LASCO). Based on the inferred relations, we further calculate the integrated energy dependence of both IP and FP, assuming that they follow an inverse power-law with respect to energy. By making use of simple physical assumptions, we combine our derived scaling laws to estimate the upper limits for VCME, IP, and FP focusing on two cases of known extreme SEP events that occurred on **February 23, 1956 (GLE05) and in AD774/775**, respectively. Given physical constraints and assumptions, several options for the upper limit VCME, associated with these events, are investigated. Results. A scaling law relating IP and FP to the CME speed as V^{5}CME for CMEs ranging between ~3400-5400 km/s is consistent with values of FP inferred for the cosmogenic nuclide event of AD774/775. At the same time, the upper CME speed that the current Sun can provide possibly falls within an upper limit of VCME <= 5500 km/s.

Revisiting Empirical Solar Energetic Particle Scaling Relations I. Solar flares
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A&A 671, A66 **2023**
https://arxiv.org/pdf/2211.15312.pdf
https://www.aanda.org/articles/aa/pdf/2023/03/aa43407-22.pdf **File**
Aims The possible influence of solar superflares on the near-Earth space radiation environment are assessed through the investigation of scaling laws between the peak proton flux and fluence of Solar Energetic Particle (SEP) events with the solar flare soft X-ray peak photon flux.
Methods We compiled a catalog of 65 well-connected (W20-90) SEP events during the last three solar cycles covering a period of ∼34 years (1984-2020) that were associated with flares of class ≥C6.0 and investigated the statistical relations between the recorded peak proton fluxes (IP) and the fluences (FP) at a set of integral energies from E >10; >30; >60; to >100 MeV versus the associated solar flare peak soft X-ray flux in the 1−8 A band (FSXR). Based on the inferred relations, we calculate the integrated energy dependence of the peak proton flux (IP) and fluence (FP) of the SEP events, assuming that they follow an inverse power-law with respect to energy. Finally, we make use of simple physical assumptions, combining our derived scaling laws, and estimate the upper limits for IP and FP focusing on the flare associated with the strongest GLE yet directly observed (GLE 05 on 23 February 1956), and that inferred for the cosmogenic radionuclide based SEP event of AD774/775.
Results We show that IP and FP scale with the solar flare SXR flux as ∝~F5/6SXR. For the AD774/775 event (with a re-scaled upper limit FSXR = X600) these scaling laws yield values of FP at E>200 MeV of ∼1010 cm−2 and ∼1.5 × 109 cm−2 at E>430 MeV that are consistent with values inferred from the measurements of 14C and 10Be. **AD774/775, 23 February 1956**

The Probabilistic Solar Particle Event foRecasting (PROSPER) Model
Athanasios **Papaioannou**, Rami Vainio, Osku Raukunen, Piers Jiggens, Angels Aran, Mark Dierckxsens, Sotirios A. Mallios, Miikka Paassilta, Anastasios Anastasiadis
J. Space Weather & Space Climate 12, 24 **2022**
https://arxiv.org/pdf/2205.07325.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc210075.pdf
https://doi.org/10.1051/swsc/2022019
The Probabilistic Solar Particle Event foRecasting (PROSPER) model predicts the probability of occurrence and the expected peak flux of Solar Energetic Particle (SEP) events. Predictions are derived for a set of integral proton energies (i.e. E>10, >30 and >100 MeV) from characteristics of solar flares (longitude, magnitude), coronal mass

ejections (width, speed) and combinations of both. Herein the PROSPER model methodology for deriving the SEP event forecasts is described and the validation of the model, based on archived data, is presented for a set of case studies. The PROSPER model has been incorporated into the new operational Advanced Solar Particle Event Casting System (ASPECS) tool to provide nowcasting (short term forecasting) of SEP events as part of ESA's future SEP Advanced Warning System (SAWS). ASPECS also provides the capability to interrogate PROSPER for historical cases via a run on demand functionality.

The First Ground Level Enhancement of Solar Cycle 25 on 28 October 2021

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A&A Let 660, L5 **2022**

https://arxiv.org/pdf/2202.07927.pdf

www.aanda.org/articles/aa/pdf/2022/04/aa42855-21.pdf **File**

https://doi.org/10.1051/0004-6361/202142855

Aims. The first relativistic solar proton event of solar cycle 25 (SC25) was detected on 28 October 2021 by neutron monitors (NMs) on the ground and particle detectors onboard spacecraft in the near-Earth space. This is the first ground level enhancement (GLE) of the current cycle. A detailed reconstruction of the NM response together with the identification of the solar eruption that generated these particles is investigated based on in-situ and remote-sensing measurements.

Methods. In-situ proton observations from a few MeV to ∼500 MeV were combined with the detection of a solar flare in soft X-rays (SXRs), a coronal mass ejection (CME), radio bursts and extreme ultraviolet (EUV) observations to identify the solar origin of the GLE. Timing analysis was performed and a relation to the solar sources was outlined.

Results. GLE73 reached a maximum particle rigidity of ∼2.4 GV and is associated with type III, type II, type IV radio bursts and an EUV wave. A diversity of time profiles recorded by NMs was observed. This points to an anisotropic nature of the event. The peak flux at E>10 MeV was only ∼30 pfu and remained at this level for several days. The release time of ≥1 GV particles was found to be ∼15:40 UT. GLE73 had a moderately hard rigidity spectrum at very high energies (γ ∼5.5). Comparison of GLE73 to previous GLEs with similar solar drivers is performed.

Movie 1 associated with Fig. 2 (SDO_AIA_20211028_Extended_full) (Access here)

Movie 2 associated with Fig. B.1 (AIA_and_ConnectFLs_v2) (Access here)

Nowcasting of Solar Energetic Particle Events using near real-time Coronal Mass Ejection characteristics in the framework of the FORSPEF tool

Athanasios **Papaioannou**, Anastasios Anastasiadis, Ingmar Sandberg and Piers Jiggens

J. Space Weather Space Clim. **2018**, 8, A37

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170060.pdf

In this work the derived occurrence probability of solar energetic particle (SEP) events (i.e. proton events measured at Earth’s position) and their peak fluxes and total fluences depending on coronal mass ejection (CME) parameters, i.e. linear speed (V) and the angular width (AW) are presented. A new SEP catalogue with associated CME data from 1997 to 2013 is utilized. It is found that the SEP probability strongly depends on the CME speed and the angular width as follows: The highest association (72.70%) is obtained for the full halo CMEs with $V \geq 1500$ km s−1 and the lowest association (0.7%) is found for the non halo CMEs with 400 km s−1 $\leq V \leq$ 1000 km s−1. The SEP occurrence probabilities are different as much as 26 times according to the CME speed (V), comparing fast versus slow CMEs and 44 times according to the AW, comparing halo to non halo CMEs. Furthermore, linear regressions of the proton peak flux and integral fluence at several integral energy channels (E > 10 MeV, E > 30 MeV, E > 60 MeV, E > 100 MeV) were obtained. Our results, were used to build a module of an operational forecasting tool (i.e. FORecasting Solar Particle Events and Flares – FORSPEF, http://tromos.space.noa.gr/forspef/). This module performs nowcasting (short term forecasting) of SEP events using near real-time CME identifications obtained from CACTus (http://sidc.oma.be/cactus/). The outputs offered by the operational module of the tool to the end user (textural, pictorial, archived data) are presented. Finally, the validation of the system, in terms of archived data is described, in terms of categorical scores (Probability of Detection – POD and a False Alarm Rate – FAR).

Table 5. SEP CME list (04.2013–09.2015).

Nowcasting Solar Energetic Particle Events Using Principal Component Analysis

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Solar Physics July **2018**, 293:100

https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1320-7.pdf
We perform a principal component analysis (PCA) on a set of six solar variables (i.e. width/size (ss) and velocity (uu) of a coronal mass ejection, logarithm of the solar flare (SF) magnitude (logSXRslogSXRs), SF longitude (lonlon), duration (DTDT), and rise time (RTRT)). We classify the solar energetic particle (SEP) event radiation impact (in terms of the National Oceanic and Atmospheric Administration scales) with respect to the characteristics of their parent solar events. We further attempt to infer the possible prediction of SEP events. In our analysis, we use 126 SEP events with complete solar information, from 1997 to 2013. Each SEP event is a vector in six dimensions (corresponding to the six solar variables used in this work). The PCA transforms the input vectors into a set of orthogonal components. By mapping the characteristics of the parent solar events, a new base defined by these components led to the classification of the SEP events. We furthermore applied logistic regression analysis with single, as well as multiple explanatory variables, in order to develop a new index (II) for the nowcasting (short-term forecasting) of SEP events. We tested several different schemes for II and validated our findings with the implementation of categorical scores (probability of detection (POD) and false-alarm rate (FAR)). We present and interpret the obtained scores, and discuss the strengths and weaknesses of the different implementations. We show that II holds prognosis potential for SEP events. The maximum POD achieved is 77.78% and the relative FAR is 40.96%.
Table 126 SEP events with complete solar information, from 1997 to 2013.

Solar flares, coronal mass ejections and solar energetic particle event characteristics

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J. Space Weather Space Clim., 6, A42 (**2016**) **File**
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf
A new catalogue of 314 solar energetic particle (SEP) events extending over a large time span from 1984 to 2013 has been compiled. The properties as well as the associations of these SEP events with their parent solar sources have been thoroughly examined. The properties of the events include the proton peak integral flux and the fluence for energies above 10, 30, 60 and 100 MeV. The associated solar events were parametrized by solar flare (SF) and coronal mass ejection (CME) characteristics, as well as related radio emissions. In particular, for SFs: ***the soft X-ray (SXR) peak flux, the SXR fluence, the heliographic location, the rise time and the duration were exploited; for CMEs the plane-of-sky velocity as well as the angular width were utilized.*** For radio emissions, type III, II and IV radio bursts were identified. Furthermore, we utilized element abundances of Fe and O. We found evidence that most of the SEP events in our catalogue do not conform to a simple two-class paradigm, with the 73% of them exhibiting both type III and type II radio bursts, and that a continuum of event properties is present. Although, the so-called hybrid or mixed events are found to be present in our catalogue, it was not possible to attribute each SEP event to a mixed/hybrid sub-category. Moreover, it appears that the start of the type III burst most often precedes the maximum of the SF and thus falls within the impulsive phase of the associated SF. At the same time, type III bursts take place within ≈5.22 min, on average, in advance from the time of maximum of the derivative of the SXR flux (Neupert effect). We further performed a statistical analysis and a mapping of the logarithm of the proton peak flux at E > 10 MeV, on different pairs of the parent solar source characteristics. This revealed correlations in 3-D space and demonstrated that the gradual SEP events that stem from the central part of the visible solar disk constitute a significant radiation risk. **The velocity of the associated CMEs, as well as the SXR peak flux and fluence, are all fairly significantly correlated to both the proton peak flux and the fluence of the SEP events in our catalogue. The strongest correlation to SEP characteristics is manifested by the CME velocity. 1986.02.14, 2000.07.14, 2003.10.26-28-29, 2003.11.02-04**
Table 2 SEP events, recorded onboard GOES from 1984 to 2013, and associated solar features
https://www.swsc-journal.org/articles/swsc/olm/2016/01/swsc150076/swsc150076-tab2-olm.pdf
Table 3. Calculated characteristics (i.e. proton peak flux and fluence) of all 314 SEP events at E>10; 30; 60 and 100 MeV.
https://www.swsc-journal.org/articles/swsc/olm/2016/01/swsc150076/swsc150076-tab3-olm.pdf

A Novel Forecasting System for Solar Particle Events and Flares (FORSPEF)

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Journal of Physics: Conference Series, Volume 632, Issue 1, article id. 012075 (**2015**).
http://sci-hub.tw/10.1088/1742-6596/632/1/012075
http://iopscience.iop.org/article/10.1088/1742-6596/632/1/012075/pdf
Solar Energetic Particles (SEPs) result from intense solar eruptive events such as solar flares and coronal mass ejections (CMEs) and pose a significant threat for both personnel and infrastructure in space conditions. In this work, we present FORSPEF (Forecasting Solar Particle Events and Flares), a novel dual system, designed to perform forecasting of SEPs based on forecasting of solar flares, as well as independent SEP nowcasting. An

overview of flare and SEP forecasting methods of choice is presented. Concerning SEP events, we make use for the first time of the newly re-calibrated GOES proton data within the energy range 6.0-243 MeV and we build our statistics on an extensive time interval that includes roughly 3 solar cycles (1984-2013). A new comprehensive catalogue of SEP events based on these data has been compiled including solar associations in terms of flare (magnitude, location) and CME (width, velocity) characteristics.

The first ground level enhancement of solar cycle 24 on 17 May 2012 and its real time detection

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Solar Physics, 289, 423-436, **2013**

http://cosray.phys.uoa.gr/publications/D99.pdf

Ground-level enhancements (GLEs) are defined as sudden increases in the recorded intensity of cosmic-ray particles, usually by neutron monitors (NMs). In this work we present a time-shifting analysis (TSA) for the first arriving particles that were detected at Earth by NMs. We also present an automated real-time GLE alert that has been developed and is operating via the Neutron Monitor Database (NMDB), which successfully identified the 17 May 2012 event, designated as GLE71. We discuss the time evolution of the real-time GLE alert that was issued for GLE71 and present the event onset-time for NMs that contributed to this GLE alert based on their archived data. A comparison with their real-time time-stamp was made to illustrate the necessity for high-resolution data (e.g. 1-min time resolution) made available at every minute. The first results on the propagation of relativistic protons that have been recorded by NMs, as inferred by the TSA, imply that they are most probably accelerated by the coronal-mass-ejection-driven shock. Furthermore, the successful usage of NM data and the corresponding achievement of issuing a timely GLE alert are discussed.

On the Analysis of the Complex Forbush Decreases of January 2005

A. **Papaioannou** · O. Malandraki · A. Belov · R. Skoug · H. Mavromichalaki · E. Eroshenko · A. Abunin · S. Lepri

Solar Phys (**2010**) 266: 181–193, **File**, DOI 10.1007/s11207-010-9601-9

In this work an analysis of a series of complex cosmic ray events that occurred between 17 January 2005 and 23 January 2005 using solar, interplanetary and ground based cosmic ray data is being performed. The investigated period was characterized both by significant galactic cosmic ray (GCR) and solar cosmic ray (SCR) variations with highlighted cases such as the noticeable series of Forbush effects (FEs) from **17 January 2005 to 20 January 2005**, the Forbush decrease (FD) on 21 January 2005 and the ground level enhancement (GLE) of the cosmic ray counter measurements on 20 January 2005. The analysis is focusing on the aforementioned FE cases, with special attention drawn on the 21 January 2005, FD event, which demonstrated several exceptional features testifying its uniqueness. Data from the ACE spacecraft, together with GOES X-ray recordings and LASCO CME coronagraph images were used in conjunction to the ground based recordings of the Worldwide Neutron Monitor Network, the interplanetary data of OMNI database and the geomagnetic activity manifestations denoted by *K*p and *D*st indices. More than that, cosmic ray characteristics as density, anisotropy and density gradients were also calculated. The results illustrate the state of the interplanetary space that cosmic rays crossed and their corresponding modulation with respect to the multiple extreme solar events of this period. In addition, the western location of the 21 January 2005 solar source indicates a new cosmic ray feature, which connects the position of the solar source to the cosmic ray anisotropy variations. In the future, this feature could serve as an indicator of the solar source and can prove to be a valuable asset, especially when satellite data are unavailable.

The unusual cosmic ray variations in July 2005 resulted from western and behind the limb solar activity

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Advances in Space Research

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One of the most interesting and unusual periods of the recent solar activity was July 2005. Despite the fact that it was a late declining phase of the 23rd solar cycle, generally a time of solar quiescence, that period was marked by extreme activity. The main events occurred at the invisible side of the Sun and did not reveal significant consequences in the Earth or near the Earth. However, cosmic ray variations testify to the high power of these events. A rather unusual Forbush effect was observed starting from July 16, 2005. It was characterized by very large cosmic ray anisotropy, the magnitude and direction of which are in accordance with a western powerful source.

Usually in such a case when the main interplanetary disturbance is far in the west, the Forbush effect is absent or it is very small and short lasting. In July 2005 a rare exclusion was observed which may testify to the giant decrease of 10 GV cosmic ray density (quite possible >=30%, indicating an unusually high cosmic ray gradient) to the west from the Sun–Earth line. In this work, a description of the July 2005 situation as well as the results of the convection- diffusion treatment with space cosmic ray gradients is presented. Some general remarks concerning extreme western solar events and their impact on cosmic rays are also discussed.

Fe/O Variations Relative to Source Longitude and Heliospheric Current Sheet in Large Solar Energetic Particle Events

Jinhye **Park**1, Radoslav Bucik2, Hyun-Jin Jeong1, and Yong-Jae Moon1,3
2024 ApJ 977 86
https://iopscience.iop.org/article/10.3847/1538-4357/ad843e/pdf
The Fe/O enhancements exhibit significant variations in gradual solar energetic particle (SEP) events. Several causes have been suggested including transport effects in the interplanetary space and flare contribution. In this study, we investigate the relationship between the integrated Fe/O ratios of 27 gradual SEP events, locations of associated solar flares, and positions along the heliospheric current sheet (HCS) between 2010 and 2014. We employ synchronic potential field source surface (PFSS) extrapolations at 2.5R⊙, derived in near real-time using Artificial Intelligence (AI)-generated far side and Helioseismic and Magnetic Imager (HMI) magnetograms, referred to as AIHMI-PFSS extrapolations. We examine low-energy (~0.5 MeV/nucleon) Fe and O ion measurements obtained from Suprathermal Ion Telescope on Solar Terrestrial Relations Observatories and Ultra Low Energy Isotope Spectrometer on Advanced Composition Explorer. We found a moderate anticorrelation between the Fe/O ratios and the absolute longitudinal separation angles from the source regions to the spacecraft magnetic footpoints. Furthermore, we investigate the variations in Fe/O ratios with respect to the separation angle, grouped by the same and opposite polarity sectors of the SEP source regions. We found that the mean and median Fe/O values are higher in the same polarity group compared to the opposite polarity group, with the largest contrast at separation angles between 25° and 50°, where the values are approximately 3 times larger. The results imply that the enhanced Fe/O ratios in the examined gradual SEP events are likely associated with direct source regions, while the HCS affects particle transport. **2013 April 11**
Table 1. Solar Sources of 27 SEP Events   2010-2014

Examining the Source Regions of Solar Energetic Particles Using an AI-generated Synchronic Potential Field Source Surface Model

Jinhye **Park**1, Hyun-Jin Jeong1, and Yong-Jae Moon1,2
2023 ApJ 953 159
https://iopscience.iop.org/article/10.3847/1538-4357/acdd00/pdf
We study the source regions of six solar energetic particle (SEP) events accelerated near or behind the limbs of the Sun. We use AI-generated farside magnetograms at a near real-time basis developed by Jeong et al. and AIHMI-PFSS extrapolations up to 2.5R⊙ computed using the input of the synchronic data combining AI-generated farside and HMI magnetograms. By comparing the AIHMI, HMI, Global Oscillations Network Group (GONG) synoptic magnetograms, and Air force Data Assimilative Photospheric flux Transport synchronic magnetograms, as well as the PFSS extrapolations, we find interesting differences between them in view of SEP source regions and magnetic field configurations. First, the structures and sizes of the source active regions (ARs) are changed. The total unsigned magnetic field fluxes of the ARs are mostly stronger in the AIHMI than in the HMI and GONG magnetograms. Second, newly emerging ARs are observed in the SEP source regions in the AIHMI magnetograms for two events. Third, the alterations in the magnetic flux, the emergence, and the dissipation of ARs lead to modifications in the locations of the global polarity inversion lines (PILs). The EUV wave propagation is typically observed to be oriented nearly perpendicular with respect to the local PIL, suggesting that the AIHMI-PFSS extrapolations around the source region are more realistic. This study shows that the continuous farside evolution of AR magnetic fields, which is accomplished by our AI synchronic magnetograms, can lead to an improved understanding of SEP source ARs. **20110921, 20110922, 20120927, 20130305, 20130621, 20140106**
Table 1. The Associated Solar Activities for the Six SEP Events, the SEP Onset Times, and the Peak Times

Dependence of the Peak Fluxes of Solar Energetic Particles on CME 3D Parameters from STEREO and SOHO

Jinhye **Park**1, Y.-J. Moon1,2, and Harim Lee2
2017 ApJ 844 17
http://sci-hub.cc/10.3847/1538-4357/aa794a
https://ui.adsabs.harvard.edu/link_gateway/2017ApJ...844...17P/PUB_PDF
https://www.academia.edu/35052617/STUDY_OF_SOLAR_ENERGETIC_PARTICLE_ASSOCIATIONS_WITH_CORONAL_EXTREME-ULTRAVIOLET_WAVES

We investigate the relationships between the peak fluxes of 18 solar energetic particle (SEP) events and associated coronal mass ejection (CME) 3D parameters (speed, angular width, and separation angle) obtained from SOHO, and STEREO-A/B for the period from 2010 August to 2013 June. We apply the STEREO CME Analysis Tool (StereoCAT) to the SEP-associated CMEs to obtain 3D speeds and 3D angular widths. The separation angles are determined as the longitudinal angles between flaring regions and magnetic footpoints of the spacecraft, which are calculated by the assumption of a Parker spiral field. The main results are as follows. (1) We find that the dependence of the SEP peak fluxes on CME 3D speed from multiple spacecraft is similar to that on CME 2D speed. (2) There is a positive correlation between SEP peak flux and 3D angular width from multiple spacecraft, which is much more evident than the relationship between SEP peak flux and 2D angular width. (3) There is a noticeable anti-correlation (r = −0.62) between SEP peak flux and separation angle. (4) The multiple-regression method between SEP peak fluxes and CME 3D parameters shows that the longitudinal separation angle is the most important parameter, and the CME 3D speed is secondary on SEP peak flux.

Table 1 The Properties of Flares and CMEs Associated with 18 SEP Events (2010-2013)

Study of Solar Energetic Particle Associations with Coronal Extreme-ultraviolet Waves

Jinhye **Park**1, D. E. Innes2, R. Bucik2,3, Y.-J. Moon1,4, and S. W. Kahler

2015 ApJ 808 3 **File**

https://iopscience.iop.org/article/10.1088/0004-637X/808/1/3/pdf

See presentation

https://community.apan.org/cfs-file.ashx/__key/telligent-evolution-components-attachments/13-7784-00-00-00-14-46-02/Park.pdf

We study the relationship between large gradual solar energetic particle (SEP) events and associated extreme-ultraviolet (EUV) wave properties in 16 events that occurred between 2010 August and 2013 May and were observed by SDO, the Solar and Heliospheric Observatory (SOHO), and/or STEREO. We determine onset times, peak times, and peak fluxes of the SEP events in the SOHO/ERNE and STEREO/LET proton channels (6–10 MeV). The EUV wave arrival times and their speeds from the source sites to the spacecraft footpoints in the photosphere, which are magnetically connected to the spacecraft by Parker spiral and potential fields, are determined by spacetime plots from the full-Sun heliographic images created by combining STEREO-A andSTEREO-B 195 Å and SDO 193 Å images. The SEP peak fluxes increase with the EUV wave speeds, and the SEP spectral indices become harder with the speeds. This shows that higher energetic particle fluxes are associated with faster EUV waves, which are considered as the lateral expansions of coronal-mass-ejection-driven shocks in the low corona.

2010 August 14, 2012 May 26, 2012 July 18, 2012 August 31, 2013 March 15, 2013 April 11, 2013 May 13

Table 1 The Solar Sources of the SEP Events (2010-2013)

Table 2 Properties of the SEP Events and Associated EUV Wave

What flare and CME parameters control the occurrence of solar proton events?

Jinhye **Park**1 andY.-J. Moon

JGR, Volume 119, Issue 12, pages 9456–9463, December **2014**

http://onlinelibrary.wiley.com/doi/10.1002/2014JA020272/pdf

In this study we examine the occurrence probabilities of solar proton events (SPEs) and their peak fluxes depending on both flare and CME parameters: flare peak flux, longitude, impulsive time, CME linear speed, and angular width. For this we use the NOAA SPEs, their associated X-ray flares and CME from 1997 to 2011. We divide the data into 16 subgroups according to the flare and CME parameters and estimate the SPE probabilities for the subgroups. The three highest probabilities are found for the following subgroups: 1) fast full halo (55.3%) and fast partial halo (42.9%) CMEs associated with strong flares from the western region and 2) slow full halo CMEs associated with strong flares from the western region (31.6%). It is noted that the events whose SPE probabilities are nearly 0% belong to the following subgroups: 1) slow and fast partial halo CMEs from the eastern region, 2) slow partial halo CMEs from the western region, and 3) slow full halo CMEs from the eastern region. These results show that important parameters to control SPE occurrences are CME linear speed, angular width, and source longitude, which can be understood by the piston-driven shock formation of fast CMEs and magnetic field connectivity from the source site to the Earth. It is also shown that when the subgroups are separately considered by flare impulsive time and source longitude, the correlation coefficients between the observed and the predicted SPE peak fluxes are greatly improved.

The Source Regions of Solar Energetic Particles Detected by Widely Separated Spacecraft

Jinhye **Park**1, D. E. Innes2, R. Bucik2, and Y.-J. Moon

2013 ApJ 779 184

We studied the source regions of 12 solar energetic particle (SEP) events seen between 2010 August and 2012 January at STEREO-A, B, and/or Earth (Advanced Composition Explorer/Solar and Heliospheric Observatory/GOES), when the two STEREO spacecraft were separated by about 180°. All events were associated with flares (C1 to X6) and fast coronal mass ejections and, except for one, accompanied by type II radio bursts. We have determined the arrival times of the SEPs at the three positions. **Extreme ultraviolet (EUV) waves**, observed in the 195 Å and 193 Å channels of STEREO and the Solar Dynamics Observatory, are tracked across the Sun to determine their arrival time at the photospheric source of open field lines connecting to the spacecraft. There is a good correlation between the EUV wave arrival times at the connecting footpoints and the SEP onset times. The delay time between electron onset and the EUV wave reaching the connecting footpoint is independent of distance from the flare site. The proton delay time increases with distance from the flare site. In three of the events, secondary flare sites may have also contributed to the wide longitudinal spread of SEPs.

Dependence of solar proton events on their associated activities: Coronal mass ejection parameters,

Park, J., Y.-J. Moon, and N. Gopalswamy

J. Geophys. Res., 117, A08108, (**2012**)

In this study we have examined the occurrence probability of solar proton events (SPEs) and their peak fluxes depending on coronal mass ejection (CME) parameters, linear speed (V), angular width (AW), and location (L). For this we used the NOAA SPE list and their associated CME data from 1997 to 2006. We found that the probability strongly depends on CME speed and angular width as follows. The highest association (36.1%) is found for the full halo CMEs with V ≥ 1500 kms−1 but the lowest association (0.9%) is found for the partial halo CMEs with 400 kms−1 ≤ V < 1000 kms−1. The SPE occurrence probabilities are different as much as 4.9 to 23 times according to CME speed and 1.6 to 6.5 times to angular width. The probabilities depending on CME speed and location increase from the eastern region to the western region and with speed. We have also examined the relationship between CME speed and SPE flux as well as its dependence on angular width (partial halo and full halo), longitude (east, center, and west) and direction parameter (<0.4 and ≥0.4). Our results show that the relationships strongly depend on longitude as well as direction parameter.

Dependence of solar proton events on their associated activities: Flare parameters

Park, Jinhye; Moon, Y.-J.; Lee, D. H.; Youn, Saepoom

J. Geophys. Res., Vol. 115, No. A10, A10105, **2010**

In this study we have examined the occurrence probability of solar proton events and their peak fluxes depending on three flare parameters (X-ray peak flux, longitude, and impulsive time). For this we used NOAA solar energetic particle events from 1976 to 2006 and their associated X-ray flare data. As a result, we selected 166 proton events that were associated with major flares: 85 events associated with X-class flares and 81 events associated with M-class flares. The occurrence probability especially strongly depends on three parameters as follows. (1) We found that about only 3.5% (1.9% for M-class and 21.3% for X-class) of the flares are associated with the proton events. (2) It is also found that this fraction strongly depends on longitude; for example, the fraction for 30°W < L ≤ 90°W is about three times larger than that for 30°E < L ≤ 90°E. (3) We also note that the occurrence probability of solar proton events associated with long-duration (≥0.3 h) flares is about 2 (X-class flare) to 7 (M-class flare) times larger than that with short-duration (<0.3 h) flares. (4) The largest difference is found between the eastern short-duration M-class flare group (0.3%) and the western long-duration X-class flare group (46.5%). In addition, the relationship between X-ray flare peak flux and proton peak flux as well as its correlation coefficient are strongly dependent on longitude and impulsive time.

Parker Solar Probe Observations of Helical Structures as Boundaries for Energetic Particles

F. **Pecora**, S. Servidio, A. Greco, W. H. Matthaeus, D. J. McComas, J. Giacalone, C. J. Joyce, T. Getachew, C. M. S. Cohen, R. A. Leske, M. E. Wiedenbeck, R. L. McNutt Jr., M. E. Hill, D. G. Mitchell, E. R. Christian, E. C. Roelof, N. A. Schwadron, S. D. Bale

MNRAS Volume 508, Issue 2, December **2021**, Pages 2114–2122,

https://doi.org/10.1093/mnras/stab2659

https://arxiv.org/pdf/2109.04571.pdf

Energetic particle transport in the interplanetary medium is known to be affected by magnetic structures. It has been demonstrated for solar energetic particles in near-Earth orbit studies, and also for the more energetic cosmic rays. In this paper, we show observational evidence that intensity variations of solar energetic particles can be correlated with the occurrence of helical magnetic flux tubes and their boundaries. The analysis is carried out using data from Parker Solar Probe orbit 5, in the period **2020 May 24 to June 2**. We use FIELDS magnetic field data and energetic particle measurements from the Integrated Science Investigation of the Sun (\isois) suite on the Parker Solar Probe. We identify magnetic flux ropes by employing a real-space evaluation of magnetic helicity, and their potential boundaries using the Partial Variance of Increments method. We find that energetic particles are either confined within or localized outside of helical flux tubes, suggesting that the latter act as transport boundaries for particles, consistent with previously developed viewpoints.

Development of a web application for monitoring solar activity and cosmic radiation
David **Pelosi**, Nicola Tomassetti, Matteo Duranti
IL NUOVO CIMENTO **2021**
https://arxiv.org/pdf/2101.09366.pdf
The flux of cosmic rays (CRs) in the heliosphere is subjected to remarkable time variations caused by the 11-year cycle of solar activity. To help the study of this effect, we have developed a web application (Heliophysics Virtual Observatory) that collects real-time data on solar activity, interplanetary plasma, and charged radiation from several space missions or observatories. As we will show, our application can be used to visualize, manipulate, and download updated data on sunspots, heliospheric magnetic fields, solar wind, and neutron monitors counting rates. Data and calculations are automatically updated on daily basis. A nowcasting for the energy spectrum of CR protons near-Earth is also provided using calculations and real-time neutron monitor data as input.

Source Energy Spectrum of the 17-05-2012 GLE
Jorge **Pérez-Peraza**, Juan C. Márquez-Adame, L. I. Mirosnichenko and Victor Velasco-Herrera
JGR **Volume123, Issue5** **2018** Pages 3262-3272
http://sci-hub.tw/10.1002/2017JA025030
Among the several GLE (Ground Level Enhancements) that have presumptuously occurred in the period 2012-2015 the 17th May 2012 is that which is more widely accepted to be a GLE, in view of the high number of high latitude Neutron Monitor (NM) stations that have registered it. In spite of the small amplitude, it was the more prominent of the predicted GLE´s of the present decade (Pérez-Peraza & Juarez-Zuñiga, 2015). However, the lack of latitude effect makes it difficult to study the characteristics of this event in the high energy extreme of the spectrum. Nevertheless, several outstanding works have been able to derive observational spectra at the top of the earth atmosphere for this peculiar GLE. Some of these works find that the flow of protons is characterized by two components. Quite a great number of works have been published in relation with observational features obtained with different instrumentation, but the source phenomena, regarding the generation processes and source physical parameters have not been scrutinized. The main goal of this work is to look at such aspects by means of the confrontation of the different approaches of the observational spectra with our analytical theoretical spectra based on stochastic acceleration and Electric field acceleration from reconnection processes. In this way, we derive a set of parameters which characterize the sources of these two GLE components, leading us to propose possible scenarios for the generation of particles in this particular GLE event.

Prognosis of GLEs of Relativistic Solar Protons
Jorge **Pérez-Peraza** and Alan Juárez-Zuñiga
2015 ApJ 803 27
Ground level enhancements (GLEs) are relativistic solar particles measured at ground level by the worldwide network of cosmic ray detectors. These sporadic events are associated with solar flares and are assumed to be of a quasi-random nature. Studying them gives information about their source and propagation processes, the maximum capacity of the Sun as a particle accelerator engine, the magnetic structure of the medium traversed, etc. Space vehicles, as well as electric transformers and gas pipes at high latitudes may be damaged by this kind of radiation. As a result, their prediction has turned out to be very important, but because of their random occurrence, up to now few efforts toward this goal have been made. The results of these efforts have been limited to possible warnings in real time, just before a GLE occurrence, but no specific dates have been predicted well enough in advance to prevent possible hazards. In this study we show that, in spite of the quasi-stochastic nature of GLEs, it is possible to predict them with relative precision, even for future solar cycles. Additionally, a previous study establishing synchronization among some periodicities of several layers of solar atmosphere argues against the full randomness of the phenomenon of relativistic particle production. Therefore, by means of wavelet spectral analysis combined with fuzzy logic tools, we reproduce previous known GLE events and present results for future events. The next GLE is expected to occur in the first semester of 2016.
ERRATUM: PROGNOSIS OF GLE OF RELATIVISTIC SOLAR PROTONS (2015, ApJ, 803, 27)

IMPULSIVE, STOCHASTIC, AND SHOCK WAVE ACCELERATION OF RELATIVISTIC PROTONS IN LARGE SOLAR EVENTS OF 1989 SEPTEMBER 29, 2000 JULY 14, 2003 OCTOBER 28, AND 2005 JANUARY 20
J. **P´erez-Peraza**1, E. V. Vashenyuk2, L. I. Miroshnichenko3, Yu. V. Balabin2, and A. Gallegos-Cruz4
Astrophysical Journal, 695:865–873, **2009** April
http://www.iop.org/EJ/toc/-alert=43190/0004-637X/695/2
Using the data from neutron monitors and applying various techniques, the parameters of relativistic solar protons (RSPs) outside the magnetosphere are currently being derived by several research groups. Such data, together

with direct proton measurements from balloons and spacecraft, allow the determination of particle energy spectra near the Earth's orbit in successive moments of time. Spectra of RSPs in a number of large solar events tend to indicate the existence of **multistep acceleration at/near the Sun**. In this paper, we study the generation of RSP by neutral current sheet, stochastic, and shock-wave acceleration, within the framework of **two-component concepts for ground level enhancements (GLEs) of solar cosmic rays (SCRs)**. Our analysis is extended to large solar events (GLEs) of 1989 September 29, 2000 July 14, 2003 October 28, and 2005 January 20. We found two different particle populations (components) in the relativistic energy range: a prompt component (PC), characterized by an early impulselike intensity increase, hard spectrum and high anisotropy, and a delayed component, presenting a gradual late increase, soft spectrum and low anisotropy. Based on a two-source model for SCR spectrum formation at the Sun, we carried out theoretical calculations of spectra in the sources for both components. *We conclude that the processes in neutral current sheet, together with stochastic acceleration in expanding magnetic trap in the solar corona, are able to explain the production of two different relativistic components. Shock acceleration in the presence of coronal mass ejection (CME) fits fairly only the nonrelativistic range of the SCR spectrum, but fails in the description of relativistic proton spectra, especially for the PC.*

Relativistic proton production at the Sun in the 20 January 2005 solar event

Advances in Space Research, Volume 41, Issue 6, Pages 947-954, **2008**

Jorge A. **Pérez-Peraza**, Eduard V. Vashenyuk, Apolonio Gallegos-Cruz, Yurii V. Balabin and Leonty I. Miroshnichenko

Based on the concept of multiple acceleration of solar energetic particles (SEP) we analyzed the super-event of 20 January 2005 by the data of ground level, balloon and spacecraft observations. The main characteristics of relativistic solar protons (energy spectra, anisotropy directions and pitch-angle distributions) are derived and their dynamics during the event is studied. It is shown that the flux of relativistic solar protons may consist of two distinct components, the so-called prompt and delayed ones. Within a two-source model of particle generation, one of which is associated with an expanding magnetic loop, we solved the transport equation in energy phase space, including adiabatic losses simultaneously with the stochastic acceleration process, and calculate the expected spectra of the delayed component at the source. The confrontation of experimental spectra with theoretical ones shows that the delayed component may be correctly described by stochastic acceleration, but not the prompt component. The required acceleration efficiencies turned out to be rather high, so that, for this particular event, adiabatic cooling is practically negligible. Our results provide a new support to the existence of two populations of relativistic solar protons in some SEP events.

Interpretation of flat energy spectra upstream of fast interplanetary shocks

Silvia **Perri**, Giuseppe Prete, Gaetano Zimbardo, Domenico Trotta, Lynn B. Wilson III, David Lario, Sergio Servidio, Francesco Valentini, Joe Giacalone

ApJ **2023**

https://arxiv.org/pdf/2301.05454.pdf

Interplanetary shocks are large-scale heliospheric structures often caused by eruptive phenomena at the Sun, and represent one of the main sources of energetic particles. Several interplanetary shock crossings by spacecraft at 1 AU have revealed enhanced energetic-ion fluxes that extend far upstream of the shock. Surprisingly, in some shock events, ion fluxes with energies between 100 keV and about 2 MeV acquire similar values (which we refer to as ``overlapped" fluxes), corresponding to flat energy spectra in that range. In contrast, closer to the shock, the fluxes are observed to depend on energy. In this work, we analyze three interplanetary shock-related energetic particle events observed by the Advanced Composition Explorer spacecraft where flat ion energy spectra were observed upstream of the shock. We interpret these observations via a velocity filter mechanism for particles in a given energy range. This reveals that low energy particles tend to be confined to the shock front and cannot easily propagate upstream, while high energy particles can. The velocity filter mechanism has been corroborated from observations of particle flux anisotropy by the Solid-State Telescope of Wind/3DP**. 4 Nov 2003, 2005 May 15, 14 Jul 2012**

Impact of solar magnetic field amplitude and geometry on cosmic rays diffusion coefficients in the inner heliosphere

Barbara **Perri**, Allan Sacha Brun, Antoine Strugarek, Victor Réville

Journal of Space Weather and Space Climate **2020**

https://arxiv.org/pdf/2010.01880.pdf

Cosmic rays (CRs) are tracers of solar events when they are associated with solar flares, but also galactic events when they come from outside our solar system. SEPs are correlated with the 11-year solar cycle while GCRs are anti-correlated due to their interaction with the heliospheric magnetic field and the solar wind. Our aim is to quantify separately the impact of the amplitude and the geometry of the magnetic field on the propagation of CRs of various energies in the inner heliosphere. We focus especially on the diffusion caused by the magnetic field along and across the field lines. To do so, we use the results of 3D MHD wind simulations running from the lower corona up to 1 AU. The wind is modeled using a polytropic approximation, and fits and power laws are used to account for the turbulence. Using these results, we compute the parallel and perpendicular diffusion coefficients of the Parker CR transport equation, yielding 3D maps of the diffusion of CRs in the inner heliosphere. By varying the amplitude of the magnetic field, we change the amplitude of the diffusion by the same factor, and the radial gradients by changing the spread of the current sheet. By varying the geometry of the magnetic field, we change the latitudinal gradients of diffusion by changing the position of the current sheets. By varying the energy, we show that the distribution of values for SEPs is more peaked than GCRs. For realistic solar configurations, we show that diffusion is highly non-axisymmetric due to the configuration of the current sheets, and that the distribution varies a lot with the distance to the Sun with a drift of the peak value. This study shows that numerical simulations and theory can help quantify better the influence of the various magnetic field parameters on the propagation of CRs. This study is a first step towards generating synthetic CR rates from numerical simulations.

Parameter estimation of superdiffusive motion of energetic particles upstream of heliospheric shocks

Silvia **Perri**1, Gaetano Zimbardo1, Frederic Effenberger2 and Horst Fichtner

A&A 578, A2 (**2015**)

Context. In-situ spacecraft observations recently suggested that the transport of energetic particles accelerated at heliospheric shocks can be anomalous, i.e. the mean square displacement can grow non-linearly in time. In particular, a new analysis technique has permitted the study of particle transport properties from energetic particle time profiles upstream of interplanetary shocks. Indeed, the time/spatial power laws of the differential intensity upstream of several shocks are indicative of superdiffusion.

Aims. A complete determination of the key parameters of superdiffusive transport comprises the power-law index, the superdiffusion coefficient, the related transition scale at which the energetic particle profiles turn to decay as power laws, and the energy spectral index of the shock accelerated particles.

Methods. Assuming large-scale spatial homogeneity of the background plasma, the power-law behaviour can been derived from both a (microscopic) propagator formalism and a (macroscopic) fractional transport equation. We compare the two approaches and find a relation between the diffusion coefficients used in the two formalisms. Based on the assumption of superdiffusive transport, we quantitatively derive these parameters by studying energetic particle profiles observed by the Ulysses and Voyager 2 spacecraft upstream of shocks in the heliosphere, for which a superdiffusive particle transport has previously been observed. Further, we have jointly studied the electron energy spectra, comparing the values of the spectral indices observed with those predicted by the standard diffusive shock acceleration theory and by a model based on superdiffusive transport.

Results. For a number of interplanetary shocks and for the solar wind termination shock, for the first time we obtain the anomalous diffusion constants and the scale at which the probability of particle free paths changes to a power-law. The investigation of the particle energy spectra indicates that a shock acceleration theory based on superdiffusive transport better explains observed spectral index values.

Conclusions. This study, together with the analysis of energetic particles upstream of shock waves, allows us to fully determine the transport properties of accelerated particles, even in the case of superdiffusion. This represents a new powerful tool to understand the transport and acceleration processes at astrophysical shocks.

Transport of Cosmic ray electrons from 1 AU to the Sun

Vahe' **Petrosian**, Elena Orlando, Andrew Strong

ApJ **943** 21 **2023**

https://arxiv.org/pdf/2212.00929.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/aca474/pdf

Gamma rays are produced by cosmic ray (CR) protons interacting with the particles at solar photosphere and by cosmic ray electrons and positrons (CRes) via inverse Compton scattering of solar photons. The former come from the solar disk while the latter extend beyond the disk. Evaluation of these emissions requires the flux and spectrum of CRs in the vicinity of the Sun, while most observations provide flux and spectra near the Earth, at around 1 AU from the Sun. Past estimates of the quiet Sun gamma-ray emission use phenomenological modulation procedures to estimate spectra near the Sun (see review by Orlando and Strong 2021 and references therein). We show that CRe transport in the inner heliosphere requires a kinetic approach and use a novel approximation to determine the variation of CRe flux and spectrum from 1 AU to the Sun including effects of (1) the structure of large scale magnetic field, (2) small scale turbulence in the solar wind from several in situ measurements, in particular, those by Parker Solar Probe that extend this information to 0.1 AU, and (3) most importantly, energy losses due to synchrotron and inverse Compton processes. We present results on the flux and spectrum variation of CRes from 1 AU to the Sun for several transport models. In forthcoming papers we will use these results for a more accurate estimate of quiet Sun inverse Compton gamma-ray spectra, and, for the first time, the spectrum of extreme ultraviolet to hard X-ray photons produced by synchrotron emission. These can be compared with the quiet Sun gamma-ray observation by Fermi (see, e.g.~Fermi-LAT Collaboration, 2011) and X-ray upper limits set by RHESSI (Hannah et al., 2010).

Particle Acceleration in Solar Flares and Associated CME Shocks

Vahe' **Petrosian**

ApJ 830 28 **2016**

http://arxiv.org/pdf/1605.04022v1.pdf

Observations relating the characteristics of electrons seen near Earth (SEPs) and those producing flare radiation show that in certain (prompt) events the origin of both population appears to be the flare site, which show strong correlation between the number and spectral index of SEP and hard X-ray radiating electrons, but in others(delayed), which are associated with fast CMEs, this relation is complex and SEPs tend to be harder. Prompt event spectral relation disagrees with that expected in thick or thin target models. We show that using a a more accurate treatment of the transport of the accelerated electrons to the footpoints and to the Earth can account for this discrepancy. Our results are consistent with those found by Chen and Petrosian (2013) for two flares using non-parametric inversion methods, according to which we have weak diffusion conditions, and trapping mediated by magnetic field convergence. The weaker correlations and harder spectra of delayed events can come about by re-acceleration of electrons in the CME shock environment. We describe under what conditions such a hardening can be achieved. Using this (acceleration at the flare and re-acceleration in the CME) scenario we show that we can describe the similar dichotomy that exists between the so called impulsive, highly enriched (3He and heavy ions) and softer SEP events, and stronger more gradual SEP events with near normal ionic abundances and harder spectra. These methods can be used to distinguish the acceleration mechanisms and to constrain their characteristics.

See Introduction and A schematic representation

Stochastic Acceleration by Turbulence Review

Vahé **Petrosian**

Space Science Reviews, November **2012**, Volume 173, Issue 1-4, pp 535-556

The subject of this paper is stochastic acceleration by plasma turbulence, a process akin to the original model proposed by Fermi. We review the relative merits of different acceleration models, in particular the so called first order Fermi acceleration by shocks and second order Fermi by stochastic processes, and point out that plasma waves or turbulence play an important role in all mechanisms of acceleration. Thus, stochastic acceleration by turbulence is active in most situations. We also show that it is the most efficient mechanism of acceleration of relatively cool non relativistic thermal background magnetized plasma particles. In addition, it can preferentially accelerate electrons relative to protons as is needed in many astrophysical radiating sources, where usually there are no indications of presence of shocks. We also point out that a hybrid acceleration mechanism consisting of initial acceleration by turbulence of background particles followed by a second stage acceleration by a shock has many attractive features. It is demonstrated that the above scenarios can account for many signatures of the accelerated electrons, protons and other ions, in particular 3He and 4He, seen directly as Solar Energetic Particles and through the radiation they produce in solar flares.

Particle Acceleration in Solar Flares and Enrichment of 3He and Heavy Ions

Vah´e **Petrosian**

E-print, July_Aug 2008, File

Хороший обзор по ускорению.

We discuss possible mechanisms of acceleration of particles in solar flares and show that turbulence plays an important role in all the mechanism. It is also argued that stochastic particle acceleration by turbulent plasma waves is the most likely mechanism for production of the high energy electrons and ions **responsible for observed radiative signatures of solar flares and for solar energetic particle or SEPs**, and that the predictions of this model agrees well with many past and recent high spectral and temporal observations of solar flares. It is shown that, in addition, the model explains many features of SEPs that accompany flares. In particular we show that it can successfully explain the observed extreme enhancement, relative to photospheric values, of 3He ions and the relative spectra of 3He and 4He. It has also the potential of explaining the relative abundances of most ions including the increasing enhancements of heavy ions with ion mass or mass-to-charge ratio.

Formation of the Injection Function of Solar Energetic Particles in Gradual Events

Ivan **Petukhov**1, Anastasia Petukhova1, and Stanislav Petukhov1

2023 ApJ 953 94

https://iopscience.iop.org/article/10.3847/1538-4357/ace31f/pdf

We present a model for solar energetic particle injection into interplanetary space in gradual events, in which particle acceleration occurs in a limited region of the solar atmosphere. The distribution function of particles accelerated by the diffusion mechanism is calculated. The flux of injected solar energetic particles is determined as a function of time and energy. We provide an explanation of the characteristic properties of the injection function and their dependence on the particle energy. Comparing the calculation results with ground-based measurements in the **2001 April 15** event shows a rough agreement with the particle density as a function of time and good agreement with the spectrum of maximum intensity values.

Solar Energetic Particle Acceleration by a Shock Wave Accompanying a Coronal Mass Ejection in the Solar Atmosphere

A. S. **Petukhova**, I. S. Petukhov, S. I. Petukhov, and L. T. Ksenofontov
2017 ApJ 836 36
http://iopscience.iop.org.sci-hub.cc/0004-637X/836/1/36/
https://arxiv.org/pdf/1702.02316.pdf
Solar energetic particle acceleration by a shock wave accompanying a coronal mass ejection (CME) is studied. The description of the accelerated particle spectrum evolution is based on the numerical calculation of the diffusive transport equation with a set of realistic parameters. The relation between the CME and shock speeds, which depend on the initial CME radius, is determined. Depending on the initial CME radius, its speed, and the magnetic energy of the scattering Alfvén waves, the accelerated particle spectrum is established 10–60 minutes from the beginning of CME motion. The maximum energies of particles reach 0.1–10 GeV. The CME radii of 3–5 and the shock radii of 5–10 agree with observations. The calculated particle spectra agree with the observed ones in events registered by ground-based detectors if the turbulence spectrum in the solar corona significantly differs from the Kolmogorov one.

Solar Source Regions for 3He-rich Solar Energetic Particle Events Identified Using Imaging Radio, Optical, and Energetic Particle Observations -- M. Pick, G. M. Mason, Y.-M. Wang, C. Tan , and L. Wang

The Astrophysical Journal, 648:1247-1255, 2006 September 10, E-print, Sep **2006**
We have identified the sources of six impulsive 3He-rich solar energetic particle events using imaging radio, optical, and energetic ion and electron data, together with calculated coronal fields obtained from extrapolating photospheric magnetograms using a potential field source surface (PFSS) model.

Comprehensive Analysis of the Geoeffective Solar Event of 21 June 2015: Effects on the Magnetosphere, Plasmasphere, and Ionosphere Systems

Mirko **Piersanti**, Tommaso Alberti, Alessandro Bemporad …
Solar Physics November **2017**, 292:169
https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1186-0.pdf
A full-halo coronal mass ejection (CME) left the Sun on 21 June 2015 from active region (AR) NOAA 12371. It encountered Earth on 22 June 2015 and generated a strong geomagnetic storm whose minimum Dst value was −204 nT. The CME was associated with an M2-class flare observed at 01:42 UT, located near disk center (N12 E16). Using satellite data from solar, heliospheric, and magnetospheric missions and ground-based instruments, we performed a comprehensive Sun-to-Earth analysis. In particular, we analyzed the active region evolution using ground-based and satellite instruments (Big Bear Solar Observatory (BBSO), Interface Region Imaging Spectrograph (IRIS), Hinode, Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO), Reuven Ramaty High Energy Solar Spectroscopic Imager(RHESSI), covering Hαα, EUV, UV, and X-ray data); the AR magnetograms, using data from SDO/Helioseismic and Magnetic Imager (HMI); the high-energy particle data, using the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) instrument; and the Rome neutron monitor measurements to assess the effects of the interplanetary perturbation on cosmic-ray intensity. We also evaluated the 1 – 8 Å soft X-ray data and the ∼1∼1 MHz type III radio burst time-integrated intensity (or fluence) of the flare in order to predict the associated solar energetic particle (SEP) event using the model developed by Laurenza et al. (Space Weather7(4), 2009). In addition, using ground-based observations from lower to higher latitudes (International Real-time Magnetic Observatory Network (INTERMAGNET) and European Quasi-Meridional Magnetometer Array (EMMA)), we reconstructed the ionospheric current system associated with the geomagnetic sudden impulse (SI). Furthermore, Super Dual Auroral Radar Network (SuperDARN) measurements were used to image the global ionospheric polar convection during the SI and during the principal phases of the geomagnetic storm. In addition, to investigate the influence of the disturbed electric field on the low-latitude ionosphere induced by geomagnetic storms, we focused on the morphology of the crests of the equatorial ionospheric anomaly by the simultaneous use of the Global Navigation Satellite System (GNSS) receivers, ionosondes, and Langmuir probes onboard the Swarm constellation satellites. Moreover, we investigated the dynamics of the plasmasphere during the different phases of the geomagnetic storm by

examining the time evolution of the radial profiles of the equatorial plasma mass density derived from field line resonances detected at the EMMA network (1.5<L<6.51.5<L<6.5). Finally, we present the general features of the geomagnetic response to the CME by applying innovative data analysis tools that allow us to investigate the time variation of ground-based observations of the Earth's magnetic field during the associated geomagnetic storm.

Stochastic Fermi Energization of Coronal Plasma during explosive magnetic energy release

Theophilos **Pisokas**, Loukas Vlahos, Heinz Isliker, Vassilios Tsiolis, Anastasios Anastasiadis
ApJ 2016
https://arxiv.org/pdf/1612.04246v1.pdf

The aim of this study is to analyze the interaction of charged particles (ions and electrons) with randomly formed particle scatterers (e.g.\ large scale local "magnetic fluctuations" or "coherent magnetic irregularities"), using the set up proposed initially by \cite{Fermi49}. These scatterers are formed by the explosive magnetic energy release and propagate with the Alfv\'en speed along the irregular magnetic fields. They are large scale local fluctuations (δB/B≈1), randomly distributed inside the unstable magnetic topology and will here be called {\bf Alfv\'enic Scatterers (AS)}. We constructed a 3D grid on which a small fraction of randomly chosen grid points are acting as AS. In particular, we study how a large number of test particles evolve inside a collection of AS, analyzing the evolution of their energy distribution and their escape time distribution. We use a well established method to estimate the transport coefficients directly from the trajectories of the particles. Using the estimated transport coefficients and solving the Fokker-Planck (FP) equation numerically, we can recover the energy distribution of the particles. We have shown that the Stochastic Fermi Energization (SFE) of mildly relativistic and relativistic plasma can heat and accelerate the tail of the ambient particle distribution as predicted by \citet{Parker58} and \citet{Ramaty79}. The temperature of the hot plasma and the tail of the energetic particles depend on the mean free path (λsc) of the particles between the scatterers inside the energization volume.

See introduction

The Ground-level Enhancement of 2012 May 17: Derivation of Solar Proton Event Properties through the Application of the NMBANGLE PPOLA Model

Christina **Plainaki**, Helen Mavromichalaki, Monica Laurenza, Maria Gerontidou, Anastasios Kanellakopoulos, and Marisa Storini
2014 ApJ 785 160
http://cosray.phys.uoa.gr/publications/D103.pdf

In this work, we apply an updated version of the Neutron Monitor (NM) Based Anisotropic GLE Pure Power Law (NMBANGLE PPOLA) model, in order to derive the characteristics of the ground-level enhancement (GLE) on 2012 May 17 (GLE71), the spectral properties of the related solar energetic particle (SEP) event, the spatial distributions of the high-energy solar cosmic ray fluxes at the top of the atmosphere, and the time evolution of the location of the GLE source. Our modeling, based uniquely on the use of ground-level NM data, leads to the following main results. The SEP spectrum related to GLE71 was rather soft during the whole duration of the event, manifesting some weak acceleration episodes only during the initial phase (at ~01:55-02:00 UT) and at ~02:30-02:35 UT and ~02:55-03:00 UT. The spectral index of the modeled SEP spectrum supports the coronal mass ejection-shock driven particle acceleration scenario, in agreement with past results based on the analysis of satellite measurements. During the initial phase of GLE71, the solar proton source at the top of the atmosphere was located above the northern hemisphere, implying that the asymptotic directions of viewing of the northern hemisphere NMs were more favorably located for registering the event than the southern ones. The spatial distribution of the solar proton fluxes at the top of the atmosphere during the main phase manifested a large variation along longitude and latitude. At the rigidity of 1 GV, the maximum primary solar proton flux resulted on the order of ~3 × 104 part. m–2 s–1 sr–1 GV–1.

Modeling the solar cosmic ray event of 13 December 2006 using ground level neutron monitor data

Adv. Space Res. **Volume 43, Issue 4,** *Pages 474-479*, **2009**
C. **Plainaki**, H. Mavromichalaki, A. Belov, E. Eroshenko, V. Yanke

The magnetic connectivity of coronal shocks to the visible solar surface during long-duration γ-ray events

Illya **Plotnikov**, Alexis P. Rouillard, Gerald H. Share
A&A **608**, A43, **2017** DOI: 10.1051/0004-6361/201730804
https://arxiv.org/pdf/1703.07563.pdf **File**
http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2017/12/aa30804-17/aa30804-17.html

Solar γ ray events measured near Earth can last several hours during so-called Long Duration Gamma Ray Flares (LDGRFs). LDGRFs suggest that a particle-acceleration mechanism operates over many hours to produce energetic protons that stream continually towards the solar surface. Coronal shocks, driven by the expansion of Coronal Mass Ejections (CMEs), could be the source of these energetic particles. For this hypothesis to work, the shock must be magnetically connected to the solar disk visible from Earth in order for particles accelerated at the shock to be channelled towards and impact the visible chromosphere. In this paper, we investigate if the spatial and temporal evolution of the coronal shocks, inferred from stereoscopic observations, could be the accelerators of the particles producing the LDGRFs. We analyse three CMEs that (1) erupted behind the solar limb viewed from Earth, (2) were associated with the early formation of coronal shocks measured by ground-based radio spectrographs, and (3) were associated with γ−ray events measured by the {\it Fermi}-Large Area Telescope (LAT) instrument. A 3D triangulation technique, based on remote-sensing observations is employed to model the expansion of these three CME shocks from above the solar surface to the upper corona. Coupling the expansion model to different models of the coronal magnetic field allows us to derive the time-dependent distribution of shock Mach numbers and the magnetic connection of particles produced by the shock to the solar surface visible from Earth. For all events, the reconstructed shock front was magnetically connected to the visible solar surface after the start of the flare and just before the onset of the > 100 MeV gamma-ray emission observed by {\it Fermi}-LAT γ-ray emission. n. The shock surface also exhibits supercritical Mach numbers required for significant particle energisation. The strongest gamma-ray emissions occur when the flanks of the shock exhibiting a quasi-perpendicular geometry are connected to the visible surface. Conclusions. This study provides further evidence that the high-energy protons producing the long duration high-energy {\gamma}-ray emission has the same CME shock origin as the Solar Energetic Particles observed in interplanetary space. **11-Oct-13, 2014 January 6, 01-Sep-14**

Proton acceleration in the solar flare

I.M.**Podgorny**   A.I.Podgorny

Journal of Atmospheric and Solar-Terrestrial Physics Volume 180, November **2018**, Pages 9-15

sci-hub.tw/10.1016/j.jastp.2017.12.010

Hundred years of cosmic ray investigations have not lead to the ultimate understanding the mechanisms of particle acceleration. Most popular theoretical mechanisms of solar comic ray generation are associated with shock waves. The discovery of sources of protons with relativistic energies, generated by the Sun (solar cosmic ray), gives us hope for the opportunity to clarify the mechanism of cosmic rays generation. The important information about the mechanism of proton acceleration in the Sun has been obtained from results by GOES of measurements. The association of a proton event with a particular flare is beyond doubt. The GOES measurements indicate propagation of the high-energy protons front without collisions from the flares that appeared on the western part of the solar disk. These protons can move along the helical magnetic field lines to the Earth. The protons from flares on the back side of the Sun can also come to the Earth's magnetosphere along magnetic lines. Protons from eastern part of the solar disk can come to the GOES across the magnetic lines. The front of the proton flux from eastern flares comes to Earth with a delay of several hours. The series of 2–3 weeks long proton events produced by several proton flares are observed one - two times in the 11 year cycle of solar activity. Nature of a trigger for initiating such series of proton events is not clear. **14-20 Jan 2005**

Propagation of Solar Energetic Particles during Multiple Coronal Mass Ejection Events

Silja **Pohjolainen**, Firas Al-Hamadani, Eino Valtonen

Solar Physics,   Vol. 291, Issue 2   **201**6

http://arxiv.org/pdf/1512.04881v1.pdf

We study solar energetic particle (SEP) events during multiple solar eruptions. The analysed sequences, on **24-26 November 2000, 9-13 April 2001, and 22-25 August 2005**, consisted of halo-type coronal mass ejections (CMEs) that originated from the same active region and were associated with intense flares, EUV waves, and interplanetary (IP) radio type II and type III bursts. The first two solar events in each of these sequences showed SEP enhancements near Earth, but the third in the row did not. We observed that in these latter events the type III radio bursts were stopped at much higher frequencies than in the earlier events, indicating that the bursts did not reach the typical plasma density levels near Earth. To explain the missing third SEP event in each sequence, we suggest that the earlier-launched CMEs and the CME-driven shocks either reduced the seed particle population and thus led to inefficient particle acceleration, or that the earlier-launched CMEs and shocks changed the propagation paths or prevented the propagation of both the electron beams and SEPs, so that they did not get detected near Earth even when the shock arrivals were recorded.

Table 5. Close-by events that show a flare, a CME, and a decametric–hectometric (DH) type II burst, found from the list of Wind/WAVES type II bursts and CMEs at http://cdaw.gsfc.nasa.gov/CME list/radio/waves type2.html.

Two New Sub-GLEs Found in Data of Neutron Monitors at South Pole and Vostok: On 09 June 1968 and 27 February 1969

Stepan **Poluianov**, Oscar Batalla, …, Ilya Usoskin

Solar Phys. Volume 299, article number 6, (**2024**)

https://link.springer.com/content/pdf/10.1007/s11207-023-02245-z.pdf

Intense solar energetic particle (SEP) events can be observed by neutron monitors (NMs) as so-called ground-level enhancements (GLEs). High-altitude polar NMs have high sensitivity for SEP due to the reduced atmospheric energy cutoff and very low geomagnetic rigidity cutoff compared to other NMs. There is a special class of sub-GLE events, viz. events that are weaker than standard GLEs and can only be observed by high-altitude polar NMs. So far, only one sub-GLE and three candidates are known, all in the period 2012 – 2015. In this work, we inspected the period from March 1964 to December 1969 in the data of the South Pole and Vostok high-altitude polar NMs on the Antarctic Plateau in search of possible sub-GLEs. We found two previously unknown events from 09 June 1968 and 27 February 1969 that formally match the definition of sub-GLE. They were associated with significant enhancements in the integral SEP intensity �(>60 MeV) measured by space-borne particle detectors, as well as with strong X-class solar flares from the western part of the solar disk. The identified sub-GLEs were analyzed and the corresponding SEP characteristics were estimated.

Solar energetic particles and galactic cosmic rays over millions of years as inferred from data on cosmogenic 26Al in lunar samples

S. **Poluianov**, G. A. Kovaltsov, I.G. Usoskin

A&A **2018**

https://arxiv.org/pdf/1807.10153.pdf

Aims. Lunar soil and rocks are not protected by a magnetic field or an atmosphere and are continuously irradiated by energetic particles that can produce cosmogenic radioisotopes directly inside rocks at different depths depending on the particle's energy. This allows the mean fluxes of solar and galactic cosmic rays to be assessed on the very long timescales of millions of years.

Methods. Here we show that lunar rocks can serve as a very good particle integral spectrometer in the energy range 20-80 MeV. We have developed a new method based on precise modeling, that is applied to measurements of 26Al (half-life ~0.7 megayears) in lunar samples from the Apollo mission, and present the first direct reconstruction (i.e., without any a priori assumptions) of the mean energy spectrum of solar and galactic energetic particles over a million of years.

Results. We show that the reconstructed spectrum of solar energetic particles is totally consistent with that over the last decades, despite the very different levels of solar modulation of galactic cosmic rays (ϕ=496±40 MV over a million years versus ϕ=660±20 MV for the modern epoch). We also estimated the occurrence probability of extreme solar events and argue that no events with the F(>30 MeV) fluence exceeding 5∗1010 and 1011 cm2 are expected on timescales of a thousand and million years, respectively.

Conclusions. We conclude that the mean flux of solar energetic particles hardly depends on the level of solar activity, in contrast to the solar modulation of galactic cosmic rays. This puts new observational constraints on solar physics and becomes important for assessing radiation hazards for the planned space missions.

GLE and Sub-GLE Redefinition in the Light of High-Altitude Polar Neutron Monitors

S. V. **Poluianov**, I. G. Usoskin, A. L. Mishev,M. A. Shea, D. F. Smart

Solar Physics November **2017**, 292:176

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1202-4.pdf

The conventional definition of ground-level enhancement (GLE) events requires a detection of solar energetic particles (SEP) by at least two differently located neutron monitors. Some places are exceptionally well suitable for ground-based detection of SEP – high-elevation polar regions with negligible geomagnetic and reduced atmospheric energy/rigidity cutoffs. At present, there are two neutron-monitor stations in such locations on the Antarctic plateau: SOPO/SOPB (at Amundsen–Scott station, 2835 m elevation), and DOMC/DOMB (at Concordia station, 3233 m elevation). Since 2015, when the DOMC/DOMB station started continuous operation, a relatively weak SEP event that was not detected by sea-level neutron-monitor stations was registered by both SOPO/SOPB and DOMC/DOMB, and it was accordingly classified as a GLE. This would lead to a distortion of the homogeneity of the historic GLE list and the corresponding statistics. To address this issue, we propose to modify the GLE definition so that it maintains the homogeneity: A GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located neutron monitors, including at least one neutron monitor near sea level and a corresponding enhancement in the proton flux measured by a space-borne instrument(s). Relatively weak SEP events registered only by high-altitude polar neutron monitors, but with no response from cosmic-ray stations at sea level, can be classified as sub-GLEs. **17 May 2012, 29 October 2015**

See https://pos.sissa.it/301/125/pdf

Modelling large solar proton events with the shock-and-particle model Extraction of the characteristics of the MHD shock front at the cobpoint

Jens **Pomoell**1*, Angels Aran2, Carla Jacobs1,3, Rosa Rodríguez-Gasén2, Stefaan Poedts1 and Blai Sanahuja

J. Space Weather Space Clim., 5, A12 (**2015**)
http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140020.pdf

We have developed a new version of a model that combines a two-dimensional Sun-to-Earth magnetohydrodynamic (MHD) simulation of the propagation of a CME-driven shock and a simulation of the transport of particles along the interplanetary magnetic field (IMF) line connecting the shock front and the observer. We assume that the shock-accelerated particles are injected at the point along the shock front that intersects this IMF line, i.e. at the cobpoint. Novel features of the model are an improved solar wind model and an enhanced fully automated algorithm to extract the necessary plasma characteristics from the shock simulation. In this work, the new algorithms have been employed to simulate the **2000 April 4 and the 2006 December 13** SEP events. In addition to quantifying the performance of the new model with respect to results obtained using previous versions of the shock-and-particle model, we investigate the semi-empirical relation between the injection rate of shock-accelerated particles, Q, and the jump in speed across the shock, VR, known as the Q(VR) relation. Our results show that while the magnetic field and density compression at the shock front is markedly different than in our previous modeling, the evolution of VR remains largely similar. As a result, we confirm that a simple relation can still be established between Q and VR, which enables the computation of synthetic intensity-time profiles at any location in interplanetary space. Furthermore, the new shock extraction tool is found to yield improved results being in general more robust. These results are important not only with regard to efforts to develop coupled magnetohydrodynamic and particle simulation models, but also to improve space weather related software tools that aim to predict the peak intensities, fluences and proton intensity-time profiles of SEP events (such as the SOLPENCO tool).

Solar-Energetic-Particle Track-Production Rates at 1 au: Comparing In-situ Particle Fluxes with Lunar Sample-Derived Track Densities

A. R. **Poppe**, P. S. Szabo, E. R. Imata, L. P. Keller, R. Christoffersen

Astrophys. J. Lett **958** L35 **2023**
https://arxiv.org/pdf/2311.10323.pdf
https://iopscience.iop.org/article/10.3847/2041-8213/ad0cf6/pdf

Heavy (Z>26) solar energetic particles (SEPs) with energies ~1 MeV/nucleon are known to leave visible damage tracks in meteoritic materials. The density of such solar flare tracks in lunar and asteroidal samples has been used as a measure of a sample's exposure time to space, yielding critical information on planetary space weathering rates, the dynamics and lifetimes of interplanetary dust grains, and the long-term history of solar particle fluxes. Knowledge of the SEP track accumulation rate in planetary materials at 1 au is critical for properly interpreting observed track densities. Here, we use in-situ particle observations of the 0.50-3.0 MeV/nuc Fe-group SEP flux taken by NASA's Advanced Composition Explorer (ACE) to calculate a flux of track-inducing particles at 1 au of 6.0x10^5 /cm2/yr/str. Using the observed energy spectrum of Fe-group SEPs, we find that the depth distribution of SEP-induced damage tracks inferred from ACE measurements matches closely to that recently measured in lunar sample 64455; however, the magnitude of the ACE-inferred rate is approximately 25x higher than that observed in the lunar sample. We discuss several hypotheses for the nature of this discrepancy, including inefficiencies in track formation, thermal annealing of lunar samples, erosion via space weathering processing, and variations in the SEP flux at the Moon, yet find no satisfactory explanation. We encourage further research on both the nature of SEP track formation in meteoritic materials and the flux of Fe-group SEPs at the lunar surface in recent and geologic times to resolve this discrepancy.

HESPERIA REleASE+: Improving Solar Proton Event Forecasting by Means of Automated Recognition of Type-III Radio Bursts

Arik **Posner**, Olga E. Malandraki, Michalis Karavolos, Kostas Tziotziou, Fanis Smanis, Bernd Heber, Henrik Dröge, Patrick Kühl, Giorgos P. Veldes

Space Weather Volume22, Issue12 December **2024** e2024SW004013
https://doi.org/10.1029/2024SW004013
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW004013

This work reports on an attempt toward improving the Relativistic Electron Alert System for Exploration (REleASE): the occurrence of a type-III radio burst as a precondition for a REleASE forecast. REleASE forecasts are based on the detection of early arrival of near-relativistic electrons ahead of more hazardous protons from Solar Energetic Particle (SEP) events. The goal is to allow astronauts on a Lunar or Mars mission sufficient advance warning to reach a radiation shelter to minimize radiation dose exposure. We test a new system that sets a condition of the occurrence of a type-III radio burst, thus adding independent evidence of particle escape from the Sun, with the aim of reducing known sources of false-alarms of the existing REleASE system. The High Energy Solar Particle

Events foRecastIng and Analysis (HESPERIA) REleASE+ system, which takes advantage of availability of real-time solar radio observations during the passage of STEREO-A by Earth in 2023, has now been incorporated in the HESPERIA framework. We discuss the techniques used for automatic detection of type-III radio bursts preparing for its real-time implementation, the determination of selection criteria for type-III bursts that are candidates for solar proton events in the Earth-moon system, and first results of the combined system. **28 Oct 2021, 9 Nov 2023, 20 Jan 2022, 14 Dec 2023**
Table 1List of All 21 Identified SPEs During the Period of September 2021 to December 2023

The "SEP Clock": A Discussion of First Proton Arrival Times in Wide-Spread Solar Energetic Particle Events.

Posner, A., Richardson, I.G. & Strauss, R.DT.
Sol Phys 299, 126 (**2024**).
https://doi.org/10.1007/s11207-024-02350-7
https://link.springer.com/content/pdf/10.1007/s11207-024-02350-7.pdf
https://link.springer.com/epdf/10.1007/s11207-024-02350-7
This work analyzes the appearance of wide-spread deka-MeV solar energetic proton (SEP) events, in particular the arrival of the first protons within ≈ 4.5 – 45 MeV measured at Earth–Sun L1, and their relationship with their relative solar source longitude. The definition of "wide-spread SEP event" for this study refers to events that are observed as a 25 MeV proton intensity increase at near 1 AU locations that are separated by at least 130∘ in solar longitude. Many of these events are seen at all three of the spacecraft, STEREO (Solar-Terrestrial Relations Observatory) A, STEREO B, and SOHO (Solar and Heliospheric Observatory), and may therefore extend far beyond 130∘ in longitude around the Sun. A large subset of these events have already been part of a study by Richardson et al. (Solar Phys., 289, 3059, 2014). The event source region identifications draw from this study; more recent events have also been added. Our focus is on answering two specific questions: (1) What is the maximum longitude over which SEP protons show energy dispersion, i.e., a clear sign of arrival of higher-energy protons before those of lower energy? (2) What implications can be drawn from the ensemble of events observed regarding either direct magnetic connectivity to shocks and/or cross-field transport from the site of the eruption in the onset phase of the event? **14 Feb. 2014, 28 March 2014, 22 Sept. 2014**
Table 1 List of all SEP events with >25 MeV protons for which SOHO and at least one STEREO spacecraft were separated by 130∘. 2009-2017

Warning Time Analysis from SEP Simulations of a Two-Tier Relativistic Electron Alert System for Exploration (REleASE) Applied to Mars Exploration

A. **Posner**, R.D. Strauss
Space Weather **2020**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019SW002354
The sudden exposure to energetic protons from solar energetic particle (SEP) events beyond the Earth's magnetosphere and en-route to and from Mars can, in extreme cases, lead to acute radiation sickness, an impairing, mission-endangering condition for astronauts. Timely warnings of their impending occurrence may significantly reduce radiation exposure by allowing astronauts sufficient time to move to a radiation shelter. The Relativistic Electron Alert System for Exploration (REleASE) has been developed to provide such early warnings for the Earth-Moon system by exploiting the time difference of the arrival of SEP electrons and ions at 1 AU. This study explores the effectiveness of REleASE in a scenario that assumes a two-element system, one placed at Earth-Sun L1 and the other at Mars-Sun L1. This system would exploit the Hohmann-Parker effect, the circumstance that a spacecraft remains close to the heliospheric magnetic field lines that connect Earth and/or Mars with the Sun while in the Hohmann transfer orbit. We investigate whether the two-element REleASE system would provide advance warnings for all phases of a mission to and from Mars. In the absence of adequate long-term SEP measurements beyond Earth orbit, we employ 2D modeling of SEP injection and transport for SEP exposure scenarios, in which the best magnetic connections, and thus most rapid flux increases of protons occur at exploration vehicle. We show the relative timing of alert occurrence and arrival of harmful ions at the spacecraft throughout a round-trip human mission to Mars.

The Hohmann–Parker effect measured by the Mars Science Laboratory on the transfer from Earth to Mars: Consequences and opportunities

A. **Posner** a,n , D. Odstrĉil b,c , P. MacNeice b , L. Rastaetter b , C. Zeitlin d , et al.
Planetary and Space Science Volume 89, December **2013**, Pages 127-139
sci-hub.si/10.1016/j.pss.2013.09.013
We show that a spacecraft launched from Earth towards Mars following a Hohmann minimum energy transfer trajectory has a strong tendency to remain well-connected magnetically to Earth, in the early phase of the transfer, or

to Mars in the late phase, via the Parker spiral magnetic field. On the return trip, the spacecraft would remain reasonably well-connected magnetically first to Mars and later to Earth. Moreover, good magnetic connectivity occurs on all Hohmann transfers between neighboring planets in the inner solar system out to Mars. We call this hitherto unnamed circumstance the Hohmann–Parker effect. We show consequences of the effect by means of simultaneous cosmic radiation proxy observations made near Earth, near Mars, and at the Mars Science Laboratory on the transfer from Earth to Mars in 2011/2012. We support the observations with simulations of the large-scale magnetic field of the inner heliosphere during this period and compare the results with our predictions. The implications of the Hohmann–Parker effect are discussed.

Two Years into Verification and Validation of the Relativistic Electron Alert System for Exploration (REleASE): An Update into Rising Solar Activity

Posner, A.; Rother, O. M.; Heber, B.; Müller-Mellin, R.; Lee, J.

American Geophysical Union, Fall Meeting **2010**, abstract #SH53C-01

For the past two years, the REleASE method of short-term forecasting of the intensity of prompt solar energetic protons of hazardous energies (~40 MeV) with relativistic electrons has been implemented. Since February 2008, REleASE translates near-real-time electron data of the SOHO/COSTEP instrument from L1 into near-future proton fluxes. The live forecasting output is available online. Electrons are well known to provide the first sign of a solar particle event in progress, approximately one hour ahead of more dangerous protons. The forecasting of the sudden increase in intensity of protons from solar energetic particle events is relevant for radiation protection of humans on exploration missions. The method utilizes the speed advantage of electrons over up to 40 MeV protons and the correlations of inverse rise time and intensity between electrons and protons in solar particle events. The effectiveness of this tool is based on the observed similarities in particle transport between the Sun and 1 AU. Electrons act as test particles by probing the ever-changing heliospheric transport conditions that act on the slower moving protons. This presentation is the first detailed analysis of the REleASE output and shows its strengths and weaknesses through the early signs of solar activity in 2010. Electrons of a Solar Energetic Particle (SEP) event arrive at 1 AU and provide an early sign of more hazardous protons. The REleASE model would issue an alert at this time.

Typically one hour into the event, the more hazardous ions from the SEP arrive at L1 or 1 AU along the same magnetic field lines as the electrons. This presentation analyzes the accuracy of this live warning system. The false/missed warning rate will be assessed and the accuracy of REleASE's forecast proton flux will be compared with measured fluxes.

A New Trend in Forecasting Solar Radiation Hazards

Posner, Arik; Guetersloh, Stephen; Heber, Bernd; Rother, Oliver

Space Weather, Vol. 7, No. 5, S05001, **2009**

(Полученный журнал Space Weather, Vol. 6, No. 3, pp.10-11, 2009)

http://www.agu.org/pubs/crossref/2009/2009SW000476.shtml

http://dx.doi.org/10.1029/2009SW000476

Several international space agencies plan to send astronauts beyond low-Earth orbit in the coming decades to explore the Moon or other nearby planetary objects. Humans leaving the Earth's magnetosphere enter the solar wind, potentially exposing themselves to prompt solar energetic particle (SEP) events, which are sudden outbursts of energetic particle radiation of solar origin. Accurate warning of SEP radiation hazards through an operational forecasting system, even if only an hour in advance, allows contingency plans to be set in motion rapidly. The potential for expanding mission operations capabilities with such warnings has been acknowledged by the NASA Space Radiation Analysis Group at Johnson Space Center. As NASA gears up to send astronauts to the Moon and Mars, projected radiation doses on such long-term missions approach current career limits, so avoiding sudden exposure from SEP events becomes crucial.

http://www.agu.org/journals/sw/swa/free/newarticle/?id=2009SW000476&page=1#citation

See Labrenz et al. (**2016**) Near realtime forecasting of MeV protons on the basis of sub relativistic electrons EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, p.8076

Up to 1-hour forecasting of radiation hazards from solar energetic ion events with relativistic electrons,

Posner, A.,

Space Weather, Vol. 5, No. 5, S05001, doi:10.1029/2006SW000268, **2007, File**.

The sudden and prompt occurrence of solar energetic particle events poses a hazard to manned space activities and interferes with robotic space science missions. This study demonstrates the possibility of short-term forecasting of the appearance and intensity of solar ion events by means of relativistic, near–light speed electrons. A list of the most severe proton events measured by GOES 8 in the years 1996–2002 serves as a basis to derive the fundamentals of the forecasting method with statistical and superposed epoch techniques. The Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) on SOHO provides relativistic electron and <50 MeV proton observations at 1 AU. With a subset of solar particle events (SPEs) where the location of the associated flare on the Sun has been determined, we find that (1) relativistic electrons always arrive at 1 AU ahead of nonrelativistic SPEs allowing their forecasting; (2) the intensity increase of both, electrons and protons alike, depends on the magnetic connection, i.e., the magnetic longitude difference between the observer and the flare; and (3) as coming from one source under near-identical propagation conditions, significant correlations exist that show that the early electron intensity and increase can be utilized as a matrix to forecast the upcoming proton intensity. The study demonstrates one initial empirical forecasting technique with electron and proton observations in 2003.

Characteristics of events with metric-to-decahectometric type II radio bursts associated with CMEs and flares in relation to SEP events

O. **Prakash**, Li Feng, G. Michalek, Weiqun Gan, Lei Lu, A. Shanmugaraju, S. Umapathy

ApSS March 2017, 362:56 **2017**

A gradual solar energetic particle (SEP) event is thought to happen when particles are accelerated at a shock due to a fast coronal mass ejection (CME). To quantify what kind of solar eruptions can result in such SEP events, we have conducted detailed investigations on the characteristics of CMEs, solar flares and m-to-DH wavelength type II radio bursts (herein after m-to-DH type II bursts) for SEP-associated and non-SEP-associated events, observed during the period of 1997-2012. Interestingly, 65% of m-to-DH type II bursts associated with CMEs and flares produced SEP events. The SEP-associated CMEs have higher sky-plane mean speed, projection corrected speed, and sky-plane peak speed than those of non-SEP-associated CMEs respectively by 30%, 39%, and 25%, even though the two sets of CMEs achieved their sky-plane peak speeds at nearly similar heights within LASCO field of view. We found Pearson's correlation coefficients between the speeds of CMEs speeds and logarithmic peak intensity of SEP events are cc = 0.62 and cc = 0.58, respectively. We also found that the SEP-associated CMEs are on average of three times more decelerated (-21.52 m/s2) than the non-SEP-associated CMEs (-5.63 m/s2). The SEP-associated m type II bursts have higher frequency drift rate and associated shock speed than those of the non-SEP-associated events by 70% and 25% respectively. The average formation heights of m and DH type II radio bursts for SEP-associated events are lower than for non-SEP-associated events. 93% of SEP-associated events originate from the western hemisphere and 65% of SEP-associated events are associated with interacting CMEs. The obtained results indicate that, at least for the set of CMEs associated with m-to-DH type II bursts, SEP-associated CMEs are more energetic than those not associated with SEPs, thus suggesting that they are effective particle accelerators. **2011-August-04**

Influence of the transport regime on the energetic particle density profiles upstream and downstream of interplanetary shocks

Giuseppe **Prete**, Silvia Perri, Gaetano Zimbardo

Advances in Space Research Volume 63, Issue 8, 15 April **2019**, Pages 2659-2671

https://reader.elsevier.com/reader/sd/pii/S0273117719300109?token=3661B901FE1614E7134530D6ACF32F343A601C700141779682DD0BD344F80E50C93B5D1960674595E80DEB24B143EE07

The spatial distribution of energetic particles accelerated at shocks depends on their transport properties. Analyses of energetic particle fluxes measured by spacecraft upstream of interplanetary shock waves have pointed out the presence of spatial profiles different from those expected for normal diffusion. We propose that anomalous, superdiffusive transport can help to interpret the observed energetic particle profiles both upstream and downstream of shock waves. We set up a numerical model to compute the energetic particle profiles on both sides of the shock: particles are injected at the shock and then propagate according to a Gaussian random walk in the case of normal diffusion and according to a Lévy random walk in the case of superdiffusion. The latter is characterized by a nonlinear growth of the mean square displacement of particles and by a power law distribution of free path lengths. A Langevin type equation is solved numerically, and energetic particle spatial profiles are obtained for a steady state configuration. A number of numerical solutions are obtained: in the case of normal diffusion, the well known exponential profile upstream of the shock is recovered. In the case of superdiffusion, varying the power exponent and the scale time characterizing the power law distribution of free path times, it is found that power law upstream profiles and spatially nonconstant downstream profiles are obtained. A preliminary comparison between the obtained numerical results and interplanetary shock observations by the ACE spacecraft is carried out, and good agreement between the energetic particle profiles is found. This shows that the present superdiffusive model can be helpful for interpreting the overall time/space trends of particles accelerated at interplanetary shock waves.

Acceleration of Solar Wind Particles by Traveling Interplanetary Shocks

P. L**. Prinsloo**1, R. D. Strauss1, and J. A. le Roux2,3

2019 ApJ 878 144

https://iopscience.iop.org/article/10.3847/1538-4357/ab211b/pdf

The acceleration of thermal solar wind (SW) protons at spherical interplanetary shocks driven by coronal mass ejections is investigated. The SW velocity distribution is represented using κ-functions, which are transformed in response to simulated shock transitions in the fixed-frame flow speed, plasma number density, and temperature. These heated SW distributions are specified as source spectra at the shock from which particles with sufficient energy can be injected into the diffusive shock acceleration process. It is shown that for shock-accelerated spectra to display the classically expected power-law indices associated with the compression ratio, diffusion length scales must exceed the width of the compression region. The maximum attainable energies of shock-accelerated spectra are found to be limited by the transit times of interplanetary shocks, while spectra may be accelerated to higher energies in the presence of higher levels of magnetic turbulence or at faster-moving shocks. Indeed, simulations suggest that fast-moving shocks are more likely to produce very high energy particles, while strong shocks, associated with harder shock-accelerated spectra, are linked to higher intensities of energetic particles. The prior heating of the SW distribution is found to complement shock acceleration in reproducing the intensities of typical energetic storm particle (ESP) events, especially where injection energies are high. Moreover, simulations of ~0.2–1 MeV proton intensities are presented that naturally reproduce the observed flat energy spectra prior to shock passages. Energetic particles accelerated from the SW, aided by its prior heating, are shown to contribute substantially to intensities during ESP events. **2003 October 29**

An Investigation of the CME of 3 November 2011 and Its Associated Widespread Solar Energetic Particle Event

A. J. **Prise**, L. K. Harra, S. A. Matthews, D. M. Long, A. D. Aylward

Solar Physics, May **2014**, Volume 289, Issue 5, pp 1731-1744

http://arxiv.org/pdf/1312.2965v1.pdf

Multi-spacecraft observations are used to study the in-situ effects of a large coronal mass ejection (CME) erupting from the farside of the Sun on 3 November 2011, with particular emphasis on the associated solar energetic particle (SEP) event. At that time both Solar Terrestrial Relations Observatory (STEREO) spacecraft were located more than 90 degrees from Earth and could observe the CME eruption directly, with the CME visible on-disk from STEREO-B and off the limb from STEREO-A. Signatures of pressure variations in the corona such as deflected streamers were seen, indicating the presence of a coronal shock associated with this CME eruption. The evolution of the CME and an associated extreme-ultraviolet (EUV) wave were studied using EUV and coronagraph images. It was found that the lateral expansion of the CME low in the corona closely tracked the propagation of the EUV wave, with measured velocities of 240±19 km s−1 and 221±15 km s−1 for the CME and wave, respectively. Solar energetic particles were observed to arrive first at STEREO-A, followed by electrons at the Wind spacecraft at L1, then STEREO-B, and finally protons arrived simultaneously at Wind and STEREO-B. By carrying out a velocity-dispersion analysis on the particles arriving at each location, it was found that energetic particles arriving at STEREO-A were released first and that the release of particles arriving at STEREO-B was delayed by about 50 minutes. Analysis of the expansion of the CME to a wider longitude range indicates that this delay is a result of the time taken for the CME edge to reach the footpoints of the magnetic-field lines connected to STEREO-B. The CME expansion is not seen to reach the magnetic footpoint of Wind at the time of solar-particle release for the particles detected here, suggesting that these particles may not be associated with this CME.

Numerical simulations of solar energetic particle event timescales associated with ICMES

S.-Y. **Qi**, G. Qin, Y. Wang

RAA Vol 17, No 4, 33 (**2017**)

http://arxiv.org/pdf/1507.07655v1.pdf

Recently, S.W. Kahler studied the solar energetic particle (SEP) event timescales associated with coronal mass ejections (CMEs) from spacecraft data analysis. They obtained different timescales of SEP events, such as TO, the onset time from CME launch to SEP onset, TR, the rise time from onset to half the peak intensity (0.5Ip), and TD, the duration of the SEP intensity above 0.5Ip. In this work, we solve SEPs transport equation considering ICME shocks as energetic particle sources. Our simulations show similar results to Kahler's spacecraft data analysis that the weighted average of TD increases with both CME speed and width. Besides, our simulations show the results which were not achieved from the observation data analysis, i.e., TD is directly dependent on CME speed, but not dependent on CME width.

Magnetic Cloud and Sheath in the Ground-level Enhancement Event of 2000 July 14. II. Effects on the Forbush Decrease

G. **Qin**1 and S.-S. Wu1

2021 ApJ 908 236

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https://iopscience.iop.org/article/10.3847/1538-4357/abd77c/pdf

Forbush decreases (Fds) in galactic cosmic ray intensity are related to interplanetary coronal mass ejections (ICMEs). The parallel diffusion of particles is reduced because the magnetic turbulence level in the sheath region bounded by the ICME's leading edge and shock is high. In the sheath and magnetic cloud (MC) energetic particles would feel an enhanced magnetic focusing effect caused by the strong inhomogeneity of the background magnetic field. Therefore, particles would be partially blocked in the sheath–MC structure. Here, we study two-step Fds by considering the magnetic turbulence and background magnetic field in the sheath–MC structure with diffusion coefficients calculated using theoretical models, to reproduce the Fd associated with the ground-level enhancement event on 2000 July 14 by solving the focused transport equation. The sheath and MC are set to spherical caps that are portions of spherical shells with enhanced background magnetic field. The magnetic turbulence levels in the sheath and MC are set to higher and lower than those in ambient solar wind, respectively. In general, the simulation result conforms to the main characteristics of the Fd observation, such as the pre-increase precursor, amplitude, total recovery time, and two-step decrease of the flux at the arrival of the sheath and MC. It is suggested that the sheath plays an important role in the amplitude of the Fd while the MC contributes to the formation of the second-step decrease and prolonged recovery time. It is also inferred that both magnetic turbulence and background magnetic field in the sheath–MC structure are important for reproducing the observed two-step Fd.

Numerical simulation and data analysis of the 23 July 2012 SEP event observed by ACE, STEREO-A, and STEREO-B

G. **Qin** and S.-Y. Qi

A&A 637, A48 (**2020**) DOI: https://doi.org/10.1051/0004-6361/201936786

https://www.aanda.org/articles/aa/pdf/2020/05/aa36786-19.pdf

An extremely powerful, superfast interplanetary coronal mass ejection (ICME) from the Sun on **23 July 2012** was detected by widely separated multiple spacecraft, namely STEREO-A, STEREO-B, and ACE, together with the ICME-driven shock and associated solar energetic particles (SEPs). We use the Parker spiral magnetic field model to analyze the relationship between the propagation of the shock and the SEP flux. Furthermore, we simulate the SEP event by numerically solving the three-dimensional focused transport equation of SEPs considering the shock as the moving source of energetic particles. To deal with the fact that protons and electrons behave completely differently for both parallel and perpendicular diffusion, for simplicity, we use the same diffusion model format for the simulations of protons and electrons but with different parameters. We find that the analysis can qualitatively explain the important features of the SEP flux observed by the multiple spacecraft simultaneously. In addition, the numerical results for both energetic protons and electrons approximately agree with multi-spacecraft observations.

Simulations of a gradual solar energetic particle event observed by Helios 1, Helios 2, and IMP 8 simultaneously

Gang **Qin**, Yang Wang

ApJ **809** 177 **2015**

http://arxiv.org/pdf/1505.02974v1.pdf

In this work, a gradual solar energetic particle (SEP) event observed by multi-spacecraft has been investigated with simulations. Based on a numerical solution of the Fokker-Planck focused transport equation, we obtain the intensity time profiles of SEPs accelerated by an interplanetary shock in the three-dimensional interplanetary space. The shock is treated as a moving source of energetic particles with a distribution function. By fitting the **1979/03/01** SEP event observed by Helios 1, Helios 2, and IMP 8 with our simulations simultaneously, we obtain the best parameters for the shock acceleration strength model. And we also find that the particle perpendicular diffusion coefficient with the level of ∼1%−3% of parallel diffusion coefficient at 1 AU should be included. In addition, the gradient of SEP fluxes in the decay phase is more sensitive to the shock acceleration strength parameters than that is to the perpendicular diffusion coefficient.

TRANSPORT OF SOLAR ENERGETIC PARTICLES ACCELERATED BY ICME SHOCKS: REPRODUCING THE RESERVOIR PHENOMENON

G. **Qin**1, Y. Wang1, M. Zhang2, and S. Dalla

2013 ApJ 766 74

In this work, gradual solar energetic particle (SEP) events observed by multiple spacecraft are investigated with model simulations. Based on a numerical solution of the Fokker-Planck focused transport equation including perpendicular diffusion of particles, we obtained the fluxes of SEPs accelerated by an interplanetary coronal mass ejection driven shock as it propagates outward through the three-dimensional Parker interplanetary magnetic field. The shock is treated as a moving source of energetic particles with an assumed particle distribution function. We look at the time profiles of particle flux as they are observed simultaneously by multiple spacecraft located at different locations. The dependence of particle fluxes on different levels of perpendicular diffusion is determined. The main purpose of our simulation is to reproduce the reservoir phenomenon, during which it is frequently observed that particle fluxes are nearly the same at very different locations in the inner heliosphere, up to 5 AU, during the decay phase of gradual SEP events. The reservoir phenomenon is reproduced in our simulation under a variety of conditions of perpendicular diffusion of particles estimated from the nonlinear guiding center theory (NLGC). As the perpendicular diffusion coefficient increases, the nonuniformity of particle fluxes becomes smaller, making the reservoir phenomenon more prominent. However, if the shock acceleration strength decreases slower than $r^{-2.5}$ with the radial distance r, the reservoir phenomenon might disappear, with limited perpendicular diffusion constrained by the NLGC theory. Therefore, observation of the reservoir phenomenon in gradual SEP events can be used to test qualitatively theories of particle diffusion and shock acceleration.

AN EFFECT OF PERPENDICULAR DIFFUSION ON THE ANISOTROPY OF SOLAR ENERGETIC PARTICLES FROM UNCONNECTED SOURCES

G. **Qin**[1], H.-Q. He[1,2] and M. Zhang

2011 ApJ 738 28

Recently, Tan and coworkers studied the **2001 September 24** solar energetic particle (SEP) event observed by the Wind spacecraft at 1 AU and found that there is a counter-streaming particle beam with a deep depression of flux at 90° pitch angle during the beginning of the event. They suggested that it is a result of a reflecting boundary at some distance outside of 1 AU. While this scenario could be true under some specific configuration of an interplanetary magnetic field, in this paper we offer another possible explanation. We simulated the SEP event by solving the five-dimensional focused transport equation numerically for 40 keV electrons with perpendicular diffusion. We find that a counter-streaming particle beam with deep depression at 90° pitch angle can form on Parker magnetic field lines that do not directly connect to the main particle source on the Sun in the beginning of an SEP event. It can happen when a significant number of observed particles come from adjacent field lines through parallel transport to large radial distance first, hopping across field lines through perpendicular diffusion, and then getting scattered back to 1 AU, where they combine with the particles directly coming from the Sun to form a counter-streaming beam.

Energetic Neutral Atoms from Solar Energetic Particles due to Shocks: Inclusion of Upstream Particles

Brent M. **Randol1**, Errol J. Summerlin1, and Jeewoo Park1,2

2023 ApJ 955 63

https://iopscience.iop.org/article/10.3847/1538-4357/acefcc/pdf

Many aspects of solar energetic particles are not well understood, including their acceleration mechanism. There has been recent interest in the potential of energetic neutral atoms (ENAs) as remote probes of solar energetic particles (SEPs) and their acceleration. The single accidental observation (in physical units) has been modeled as accelerated by a coronal mass ejection (CME)-driven shock by several authors, all of whom have assumed that the upstream component of the shock can be ignored. In this article, we relax this assumption and model the flux of ENAs at 1 au due to a CME-driven shock with an upstream component. We show the effect of varying parameters of the shock acceleration model, specifically α, the exponent of the power law in momentum of the mean free path, and η, a measure of the relative turbulence level. The main result is that including the upstream component significantly increases the flux at 1 au for typically assumed parameters in the energy range of the STEREO observation. We also derive the form of the ENA transport equation that we used in this study. These results enable a better understanding of potential observations of ENAs due to SEPs.

Anomalous Cosmic-Ray Oxygen Observations into 0.1 au

J. S. **Rankin**1, D. J. McComas1, R. A. Leske2, E. R. Christian3, C. M. S. Cohen2, A. C. Cummings2, C. J. Joyce1, A. W. Labrador2, R. A. Mewaldt2, N. A. Schwadron1,4

2022 ApJ 925 9

https://iopscience.iop.org/article/10.3847/1538-4357/ac348f/pdf

The Integrated Science Investigation of the Sun instrument suite onboard NASA's Parker Solar Probe mission continues to measure solar energetic particles and cosmic rays closer to the Sun than ever before. Here, we present the first observations of cosmic rays into 0.1 au (21.5 solar radii), focusing specifically on oxygen from ∼2018.7 to ∼2021.2. Our energy spectra reveal an anomalous cosmic-ray-dominated profile that is comparable to that at 1 au, across multiple solar cycle minima. The galactic cosmic-ray-dominated component is similar to that of the previous solar minimum (Solar Cycle 24/25 compared to 23/24) but elevated compared to the past (Solar Cycle 20/21). The findings are generally consistent with the current trend of unusually weak solar modulation that originated during the previous solar minimum and continues today. We also find a strong radial intensity gradient: 49.4 ± 8.0% au^{-1} from 0.1 to 0.94 au, for energies of 6.9–27 MeV nuc^{-1}. This value agrees with that measured by Helios nearly 45 yr ago from 0.3 to 1.0 au (48% ± 12% au^{-1}; 9–29 MeV nuc^{-1}) and is larger than predicted by models. The large anomalous cosmic-ray gradients observed close to the Sun by the Parker Solar Probe Integrated Science Investigation of the Sun instrument suite found here suggest that intermediate-scale variations in the magnetic field's structure strongly influence cosmic-ray drifts, well inside 1 au.

Parker Solar Probe: Four Years of Discoveries at Solar Cycle Minimum **Review**

N. E. **Raouafi**, L. Matteini, J. Squire, S. T. Badman, M. Velli, +++

Space Science Reviews **2023** 157 pages, 65 figures

https://arxiv.org/pdf/2301.02727.pdf

Launched on 12 Aug. 2018, NASA's Parker Solar Probe had completed 13 of its scheduled 24 orbits around the Sun by Nov. 2022. The mission's primary science goal is to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what processes accelerate energetic particles. Parker Solar Probe returned a treasure trove of science data that far exceeded quality, significance, and quantity expectations, leading to a significant number of discoveries reported in nearly 700 peer-reviewed publications. The first four years of the 7-year primary mission duration have been mostly during solar minimum conditions with few major solar events. Starting with orbit 8 (i.e., 28 Apr. 2021), Parker flew through the magnetically dominated corona, i.e., sub-Alfvénic solar wind, which is one of the mission's primary objectives. In this paper, we present an overview of the scientific advances made mainly during the first four years of the Parker Solar Probe mission, which go well beyond the three science objectives that are: (1) Trace the flow of energy that heats and accelerates the solar corona and solar wind; (2) Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind; and (3) Explore mechanisms that accelerate and transport energetic particles. **1 Nov. 2018, 5 Nov. 2018, 11-12 Nov. 2018, 15 Mar. 2019, 2 and 4 Apr. 2019, 20-21 Apr. 2019, 13 Oct. 2019, 20 Jan. 2020, 26-27 Jan. 2020, 25 Jun. 2020, 19 Nov. 2020, 29 Nov. 2020**

Very high energy proton peak flux model

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J. Space Weather Space Clim. **2020**, 10, 24

https://doi.org/10.1051/swsc/2020024

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc190089.pdf

Solar energetic particles (SEPs) pose a serious radiation hazard to spacecraft and astronauts. The highest energy SEPs are a significant threat even in heavily shielded applications. We present a new probabilistic model of very high energy differential peak proton fluxes. The model is based on GOES/HEPAD observations between 1986 and 2018, i.e., covering very nearly three complete solar cycles. The SEP event list for the model was defined using a statistical criterion derived by setting the possibility of false detection of an event to 1%. The peak flux distributions were calculated for the interpolated energies 405 MeV, 500 MeV and 620 MeV, and modelled with exponentially cut off power law functions. The HEPAD data were cleaned and corrected using a “bow-tie” method which is based on the response functions of the HEPAD channels P8–P10 found in the instrument calibration reports. The results of the model are available to the Space Weather community as a web-based tool at the ESA’s Space Situational Awareness Programme Space Weather Service Network. **19-29 October 1989**

Two solar proton fluence models based on ground level enhancement observations

Osku **Raukunen**1*, Rami Vainio1, Allan J. Tylka2, William F. Dietrich3, Piers Jiggens4, Daniel Heynderickx5, Mark Dierckxsens6, Norma Crosby6, Urs Ganse7 and Robert Siipola1

J. Space Weather Space Clim. **2018**, 8, A04

https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170071.pdf

Solar energetic particles (SEPs) constitute an important component of the radiation environment in interplanetary space. Accurate modeling of SEP events is crucial for the mitigation of radiation hazards in spacecraft design. In this study we present two new statistical models of high energy solar proton fluences based on ground level enhancement (GLE) observations during solar cycles 19–24. As the basis of our modeling, we utilize a four parameter double power law function (known as the Band function) fits to integral GLE fluence spectra in rigidity. In the first model, the integral and differential fluences for protons with energies between 10 MeV and 1 GeV are

calculated using the fits, and the distributions of the fluences at certain energies are modeled with an exponentially cut-off power law function. In the second model, we use a more advanced methodology: by investigating the distributions and relationships of the spectral fit parameters we find that they can be modeled as two independent and two dependent variables. Therefore, instead of modeling the fluences separately at different energies, we can model the shape of the fluence spectrum. We present examples of modeling results and show that the two methodologies agree well except for a short mission duration (1 year) at low confidence level. We also show that there is a reasonable agreement between our models and three well-known solar proton models (JPL, ESP and SEPEM), despite the differences in both the modeling methodologies and the data used to construct the models.
Table 1. Observed GLEs since 1942 and their solar event associations. Data references are given in the notes below the table.
Table 2. Spectral parameters of GLEs and their ESP counterparts
Table 3. Spectral parameters of sub-GLEs and an ESP counterpart.

Iron-rich solar particle events measured by SOHO/ERNE during two solar cycles

O. **Raukunen**, E. Valtonen, R. Vainio
A&A 589, A138 **2016**
http://arxiv.org/pdf/1603.04768v1.pdf

We study the differences in the heavy ion composition of solar energetic particle (SEP) events between solar cycles 23 and 24. We have surveyed the SOHO/ERNE heavy ion data from the beginning of solar cycle 23 until the end of June 2015, that is, well into the declining phase of cycle 24. We used this long observation period to study the properties of heavy ions (from C to Fe) and to compare the two solar cycles in this respect. We surveyed the data for SEP events with enhancements in the Fe/C and Fe/O intensity ratios in the energy range 5-15 MeV per nucleon, and associated the events with solar flare and coronal mass ejections (CME) when possible. We studied the properties of heavy ions in these events and compared the average relative abundances of heavy ions between the two solar cycles. We found that fewer days had C and O intensities higher than ~10−3 cm−2sr−1s−1(MeVn−1)−1 during solar cycle 24 than during cycle 23. For Fe this difference was clear even at lower intensities. We also found that fewer days had Fe/(C+O) > 0.183 during cycle 24. We identified 86 SEP events with at least one Fe-rich day, 65 of which occurred during cycle 23 and only 21 during cycle 24. We found that impulsive events have been almost completely absent during cycle 24. Mean abundances of heavy ions in the events were found to be significantly lower during cycle 24 than in cycle 23. Our results reflect the reduced solar activity in cycle 24 and indicate lower efficiency of particle acceleration processes for both gradual and impulsive SEP events in cycle 24.

Relationship between solar energetic particle intensities and coronal mass ejection kinematics using STEREO/SECCHI field of view

Anitha **Ravishankar** and Grzegorz Michalek
A&A 646, A142 (**2021**)
https://www.aanda.org/articles/aa/pdf/2021/02/aa39537-20.pdf
https://doi.org/10.1051/0004-6361/202039537
https://arxiv.org/pdf/2102.12640.pdf

Solar energetic particles (SEPs) accelerated from shocks driven by coronal mass ejections (CMEs) are one of the major causes of geomagnetic storms on Earth. Therefore, it is necessary to predict the occurrence and intensity of such disturbances. For this purpose we analyzed in detail 38 non-interacting halo and partial halo CMEs, as seen by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph, generating SEPs (in > 10 MeV, > 50 MeV, and > 100 MeV energy channels) during the quadrature configuration of the Solar TErrestrial RElations Observatory (STEREO) twin spacecrafts with respect to the Earth, which marks the ascending phase of solar cycle 24 (i.e., 2009–2013). The main criteria for this selection period is to obtain height–time measurements of the CMEs without significant projection effects and in a very large field of view. Using the data from STEREO/Sun Earth Connection Coronal and Heliospheric Investigation (STEREO/SECCHI) images we determined several kinematic parameters and instantaneous speeds of the CMEs. First, we compare instantaneous CME speed and Mach number versus SEP fluxes for events originating at the western and eastern limb; we observe high correlation for the western events and anticorrelation for the eastern events. Of the two parameters, the Mach number offers higher correlation. Next we investigated instantaneous CME kinematic parameters such as maximum speed, maximum Mach number, and the CME speed and Mach number at SEP peak flux versus SEP peak fluxes. Highly positive correlation is observed for Mach number at SEP peak flux for all events. The obtained instantaneous Mach number parameters from the emperical models was verified with the start and end time of type II radio bursts, which are signatures of CME-driven shock in the interplanetary medium. Furthermore, we conducted estimates of delay in time and distance between CME, SEP, and shock parameters. We observe an increase in the delay in time and distance when SEPs reach peak flux with respect to CME onset as we move from the western to the eastern limb. Western limb events (longitude 60°) have the best connectivity and this decreases as we move towards the eastern limb. This variation is due to the magnetic connectivity from the Sun to the Earth, called the Parker spiral interplanetary magnetic field. Comparative studies of the considered energy channels of the SEPs also throw light on the reacceleration of suprathermal seed ions by CME-driven shocks that are pre-accelerated in the magnetic reconnection. **22 September 2011, 13 March 2012, 12 July 2012**

Non-interacting coronal mass ejections and solar energetic particles near the quadrature configuration of Solar TErrestrial RElations Observatory

Anitha **Ravishankar** and Grzegorz Michałek

A&A 638, A42 (**2020**) **File**

https://www.aanda.org/articles/aa/pdf/2020/06/aa37528-20.pdf

https://arxiv.org/pdf/2010.01443

https://doi.org/10.1051/0004-6361/202037528

We present our results on the correlation of non-interacting coronal mass ejections (CMEs) and solar energetic particles (SEPs). A statistical analysis was conducted on 25 SEP events and the associated CME and flare during the ascending phase of solar cycle 24, i.e., 2009–2013, which marks the quadrature configuration of Solar TErrestrial RElations Observatory (STEREO). The complete kinematics of CMEs is well studied near this configuration of STEREO. In addition, we have made comparison studies of STEREO and SOlar and Heliospheric Observatory results. It is well known that the CME speeds and SEP intensities are closely correlated. We further examine this correlation by employing instantaneous speeds (maximum speed and the CME speed and Mach number at SEP peak flux) to check whether they are a better indicator of SEP fluxes than the average speed. Our preliminary results show a better correlation by this approach. In addition, the correlations show that the fluxes of protons in energy channel >10 MeV are accelerated by shock waves generated by fast CMEs, whereas the particles of >50 MeV and >100 MeV energy bands are mostly accelerated by the same shock waves but partly by the associated flares. In contrast, the X-ray flux of solar flares and SEP peak flux show a poor correlation. **2012-07-12**

Table A.1. Observational parameters of 25 CMEs and the associated SEPs and Flares during the period 2009–2013.

See Comment on "Non-interacting coronal mass ejections and solar energetic particles near the quadrature configuration of solar terrestrial relations observatory": CME shocks are fast magnetosonic shocks and not intermediate Alfvén shocks

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A&A 656, A152 (**2021**)

https://www.aanda.org/articles/aa/pdf/2021/12/aa41029-21.pdf

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Observational Aspects of Particle Acceleration in Large Solar Flares **Review**

John C. **Raymond** · Säm Krucker · Robert P. Lin · Vahé Petrosian

Space Sci. Rev., 173:197–221, **2012, File**

Solar flares efficiently accelerate electrons to several tens of MeV and ions to 10 GeV. The acceleration is usually thought to be associated with magnetic reconnection occurring high in the corona, though a shock produced by the CoronalMass Ejection (CME) associated with a flare can also accelerate particles. Diagnostic information comes from emission at the acceleration site, direct observations of Solar Energetic Particles (SEPs), and emission at radio wavelengths by escaping particles, but mostly from emission from the chromosphere produced when the energetic particles bombard the footpoints magnetically connected to the acceleration region. This paper provides a review of observations that bear upon the acceleration mechanism.

Seeds and Sequences of Element Abundances in Solar Energetic Particle Events

Donald V. **Reames**

Space Sci. Rev **2024**

https://arxiv.org/pdf/2404.05048.pdf **File**

Solar energetic particles (SEPs) in the small "impulsive" events, primarily accelerated during magnetic reconnection in solar jets, have strong enhancements of the abundances of increasingly heavy elements. In contrast, the shock acceleration of ambient coronal plasma in most large "gradual" SEP events produces flat or decreasing abundances vs. element mass-to-charge ratios A/Q. However, heavy-ion enhancements in the largest gradual SEP events can occur in two ways: (1) strong streaming of protons away from the shock amplifies Alfven waves that preferentially scatter and retard protons near the shock while increasingly-heavy ions can leak out, and (2) strong shock waves re-accelerate SEPs fed from persistent impulsive SEP events streaming from some active regions, with their pre-enhanced heavy ions becoming dominant. Power-law fits of abundance enhancements vs. A/Q can distinguish the latter events by the presence of both impulsive and coronal-seed components, and the best-fit charges Q define characteristic source temperatures. Intense impulsively-seeded events can occur in sequences fed from a single persistent active-region as it rotates across the disk of the Sun. Three week-long event sequences, each producing two or three very large events, occur early in the strong solar-cycle 23. The weak solar-cycle 24, produces only one impulsively-seeded event sequence - perhaps a dearth of both impulsive seeds and sufficiently strong shocks. In contrast, there are other active regions where large events alternate SEPs with and without impulsively-seeded sources. We also find that events with moderate Alfven-wave trapping near the shock can release ions slowly or rapidly as a function of A/Q. This A/Q-dependent trapping acts almost as a magnetic spectrometer that separates elements in space and time. **18-21 Sep 1997, 4-8 Nov 1997, 2-7 May 1998, 25-27 Aug 1998, 15-19 Apr 2001, 28 Oct-4 Nov 2003, 2-3 Dec 2003, 11-13 Apr 2004, 4-9 Aug 2011, 22-25 May 2013, 23 July 2016,**

Element Abundances and the Physics of Solar Energetic Particles Review

Donald **Reames**

Front. Astron. Space Sci. 11:1368043. **2024**

doi: 10.3389/fspas.2024.1368043

https://www.frontiersin.org/articles/10.3389/fspas.2024.1368043/full

https://www.frontiersin.org/articles/10.3389/fspas.2024.1368043/pdf **File**

The acceleration and transport of solar energetic particles (SEPs) cause their abundance, measured at a constant velocity, to be enhanced or suppressed as a function of the magnetic rigidity of each ion, and hence, of its atomic mass-to-charge ratio of A/Q. Ion charges, in turn, depend upon the source electron temperature. In small “impulsive” SEP events, arising from solar jets, acceleration during magnetic reconnection causes steep power-law abundance enhancements. These impulsive SEP events can have 1,000-fold enhancements of heavy elements from sources at ∼2.5 MK and similar enhancements of 3He/4He and of streaming electrons that drive type-III radio bursts. Gamma-ray lines show that solar flares also accelerate 3He-rich ions, but their electrons and ions remain trapped in magnetic loops, so they dissipate their energy as X-rays, γ-rays, heat, and light. “Gradual” SEPs accelerated at shock waves, driven by fast coronal mass ejections (CMEs), can show power-law abundance enhancements or depressions, even with seed ions from the ambient solar corona. In addition, shocks can reaccelerate seed particles from residual impulsive SEPs with their pre-existing signature heavy-ion enhancements. Different patterns of abundance often show that heavy elements are dominated by a source different from that of H and He. Nevertheless, the SEP abundance, averaged over many large events, defines the abundance of the corona itself, which differs from the solar photosphere as a function of the first ionization potential (FIP) since ions, with FIP <10 eV, are driven upward by forces of electromagnetic waves, which neutral atoms, with FIP >10 eV, cannot feel. Thus, SEPs provide a measurement of element abundance in the solar corona, distinct from solar wind, and may even better define the photosphere for some elements.

Element Abundances in Impulsive Solar Energetic-Particle Events Review

Donald **Reames**

2023

https://arxiv.org/ftp/arxiv/papers/2309/2309.09327.pdf **File**

Impulsive solar energetic-particle (SEP) events were first distinguished as the streaming electrons that produce type III radio bursts as distinct from shock-induced type II bursts. They were then observed as the surprisingly-enhanced 3He-rich SEP events, which were also found to have element enhancements rising smoothly with the mass-to-charge ratio A/Q through the elements, even up to Pb. These impulsive SEPs have been found to originate during magnetic reconnection in solar jets where open magnetic field lines allow energetic particles to escape. In contrast, impulsive solar flares are produced when similar reconnection involves closed field lines where energetic ions are trapped on closed loops and dissipate their energy as X-rays, {\gamma}-rays, and heat. Abundance enhancements that are power-laws in A/Q can be used to determine Q values and hence the coronal source temperature in the events. Proton and He excesses that contribute their own power-law may identify events with re-acceleration of SEPs by shock waves driven by accompanying fast, narrow coronal mass ejections (CMEs) in many of the stronger jets. **18-21 Sep 1997, 7 Aug 1999, 1 May 2000, 27 Dec 2000, 1 Nov 2004, 23 Jul 2016**

1 Introduction

Review and Outlook of Solar-Energetic-Particle Measurements on Multispacecraft Missions

Donald V. **Reames**

Frontiers of Space Science 10: 1254266 **2023**

https://arxiv.org/ftp/arxiv/papers/2307/2307.04182.pdf

https://www.frontiersin.org/articles/10.3389/fspas.2023.1254266/pdf

The earliest evidence on spatial distributions of solar energetic particles (SEPs) compared events from many different source longitudes on the Sun, but the early Pioneers provided the first evidence of the large areas of equal SEP intensities across the magnetically-confined "reservoirs" late in the events. More-detailed measurements of the importance of self-generated waves and trapping structures around the shock waves that accelerate SEPs were obtained from the Helios mission plus IMP 8, especially during the year when the two Voyager spacecraft also happened by. The extent of the dozen widest SEP events in a solar cycle, that effectively wrap around the Sun, was revealed by the widely separated STEREO spacecraft with three-point intensities fit to Gaussians. Element abundances of the broadest SEP events favor average coronal element abundances with little evidence of heavy-element-enhanced "impulsive suprathermal" ions that often dominate the seed population of the shocks, even in extremely energetic local events. However, it is hard to define a distribution with two or three points. Advancing the physics of SEPs may require a return to the closer spacing of the Helios era with coverage mapped by a half-dozen spacecraft to help disentangle the distribution of the SEPs from the underlying structure of the magnetic field and the accelerating shock.

How Do Shock Waves Define the Space-Time Structure of Gradual Solar Energetic Particle Events? Review

Donald V. **Reames**

Space Sci. Rev **219**, Article number: 14 **2023**

https://arxiv.org/ftp/arxiv/papers/2210/2210.16693.pdf

https://link.springer.com/content/pdf/10.1007/s11214-023-00959-x.pdf

We revisit the full variety of observed temporal and spatial distributions of energetic solar protons in "gradual" solar energetic-particle (SEP) events resulting from the spatial variations in the shock waves that accelerate them. Differences in the shock strength at the solar longitude of a spacecraft and at the footpoint of its connecting magnetic field line, nominally 55 degrees to the west, drive much of that variation. The shock wave itself, together with energetic particles trapped near it by self-amplified Alfven waves, forms an underlying autonomous structure that can drive across magnetic field lines intact, spreading proton intensities in a widening SEP longitude distribution. During the formation of this fundamental structure, historically called an "energetic storm particle" (ESP) event, many SEPs leak away early, amplifying waves as they flow along well-connected field lines and broaden the distribution outward; behind this structure between the shock and the Sun a "reservoir" of quasi-trapped SEPs forms. Very large SEP events are complicated by additional extensive wave growth that can spread an extended ESP-like trapping region. The multiplicity of shock-related processes contributing to the observed SEP profiles causes correlations of the events to be poorly represented by the peak intensities commonly used. In fact, the extensive spatial distributions of SEPs are sometimes interwoven with the structures of the shocks that have accelerated them and sometimes free. We should consider new questions: Which extremes of the shock contribute most to the SEPs profile of an event, (1) the shock at the longitude of a spacecraft, (2) the shock ~55 degrees to the west at the footpoint of the field, or (3) SEPs that have collected in the reservoir? How does the space-time distribution of SEPs correspond with the underlying space-time distribution of shock strength? **1-6 Jan 1978, 23-29 Sep 1978, 1-6 Mar 1979, 20-21 Apr 1998, 21-25 Sep 1998, 21-22 Jan 1999, 6-9 Jun 2000, 28-29 Jan 2001, 29-31 Mar 2001, 26-28 Apr 2001,**

Solar Energetic Particles: Spatial Extent and Implications of the H and He Abundances Review

Donald V. **Reames**

Space Sci. Rev **218**, Article number: 48 **2022**

https://arxiv.org/ftp/arxiv/papers/2205/2205.06883.pdf

https://link.springer.com/content/pdf/10.1007/s11214-022-00917-z.pdf

One of the earliest indicators of the importance of shock acceleration of solar energetic particles (SEPs) was the broad spatial extent of the "gradual" SEP events produced as the shock waves, driven by wide, fast coronal mass ejections (CMEs), expand across the Sun. Contrasting "impulsive" SEP events, with characteristic enhancements of 3He and of heavy elements, are now associated with magnetic reconnection on open field lines in solar jets. However, large shock waves can also traverse pools of residual impulsive suprathermal ions and jets can produce fast CMEs that drive shock waves; in both cases shocks reaccelerate ions with the "impulsive" abundance signatures as well as coronal plasma. These more-complex events produce "excess protons" that identify this process, and recently, differences in the distribution of 4He abundances have also been found to depend upon the combination of seed population and acceleration mode. Extreme differences in the 4He abundances may reflect underlying differences in the abundances of the coronal regions being sampled by solar jets and, surprisingly, SEP events where shock waves sample two seed-particle populations seem to have about twice the 4He/O ratio of those with a single source. **1-3 Apr 1995, 14 Nov 1998, 8 Aug 1999, 15-18 Apr 2001, 26 and 28 Oct 2003, 23 January 2012, 4-10 Jan 2014, 18 Apr 2014, 23 July 2016, 28 Sep 2021**

A Perspective on Solar Energetic Particles personal Review

Donald V **Reames**

Frontiers in Astron. and Space Sci. 9: 890864 **2022**

https://arxiv.org/ftp/arxiv/papers/2203/2203.15886.pdf **File**

https://www.frontiersin.org/articles/10.3389/fspas.2022.890864/full

The author has been fortunate to observe and participate in the rise of the field of solar energetic particles (SEPs), from the early abundance studies, to the contemporary paradigm of shock acceleration in large SEP events, and element abundance enhancements that are power laws in mass-to-charge ratios from H to Pb. Through painful evolution the "birdcage" model and the "solar-flare myth" came and went, leaving us with shock waves and solar jets that can interact as sources of SEPs.

Energy Spectra vs. Element Abundances in Solar Energetic Particles and the Roles of Magnetic Reconnection and Shock Acceleration **Review**

Donald V. **Reames**

Solar Phys. **297**, Article number: 32 **2022**

https://arxiv.org/ftp/arxiv/papers/2112/2112.01568.pdf

https://link.springer.com/content/pdf/10.1007/s11207-022-01961-2.pdf **File**

https://doi.org/10.1007/s11207-022-01961-2

We reexamine the relationship between energy spectral indices and element abundance enhancements in solar energetic particle (SEP) events at energies of a few MeV/amu. We find correlated behavior only in the largest gradual SEP4 events when all ions are accelerated from the ambient coronal plasma by shock waves driven by fast, wide coronal mass ejections (CMEs). This correlated abundance behavior can track complex time variations in the spectral indices during an event. In other (SEP3) events, CME-driven shock waves, days apart, sample seed particles from a single pool of suprathermal impulsive ions contributed earlier. Of the smaller, Fe-rich, impulsive SEP events, previously related to magnetic reconnection in solar jets, over half are subsequently reaccelerated by CME-driven shock waves (SEP2) causing typical ion intensities to have a 64% correlation with shock speed. In these SEP2 events, onset of shock acceleration is signaled by a new component in the abundances, large proton excesses. The remaining SEP1 events lack evidence of shock acceleration. However, for all these events (SEP1 - SEP3) with abundances determined by magnetic reconnection, spectra and abundances are decoupled. **4-8 Nov 1997, 2-6 May 1998, 24-26 Aug 1998, 14 Nov 1998, 14 Jul 2000, 3-10 Nov 2000, 15-19 Apr 2001, 26-29 Oct 2003, 13-15 May 2005, 22-24 May 2013**

Fifty Years of 3He-Rich Events **Review**

Donald V. **Reames***

Front. Astron. Space Sci., **8** 760261 **2021** |

https://doi.org/10.3389/fspas.2021.760261

https://www.frontiersin.org/articles/10.3389/fspas.2021.760261/full

https://arxiv.org/pdf/2110.06251

The early 1970s saw a new and surprising feature in the composition of solar energetic particles (SEPs), resonant enhancements up to 10,000-fold in the ratio 3He/4He that could even make 3He dominant over H in rare events. It was soon learned that these events also had enhancements in the abundances of heavier elements, such as a factor of ∼10 enhancements in Fe/O, which was later seen to be part of a smooth increase in enhancements vs. mass-to-charge ratio A/Q from H to Pb, rising by a factor of ∼1000. These events were also associated with streaming 10–100 keV electrons that produce type III radio bursts. In recent years we have found these “impulsive” SEP events to be accelerated in islands of magnetic reconnection from plasma temperatures of 2–3 MK on open field lines in solar jets. Similar reconnection on closed loops traps the energy of the particles to produce hot (>10 MK), bright flares. Sometimes impulsive SEP intensities are boosted by shock waves when the jets launch fast coronal mass ejections. No single theory yet explains both the sharp resonance in 3He and the smooth increase up to heavier elements; two processes seem to occur. Sometimes the efficient acceleration even exhausts the rare 3He in the source region, limiting its fluence. **1997 Sep 18-20, 1999 Aug 8, 2000 May 1-2, 2002 Aug 4-5, 2002 Dec 12-13, 2003 Dec 1-2**

Sixty Years of Element Abundance Measurements in Solar Energetic Particles **Review**

Donald V. **Reames**

Space Science Reviews **217**, Article number: 72 **2021**

https://arxiv.org/ftp/arxiv/papers/2107/2107.14313.pdf

https://link.springer.com/content/pdf/10.1007/s11214-021-00845-4.pdf **File**

https://doi.org/10.1007/s11214-021-00845-4

Sixty years ago the first observation was published showing solar energetic particles (SEPs) with a sampling of chemical elements. Thus began study of the direct products of dynamic physics in the solar corona. As we have progressed from 4-min sounding-rocket samples to continuous satellite coverage of SEP events, we have extended the observations to the unusual distribution of element abundances throughout the periodic table. Small "impulsive" SEP events from islands of magnetic reconnection on open magnetic-field lines in solar jets generate huge enhancements in abundances of 3He and of the heaviest elements. Solar flares involve the same physics but there the SEPs are trapped on closed loops, expending their energy as heat and light. The larger, energetic "gradual" SEP events are accelerated at shock waves driven by fast, wide coronal mass ejections (CMEs). However, these shocks can also reaccelerate ions from pools of residual suprathermal impulsive ions, and CMEs from jets can also drive fast shocks, complicating the picture. The underlying element abundances in SEP events represent the solar corona, which differs from corresponding abundances in the photosphere as a function of the first ionization potential (FIP) of the elements, distinguishing low-FIP (<10 eV) ions from high-FIP neutral atoms as they expand through the chromosphere. Dependence of SEP acceleration upon A/Q allows best-fit estimation of ion Q-values and hence of the source plasma temperature of ~1 - 3 MK, derived from abundances, which correlates with recent measures of temperatures using extreme ultraviolet emission from jets. New questions arise, however, about the theoretical basis of correlations of energy-spectral indices with power-laws of abundances, about the coexistence of mechanisms for enhancements of 3He and of heavy elements, and about the overall paucity of C in FIP comparisons.

The Correlation between Energy Spectra and Element Abundances in Solar Energetic Particles

Donald V. **Reames**

Solar Phys. **296**, Article number: 24 **2021**

https://arxiv.org/ftp/arxiv/papers/2008/2008.06985.pdf

https://link.springer.com/content/pdf/10.1007/s11207-021-01762-z.pdf

In solar energetic particle (SEP) events, the physical processes of both shock acceleration and scattering during transport can cause energy-spectral indices to be correlated with enhancement or suppression of element abundances versus mass-to-charge ratios A/Q. We observe correlations for those "gradual" SEP events where shock waves accelerate ions from the ambient coronal plasma, but there are no such correlations for "impulsive" SEP events produced by magnetic re-connection in solar jets, where abundance enhancement in different events vary from (A/Q) powers of +2 to +8, nor are there correlations when shock waves re-accelerate these residual impulsive ions. In these latter events the abundances are determined separately, prior to the accelerated spectra. Events with correlated spectra and abundances show a wide variety of interesting behavior that has not been described previously. Small and moderate gradual SEP events, with relative abundances typically depending approximately upon (A/Q)to the -1 and the spectra upon energy E to the -2.5, vary little with time. Large SEP events show huge temporal variations skirting the correlation line; in one case O spectra vary with time from E to the -1 to E to the -5 while abundances vary from (A/Q) to the +1 to (A/Q)to the -2 during the event. In very large events, streaming-limited transport through proton-generated resonant Alfve'n waves flattens the spectra and enhances heavy ion abundances prior to local shock passage, then steepens the spectra and reduces enhancements afterward, recapturing the typical correlation. Systematic correlation of spectra and element abundances provide a new perspective on the physics of SEP acceleration and transport. **24 August 1998, 14 November, 1998, 12 September, 2000, 4 November 2001, 2 November, 2003, 13 September, 2005, 4 August, 2011, 29 September, 2013**,

Solar Energetic Particles (Second Edition) Review Book

A Modern Primer on Understanding Sources, Acceleration and Propagation

Donald V. **Reames**

Lecture Notes in Physics v.978 **2020→ 2021 File**

https://arxiv.org/ftp/arxiv/papers/2010/2010.08517.pdf

https://link.springer.com/book/10.1007%2F978-3-030-66402-2

https://doi.org/10.1007/978-3-030-66402-2

In a field overflowing with beautiful images of the Sun, solar energetic particle (SEP) events are a hidden asset, perhaps a secret weapon, that can sample the solar corona and carry away unique imprints of its most bizarre and violent physics. Only recently have we found that the abundances of the elements in SEPs carry a wealth of data, not only on their own acceleration and history, but on plasma temperatures at their source, and on aspects of the genesis of the corona itself. SEPs are the tangible product of differing energetic outbursts at the Sun. They come in extremes. Little "impulsive" SEP events from magnetic reconnection in solar jets (also in flares), have most unusual 1000-fold resonant enhancements of 3He and of heavy elements like Au or Pb, while large "gradual" SEP events accelerated at shock waves driven by coronal mass ejections (CMEs), sample the composition of the corona itself, but also accelerate GeV protons that threaten Mars-bound astronauts with hazardous radiation. Direct SEP measurements plus solar images provide complimentary, "multi-messenger" data on high-energy physics at the Sun.

Distinguishing the Rigidity Dependences of Acceleration and Transport in Solar Energetic Particles

Donald V. **Reames**

Solar Phys. **295**, Article number: 113 **2020**

https://arxiv.org/ftp/arxiv/papers/2006/2006.11338.pdf

https://link.springer.com/content/pdf/10.1007/s11207-020-01680-6.pdf

In solar energetic particle (SEP) events, the power-law dependence of element abundance enhancements on their mass-to-charge ratios A/Q provides a new tool that measures the combined rigidity dependences from both acceleration and transport. Distinguishing these two processes can be more challenging. However, the effects of acceleration dominate when SEP events are small or when the ions even propagate scatter-free, and transport can dominate the time evolution of large events with streaming-limited intensities. Magnetic reconnection in solar jets produces positive powers of A/Q from +2 to +7 and shock acceleration produces mostly negative powers from -2 to +1 in small and moderate SEP events where transport effects are minimal. This variation in the rigidity dependence of shock acceleration may reflect the non-planer structure, complexity, and time variation of coronal shocks themselves. Wave amplification by streaming protons in the largest SEP events suppresses the escape of ions with low A/Q, creating observed powers of A/Q from +1 to +3 upstream of the accelerating shock, decreasing to small negative powers downstream. **17 June 1998, 4 June 1999, 14 July 2000 , 12 September 2000, 4 November 2001, 4 August 2011**

Virtues of Including Hydrogen in the Patterns of Element Abundances in Solar Energetic Particles

Donald V. **Reames**

Solar Phys. **2020**

https://arxiv.org/ftp/arxiv/papers/2004/2004.12229.pdf

We revisit a multi-spacecraft study of the element abundances of solar energetic particles (SEPs) in the **23 January 2012** event, where the power-law pattern of enhancements versus the mass-to-charge ratio A/Q for the elements C through Fe was partly disrupted by a break near Mg, which turned out to be an unfortunate distraction. In the current article we find that extending that least-squares fits for C - Fe down to H at A/Q = 1 lends much more credence to the power laws, even though H itself was not included in the fits. We also investigate the extent of an adiabatically invariant "reservoir" of magnetically-trapped particles behind the shock wave in this event.

Four Distinct Pathways to the Element Abundances in Solar Energetic Particles Review

Donald V. **Reames**

Space Sci. Rev **216**:20 **2020**

https://arxiv.org/ftp/arxiv/papers/1912/1912.06691.pdf

https://link.springer.com/content/pdf/10.1007%2Fs11214-020-0643-5.pdf

Recent evidence from abundance patterns of chemical elements in solar energetic particles (SEPs), and, ironically, the belated inclusion of H and He, has provided evidence for four distinct physical pathways of SEP acceleration. Abundance measurements divide each of the previous categories of impulsive and gradual SEP events, based upon the presence or absence of shock acceleration, or upon the dominance of either preaccelerated ions or ambient coronal plasma. SEPs are drawn from plasma that originally entered the solar corona on magnetic loops in active regions where, relative to the photosphere, abundances of elements depends upon the first ionization potential (FIP) so that SEPs differ from the solar wind which rises on open magnetic fields. After FIP fractionation, acceleration of impulsive-source SEP1 ions, at islands of magnetic reconnection in solar jets, generates an additional steep power-law dependence of abundance enhancements vs. the ion mass-to-charge ratio A/Q, with Q-values determined by a source temperature of T~3 MK. For these SEP1 ions, proton abundances at A/Q=1 fall on the power-law-fit line from elements Z=6-56. More acceleration of SEP1 ions by shock waves can add protons from the ambient plasma to supply "excess protons" above the fit line, a new signature of shock acceleration, either locally in the same jet to define SEP2 ions or at an extensive shock averaging residual ions from a multi-jet active region to defining SEP3. Larger gradual SEP events, with stronger shocks, sample more deeply the ambient coronal material with T =0.8-1.6 MK, and, for these SEP4 events, proton abundances can again fit the power-law extrapolated from the fit of Z>2 ions. Particle acceleration and transport with simple power-law dependences on velocity and A/Q has provided an unexpected but powerful new tool with signatures of the dominant physical processes involved. **24 August 1998, 26 and 28 October 2003, 21-23 Nov 2006, 29 September 2013, 6-10 Jan 2014, 18 April 2014.**

Element Abundances of Solar Energetic Particles and the Photosphere, the Corona, and the Solar Wind Review

Donald V **Reames**

Atoms **7**(4), 104 **2019**

https://www.mdpi.com/2218-2004/7/4/104/pdf

https://arxiv.org/ftp/arxiv/papers/1910/1910.01209.pdf

From a turbulent history, the study of abundances of elements in solar energetic particles (SEPs) has grown into an extensive field that probes the solar corona and the physical processes of SEP acceleration and transport. Underlying SEPs are the abundances of the solar corona, which differ from photospheric abundances as a function of the first ionization potentials (FIPs) of the elements. The FIP-dependence of SEPs also differs from that of the solar wind; each has a different magnetic environment where low-FIP ions and high-FIP neutral atoms rise toward the corona. Two major sources generate SEPs: The small "impulsive" SEP events are associated with magnetic reconnection in solar jets that produce 1000-fold enhancements from H to Pb as a function of mass-to-charge ratio A/Q, and also 1000-fold enhancements in 3He/4He produced by resonant wave-particle interactions. In large "gradual" events, SEPs are accelerated at shock waves driven out from the Sun by wide, fast coronal mass ejections (CMEs). A/Q dependence of ion transport allows us to estimate Q and hence the source plasma temperature T. Weaker shock waves favor reacceleration of suprathermal ions accumulated from earlier impulsive SEP events, along with protons

from the ambient plasma. In strong shocks the ambient plasma dominates. Ions from impulsive sources have T ~ 3 MK; those from ambient coronal plasma have T = 1 - 2 MK. These FIP- and A/Q-dependences explore complex new interactions in the corona and in SEP sources.
Table 1. Element Abundances of the Photosphere and of the Corona as measured by SEPs and the SSW.

Excess H, Suppressed He, and the Abundances of Elements in Solar Energetic Particles
Donald V. **Reames**
Solar Phys. 294:141 **2019**
https://arxiv.org/ftp/arxiv/papers/1908/1908.02321.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1533-4.pdf
Recent studies of the abundances of H and He relative to those of heavier ions in solar energetic particle (SEP) events suggest new features in the underlying physics. Impulsive SEP events, defined by uniquely large enhancements of Fe/O, emerge from magnetic reconnection in solar jets. In small, "pure," shock-free, impulsive SEP events, protons with mass-to-charge ratio A/Q = 1 fit the power-law dependence of element abundance enhancements versus A/Q extrapolated from the heavier elements 2 < Z < 57. Sometimes these events have order-of-magnitude suppressions of He, even though H fits with heavier elements, perhaps because of the slower ionization of He during a rapid rise of plasma from the chromosphere. In larger impulsive SEP events, He fits, but there are large proton excesses relative to the power-law fit of Z > 2 ions, probably because associated coronal mass ejections (CMEs) drive shock waves fast enough to reaccelerate the impulsive SEPs but also to sample protons from the ambient solar plasma. In contrast, gradual SEP events are accelerated by wide, fast CME-driven shock waves, but those with smaller, weaker shocks, perhaps quasi-perpendicular, favor impulsive suprathermal residue left by many previous jets, again supplemented with excess protons from ambient coronal plasma. In the larger, more common gradual SEP events, faster, stronger shock waves sample the ambient coronal plasma more deeply, overwhelming any impulsive-ion component, so that proton abundances again fit the same power-law distribution as all other elements. Thus, studies of the power-law behavior in A/Q of SEP element abundances give compelling new information on the varying physics of SEP acceleration and properties of the underlying corona**. 2000 May 1, 2003 Dec 30, 13 September 2005, 18 April 2014**

Hydrogen and the Abundances of Elements in Gradual Solar Energetic-Particle Events
Donald V. **Reames**
Solar Phys. 294:69 **2019**
https://arxiv.org/ftp/arxiv/papers/1902/1902.03208.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1427-5.pdf
Despite its dominance, hydrogen has been largely ignored in studies of the abundance patterns of the chemical elements in gradual solar energetic-particle (SEP) events; those neglected abundances show a surprising new pattern of behavior. Abundance enhancements of elements with 2 <= Z <= 56, relative to coronal abundances, show power-law dependence, versus their average mass-to-charge ratio A/Q, that varies from event to event and with time during events; the ion charge states Q depend upon the source plasma temperature T. For most gradual SEP events, shock waves have accelerated ambient coronal material with T < 2 MK to produce a decreasing power-laws in A/Q; here the proton abundances agree rather well with the power-law fits extrapolated from elements with Z >= 6 at A/Q > 2 down to hydrogen at A/Q = 1. Thus the abundances of the elements with Z >= 6 fairly accurately predict the observed abundance of H, at a similar velocity, in most SEPs. However, for those gradual SEP events where ion enhancements follow positive powers of A/Q, especially those with T > 2 MK where shock waves have reaccelerated residual suprathermal ions from previous impulsive SEP events, pro-ton abundances commonly exceed the extrapolated expectation, usually by a factor of order 10. This is a new and unexpected pattern of behavior that is unique to the abun-dances of protons. This proton behavior is a signature that can help distinguish the presence or absence of shock acceleration when Fe-rich impulsive material is observed. **6 November 1997, 24 August 1998, 2 April 2001, 26 and 28 October 2003, 29 October 2003, 23 January 2012, 29 September 2013**
Хорошее Введение

Hydrogen and the Abundances of Elements in Impulsive Solar Energetic-Particle Events
Donald V. **Reames**
Solar Phys. 294:69 **2019**
https://arxiv.org/ftp/arxiv/papers/1901/1901.04369.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1460-4.pdf
Hydrogen has been almost completely ignored in studies of the abundance patterns of the chemical elements in solar energetic particles (SEPs). We seek to find impulsive events where H fits these abundance patterns and document the events that do not, suggesting possible reasons for the disparity. For 24% of the smaller impulsive SEP events, the relative abundance of H fits within one standard deviation of the power-law fit of the abundances of elements 5 < Z < 57, relative to coronal abundances; 64% of events are within two standard deviations of this value. In

impulsive events with high intensities, H can be 10 to 100 times its expected value. In some of these larger events, increased scattering at high wave number may preferentially detain H, perhaps with self-amplified waves. In most large impulsive SEP events, however, associated shock waves may play a greater role than previously thought, contributing to 45% of impulsive events. Shocks may sample protons from the ambient coronal plasma or residual background as well as re-accelerating heavier impulsive SEP ions injected from the region of magnetic reconnection in solar jets. Excess H may be a signature of shock acceleration. **17 Sept 1997, 7 March 2000, 1 May 2000, 14 Apr 2001, 20 Feb 2002, 14 Dec 2011, 8 Jun 2012,**

Хорошее Введение

Helium Suppression in Impulsive Solar Energetic-Particle Events

Donald V. **Reames**

Solar Phys. 294:32 **2019**

https://arxiv.org/ftp/arxiv/papers/1812/1812.01635.pdf

We have studied the element abundances and energy spectra of the small "He-poor" impulsive solar energetic-particle (SEP) events, comparing them with other impulsive SEP events with more-normal abundances of He. He-poor events can have abundances as low as He/O ~ 2, while both impulsive and gradual SEP events usually have source abundances of 30 < He/O < 100 with mean values of 50 - 60. He/C ratios are not only low, but often decrease with energy in He-poor events. Abundance enhancement patterns of other elements with atomic numbers 6 < Z < 56, and likely values of their mass-to-charge ratios A/Q, are generally unaltered in He-poor events, as are the probable source-plasma temperatures of 2.5 - 3.2 MK for all impulsive SEP events. One He-poor event is also an example of a rarer C-poor event with C/O = 0.08 +- 0.04, sup-pressed by a factor over 5 from the mean. We discuss suggestions of a possible A/Q threshold during acceleration and of the sluggish ionization of He entering the corona, because of its uniquely high first ionization potential (FIP), but the suppression of He and the decline of He/C with energy is difficult to explain if both He and C are fully ionized with A/Q = 2 as expected at 2.5 - 3.2 MK. Although less dramatic, a possible excess enhancement of Ne in some impulsive SEP events is also considered. Possible causes of the large ~30% spectral and abundance variations in impulsive events are also discussed. However, the physics of the He-poor events remains a mystery.

Corotating Shock Waves and the Solar-Wind Source of Energetic Ion Abundances: Power Laws in A/Q

Donald V. **Reames**

Solar Phys. 293:144 **2018**

https://arxiv.org/ftp/arxiv/papers/1808/1808.06132.pdf

sci-hub.tw/10.1007/s11207-018-1369-3

We find that element abundances in energetic ions accelerated by shock waves formed at corotating interaction regions (CIRs) mirror the abundances of the solar wind modified by a decreasing power-law dependence on the mass-to-charge ratio A/Q of the ions. This behavior is similar in character to the well-known power-law dependence on A/Q of abundances in large gradual solar energetic particles (SEP). The CIR ions reflect the pattern of A/Q, with Q values of the source plasma temperature or freezing-in temperature of 1.0 - 1.2 MK typical of the fast solar wind in this case. Thus the relative ion abundances in CIRs are of the form (A/Q)**a where a is nearly always negative and evidently decreases with distance from the shocks, which usually begin beyond 1 AU. For one unusual historic CIR event where a ~ 0, the reverse shock wave of the CIR seems to occur at 1 AU, and these abundances of the energetic ions become a direct proxy for the abundances of the fast solar wind.

Table 1. CIR Event Intervals, Source T, and Power of A/Q

The "FIP Effect" and the Origins of Solar Energetic Particles and of the Solar Wind

Donald V. **Reames**

Solar Phys. 293:47 **2018**

https://arxiv.org/ftp/arxiv/papers/1801/1801.05840.pdf

We find that the element abundances in solar energetic particles (SEPs) and in the slow solar wind (SSW), relative to those in the photosphere, show different patterns as a function of the first ionization potential (FIP) of the elements. Generally, the SEP and SSW abundances reflect abundance samples of the solar corona, where low-FIP elements, ionized in the photosphere, are more efficiently conveyed upward to the corona than high-FIP elements that are initially neutral atoms. Abundances of the elements, especially C, P, and S show a crossover from low to high FIP at ~10 eV in the SEPs but ~14 eV for the solar wind, suggesting that cooler photospheric plasma, perhaps from cool sunspots beneath active regions, supply the coronal source material that eventually will be shock-accelerated as SEPs, while the source of the SSW may lie at the base of diverging open-field lines surrounding but outside active regions. Meanwhile, energetic particles accelerated from the solar wind itself by shock waves at corotating interaction regions (CIRs), generally beyond 1 AU, confirm the FIP pattern of the solar wind.

Abundances, Ionization States, Temperatures, and FIP in Solar Energetic Particles
Review
Donald V. **Reames**
Space Sci. Rev 214: 61 **2018**
https://arxiv.org/ftp/arxiv/papers/1709/1709.00741.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11214-018-0495-4.pdf
The relative abundances of chemical elements and isotopes have been our most effective tool in understanding the physical processes that control populations of energetic particles. The early surprise in solar energetic particles (SEPs) was 1000-fold enhancements in 3He/4He from resonant wave-particle interactions in the small "impulsive" SEP events with electron beams that produce type III radio bursts. Further studies found enhancements in Fe/O, and abundances increasing with mass-to-charge ratio A/Q, rising by a factor of 1000 from He to Pb arising in magnetic reconnection on open field lines in solar jets. In contrast, in the largest SEP events, the "gradual" events, acceleration occurs at shock waves driven out from the Sun by fast, wide coronal mass ejections (CMEs). Averaging events measures solar coronal abundances, but A/Q-dependent scattering during transport causes variations with time. To complicate matters, shock waves often reaccelerate impulsive suprathermal ions left over or trapped above active regions that have spawned many impulsive events. Since both impulsive and gradual SEP events have abundance enhancements that vary as powers of A/Q, we can use abundances to deduce the probable Q-values and the source plasma temperatures during acceleration, ~3 MK for impulsive SEPs. This new technique also allows multiple spacecraft to measure temperature variations across the face of a shock wave. Comparing coronal abundances from SEPs and from the slow solar wind, remaining differences are for the elements C, P, and S. We propose that these elements, with intermediate values of first ionization potential (FIP), act like high-FIP neutral atoms in cool sunspots beneath active regions where SEPs are accelerated, but behave like low-FIP ions in the warmer photosphere that contributes to the slow solar wind, ions being more readily swept into the corona than neutral atoms. **6 November 1997 , 2000 May 1, 14 July 2000, 23 August 2005 , 31 August 2012 , 1 September 2012 , 22 May 2013**

The Abundance of Helium in the Source Plasma of Solar Energetic Particles
Donald V. **Reames**
Solar Phys. 292:156 **2017**
https://arxiv.org/ftp/arxiv/papers/1708/1708.05034.pdf
Studies of patterns of abundance enhancements of elements, relative to solar-coronal abundances, in large solar energetic-particle (SEP) events, and of their power-law dependence on the mass-to-charge ratio A/Q of the ions, have been used to determine the effective source-plasma temperature T that defines the Q-values of the ions. We find that a single assumed value for the coronal reference He/O ratio in all SEP events is often inconsistent with the transport-induced power-law trend of the other elements. In fact, the coronal He/O actually varies rather widely from one SEP event to another. In the large Fe-rich SEP events with T = 3 MK, where shock waves, driven out by coronal mass ejections (CMEs), have reaccelerated residual ions from impulsive suprathermal events that occur earlier in solar active regions, He/O = 90, a ratio similar to that in the slow solar wind, which may also originate from active regions. Ions in the large SEP events with T < 2 MK may be accelerated outside active regions, and have values of 40 < He/O < 60. Mechanisms that determine coronal abundances, including variations of He/O, are likely to occur near the base of the corona (at ~ 1.1 RS) and thus to affect both SEPs (at ~2 - 3 RS) and the solar wind. Other than He, reference coronal abundances for heavier elements show little temperature dependence or systematic difference between SEP events; He, the element with the highest first ionization potential, is unique. The CME-driven shock waves probe the same regions of space, at ~2 RS near active regions, which are also likely sources of the slow solar wind, providing complementary information on conditions in those regions. **4 November 1997, 6 November 1997, 20 April 1998, 14 July 2000, 23 August 2005, 13 September 2005, 16 January 2005, 6 July 2012, 30 September 2013**

Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration and Propagation **Book** **Review**
Donald V. **Reames**
Lecture Notes in Physics, Vol. 932
Springer International Publishing AG **2017**, 136 p. **File**
http://sci-hub.cc/10.1007/978-3-319-50871-9
https://link.springer.com/content/pdf/10.1007%2F978-3-319-50871-9.pdf

On the Spatial Distribution of Element Abundances and Ionization States in Solar Energetic-Particle Events
Donald V. **Reames**
Solar Phys. August 2017, 292:113 **2017**

https://arxiv.org/pdf/1705.07471.pdf
We have studied the spatial and temporal distribution of element abundances of large "gradual" solar energetic-particle (SEP) events, and especially the source plasma temperatures, derived from those abundances, using measurements from the Wind and Solar Terrestrial Relations Observatory (STEREO) spacecraft, widely separated in solar longitude. A power-law relationship between abundance enhancements and mass-to- charge ratio A/Q of the ions can be used to determine Q values and source plasma temperatures at remote spacecraft with instruments that were not designed for charge-state measurements. We search for possible source variations along the accelerating shock wave, finding one clear case where the accelerating shock wave appears to dispatch ions from 3.2+-0.8 MK plasma toward one spacecraft and those from 1.6+-0.2 MK plasma to- ward the other, 116 deg away. The difference persists three days and then fades away. Three other SEP events show similar abundances and source temperatures at different spacecraft, in one case, over 222 deg in longitude. This initial study shows how the power- law relation between abundance enhancements and ion A/Q values provides a new technique to determine Q and plasma temperatures in the seed population of SEP ions over a broad region of space using remote spacecraft with instruments that were not originally designed for measurements of ionization states. **19 January 2012, 23 January 2012, 17 May 2012, 31 August 2012**

Element Abundances and Source Plasma Temperatures of Solar Energetic Particles

Donald V. **Reames**

15th Ann. Intl. Astrophys. Conf. "The Science of Ed Stone: Celebrating his 80th Birthday" **2016**

Journal of Physics: Conference Series 767 (**2016**) 012023

https://arxiv.org/pdf/1612.00030v1.pdf

Thirty years ago Breneman and Stone observed that the enhancement or suppression of element abundances in large solar energetic-particle (SEP) events varies as a power of the mass-to-charge ratio, A/Q, of the elements. Since Q during acceleration or transport may depend upon the source plasma temperature T, the pattern of element enhancements can provide a best-fit measure of T. The small SEP events we call 3He-rich or "impulsive" show average enhancements, relative to coronal abundances, rising as the 3.6 power of A/Q to a factor of ~1000 for (76<=Z<=82)/O and temperature in the range 2-4 MK. This acceleration is believed to occur in islands of magnetic reconnection on open field lines in solar flares and jets. It has been recently found that the large shock-accelerated "gradual" SEP events have a broad range of source plasma temperatures; 69% have coronal temperatures of T < 1.6 MK, while 24% have T ~ 3 MK, the latter suggesting a seed population containing residual impulsive suprathermal ions. Most of the large event-to-event abundance variations and their time variation are largely explained by variations in T magnified by A/Q-dependent fractionation during transport. However, the non-thermal variance of impulsive SEP events (~30%) exceeds that of the ~3 MK gradual events (~10%) so that several small impulsive events must be averaged together with the ambient plasma to form the seed population for shock acceleration in these events. **8-9 November 2000**

Temperature of the Source Plasma in Gradual Solar Energetic Particle Events

Donald V. **Reames**

Solar Physics volume 291, pages 911–930 (**2016**)

https://link.springer.com/content/pdf/10.1007/s11207-016-0854-9.pdf

https://doi.org/10.1007/s11207-016-0854-9

Scattering during interplanetary transport of particles during large, “gradual” solar energetic-particle (SEP) events can cause element abundance enhancements or suppressions that depend upon the mass-to-charge ratio [A/QA/Q] of the ions as an increasing function early in events and a decreasing function of the residual scattered ions later. Since the QQ-values for the ions depend upon the source plasma temperature [TT], best fits of the power-law dependence of enhancements vs. A/QA/Q can determine TT. These fits provide a fundamentally new method to determine the most probable value of TT for these events in the energy region 3--10 MeVamu−13--10 MeVamu−1. Complicated variations in the grouping of element enhancements or suppressions match similar variations in A/QA/Q at the best-fit temperature. We find that fits to the times of increasing and decreasing powers give similar values of TT, in the range of 0.8 – 1.6 MK for 69 % of events, consistent with the acceleration of ambient coronal plasma by shock waves driven out from the Sun by coronal mass ejections (CMEs). However, 24 % of the SEP events studied showed plasma of 2.5 – 3.2 MK, typical of that previously determined for the smaller impulsive SEP events; these particles may be reaccelerated preferentially by quasi-perpendicular shock waves that require a high injection threshold that the impulsive-event ions exceed or simply by high intensities of impulsive suprathermal ions at the shock. The source-temperature distribution of ten higher-energy ground-level events (GLEs) in the sample is similar to that of the other gradual events, at least for SEPs in the energy-range of 3--10 MeVamu−13--10 MeVamu−1. Some events show evidence that a portion of the ions may have been further stripped of electrons before the shock acceleration; such events are smaller and tend to cluster late in the solar cycle.
Table 2 Source plasma temperatures of gradual SEP events (1997-2014)

The Origin of Element Abundance Variations in Solar Energetic Particles

Donald V. **Reames**
Solar Phys. Volume 291, Issue 7, pp 2099–2115 **2016**
Abundance enhancements, during acceleration and transport in both gradual and impulsive solar energetic particle (SEP) events, vary approximately as power laws in the mass-to-charge ratio A/Q of the ions. Since the Q values depend upon the electron temperature of the source plasma, this has allowed a determination of this temperature from the pattern of element abundance enhancements and a verification of the expected inverse-time dependence of the power of A/Q for diffusive transport of ions from the SEP events, with scattering mean free paths found to be between 0.2 and 1 AU. SEP events derived from plasma of different temperatures map into different regions in typical cross-plots of abundances, spreading the distributions. In comparisons of SEP events with temperatures above 2 MK, impulsive events show much broader non-thermal variation of abundances than do gradual events. The extensive shock waves accelerating ions in gradual events may average over much of an active region where numerous but smaller magnetic reconnections, "nanojets", produce suprathermal seed ions, thus averaging over varying abundances, while an impulsive SEP event only sample one local region of abundance variations. Evidence for a reference He/O abundance ratio of 91, rather than 57, is also found for the hotter plasma. However, while this is similar to solar-wind abundance of He/O, the solar-wind abundances otherwise provide an unacceptably poor reference for the SEP abundance enhancements, generating extremely large errors. **6 November 1997, 25 August 1998, 24 August and 30 September 1998, 12 September 2000, 15 April 2001, 26 December 2001**
See 1. Introduction

What are the Sources of Solar Energetic Particles? Element Abundances and Source Plasma Temperatures

Review
Donald V. **Reames**
Space Sci. Rev Volume 194, Issue 1, pp 303-327 Nov **2015**
http://arxiv.org/pdf/1510.03449v1.pdf **File**
https://link.springer.com/content/pdf/10.1007/s11214-015-0210-7.pdf
We have spent 50 years in heated discussion over which populations of solar energetic particles (SEPs) are accelerated at flares and which by shock waves driven out from the Sun by coronal mass ejections (CMEs). The association of the large "gradual" SEP events with shock acceleration is supported by the extensive spatial distribution of SEPs and by the delayed acceleration of the particles. The relative abundances of the elements in these gradual events are a measure of those in the ambient solar corona, differing from those in the photosphere by a widely-observed function of the first ionization potential (FIP) of the elements. SEP events we call "impulsive", the traditional "3He-rich" events with enhanced heavy-element abundances, are associated with type III radio bursts, flares, and narrow CMEs; they selectively populate flux tubes that thread a localized source, and they are fit to new particle-in-cell models of magnetic reconnection on open field lines as found in solar jets. These models help explain the strong enhancements seen in heavy elements as a power (of 2 - 8) in the mass-to-charge ratio A/Q throughout the periodic table from He to Pb. A study of the temperature dependence of A/Q shows that the source plasma in impulsive SEP events must lie in the range of 2-4 MK to explain the pattern of abundances. This is much lower than the temperatures of >10 MK seen on closed loops in solar flares. Recent studies of A/Q-dependent enhancements or suppressions from scattering during transport show source plasma temperatures in gradual SEP events to be 0.8-1.6 MK in 69% of the events, i.e. coronal plasma; 24% of the events show reaccelerated impulsive-event material.

Temperature of the Source Plasma in Gradual Solar Energetic Particle Events

Donald V. **Reames**
Solar Phys. Volume 291, Issue 3, pp 911-930 **2015**
http://arxiv.org/pdf/1509.08948v1.pdf
Scattering, during interplanetary transport in large, "gradual" solar energetic-particle (SEP) events, can cause element abundance enhancements or suppressions that depend upon the mass-to-charge ratio A/Q of the ions as an increasing power law early in events and a decreasing power law of the residual ions later. Since the Q values for the ions depend upon the source plasma temperature T, best fits to the power-law dependence of enhancements vs. A/Q provide a fundamentally new method to determine the most probable value of T for these events. We find that fits to the times of increasing and decreasing powers give similar values of T, most commonly (69%) in the range of 0.8-1.6 MK, consistent with the acceleration of ambient coronal plasma by shock waves driven out from the Sun by coronal mass ejections (CMEs). However, 24% of the SEP events studied showed plasma of 2.5-3.2 MK, typical of that previously determined for the smaller impulsive SEP events; these particles may be reaccelerated preferentially by quasi-perpendicular shock waves that require a high injection threshold that the impulsive-event ions exceed or simply by high intensities of impulsive suprathermal ions at the shock. The source-temperature distribution of ten higher-energy ground-level events (GLEs) in the sample is similar to that of the other gradual events. Some events

show evidence that a portion of the ions have been further stripped of electrons; such events are smaller and tend to cluster late in the solar cycle.

Table A1 Source plasma temperatures of gradual SEP events

14 November 1998, 8 November 2000, 22 August 2005, 13 September 2005, 22 May 2013

Temperature of the Source Plasma for Impulsive Solar Energetic Particles

Donald V. **Reames**, Edward W. Cliver, Stephen W. Kahler

Solar Phys. Volume 290, Issue 6, pp 1761-1774 **2015, File**

http://arxiv.org/pdf/1505.02741v1.pdf

The steep power-law dependence of element abundance enhancements on the mass-to-charge ratios [A/Q] of the ions in impulsive solar energetic-particle (SEP) events causes these enhancements to reflect the temperature-dependent pattern of Q of the ions in the source plasma. We searched for SEP events from coronal plasma that is hotter or cooler than the limited region of 2.5 - 3.2 MK previously found to dominate 111 impulsive SEP events. Fifteen new events were found, four (three) originated in 2-MK (4-MK) plasma, but none from outside this temperature range. Although the impulsive SEP events are strongly associated with flares, this result indicates that these ions are not accelerated from flare-heated plasma, which can often exceed 10 MK. Evidently the ions of 2 - 20 MeV/amu that we observe in space are accelerated from active-region plasma on open magnetic-field lines near the flare, but not from the closed loops of the flare. The power-law dependence of the abundance enhancements on A/Q of the ions is expected from theoretical models of acceleration from regions of magnetic reconnection.

Element abundances in solar energetic particles: two physical processes, two abundance patterns

Donald V. **Reames**

2015 Presented at the 2014 Huntsville Workshop, Solar and Stellar Processes from the Chromosphere to the Outer Corona, in Orlando, FL, March 23-27, 2014

http://arxiv.org/ftp/arxiv/papers/1501/1501.00610.pdf

Abundances of elements comprising solar energetic particles (SEPs) come with two very different patterns. Historically called "impulsive" and "gradual" events, they have been studied for 40 years, 20 years by the Wind spacecraft. Gradual SEP events measure coronal abundances. They are produced when shock waves, driven by coronal mass ejections (CMEs), accelerate the ambient coronal plasma; we discuss the average abundances of 21 elements that differ from corresponding solar photospheric abundances by a well-known dependence on the first ionization potential (FIP) of the element. The smaller impulsive ("3He-rich") SEP events are associated with magnetic reconnection involving open field lines from solar flares or jets that also eject plasma to produce accompanying CMEs. These events produce striking heavy-element abundance enhancements, relative to coronal abundances, by an average factor of 3 at Ne, 9 at Fe, and 900 for elements with 76<Z<82. This is a strong, power-law dependence on A/Q with a ~3.6 power when Q values are determined at coronal temperatures near 3 MK. Small individual SEP events with the steepest enhancements (~6th power of A/Q), from ~2.5 MK plasma, are associated with B- and C-class X-ray flares, and with narrow (<100 deg) CMEs. Enhancements in 3He/4He can be as large as those in heavy elements but are uncorrelated with them. However, events with 3He/4He > 0.1 are even more strongly associated with narrow, slow CMEs, cooler coronal plasma, and smaller X-ray flares. The impulsive SEP events do not come from hot flare plasma; they are accelerated early and/or on adjacent open field lines.

Variations in Abundance Enhancements in Impulsive Solar Energetic-Particle Events and Related CMEs and Flares

Donald V. **Reames**, Edward W. Cliver, and Stephen W. Kahler

Solar Physics, **289**, 4675 **2014**

http://arxiv.org/pdf/1407.7838v1.pdf

https://link.springer.com/content/pdf/10.1007/s11207-014-0589-4.pdf

https://doi.org/10.1007/s11207-014-0589-4

We study event-to-event variations in the abundance enhancements of the elements He through Pb for Fe-rich impulsive solar energetic-particle (SEP) events, and their relationship with properties of associated coronal mass ejections (CMEs) and solar flares. Using a least-squares procedure we fit the power-law enhancement of element abundances as a function of their mass-to-charge ratio A/Q to determine both the power and the coronal temperature (which determines Q) in each of 111 impulsive SEP events identified previously. Individual SEP events with the steepest element enhancements, e.g. ~(A/Q)^6, tend to be smaller, lower-fluence events with steeper energy spectra that are associated with B- and C-class X-ray flares, with cooler (~2.5 MK) coronal plasma, and with narrow (<100 deg), slower (<700 km/s) CMEs. On the other hand, higher-fluence SEP events have flatter energy spectra, less-dramatic heavy-element enhancements, e.g. ~(A/Q)^3, and come from somewhat hotter coronal plasma (~3.2 MK) associated with C-, M- and even X-class X-ray flares and with wider CMEs. Enhancements in 3He/4He are uncorrelated with those in heavy elements. However, events with 3He/4He > 0.1 are even more strongly associated with narrow, slow CMEs, with cooler coronal plasma, and with B- and C-class X-ray flares than are other Fe-rich impulsive SEP events with smaller enhancements of 3He.

Abundance Enhancements in Impulsive Solar Energetic-Particle Events with Associated Coronal Mass Ejections

Donald V. **Reames**, Edward W. Cliver, Stephen W. Kahler

E-print, May 2014; Solar Phys., Volume 289, Issue 10, pp 3817-3841, **2014**

http://arxiv.org/pdf/1404.3322v1.pdf

https://link.springer.com/article/10.1007%2Fs11207-014-0547-1

https://doi.org/10.1007/s11207-014-0547-1

We study the abundances of the elements He through Pb in Fe-rich impulsive solar energetic-particle (SEP) events with measurable abundances of ions with atomic number Z>2 observed on the Wind spacecraft, and their relationship with coronal mass ejections (CMEs) observed by the Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (SOHO). On average the element abundances in these events are similar to coronal abundances at low Z but, for heavier elements, enhancements rise as a power law in the mass-to-charge ratio A/Q of the ions (at coronal temperatures of 2.5-3 MK) to a factor of 3 at Ne, 9 at Fe, and 900 for 75<Z<83. Energy dependences of abundances are minimal in the 2-15 MeV/amu range. The 111 of these Fe-rich impulsive SEP events we found, between November 1994 and August 2013 using the Wind spacecraft, have a 69% association rate with CMEs. The CMEs are narrow with a median width of 75 deg, are characteristically from western longitudes on the Sun, and have a median speed of ~600 km/s. Nearly all SEP onsets occur within 1.5-5 h of the CME onset. The faster (>700 km/s), wider CMEs in our sample are related to SEPs with coronal abundances indicating hot coronal plasma with fully ionized He, C, N and O and moderate enhancements of heavier elements, relative to He, but slower (<700 km/s), narrower CMEs emerge from cooler plasma where higher SEP mass-to-charge ratios, A/Q, yield much greater abundance enhancements, even for C/He and O/He. Apparently, the open magnetic-reconnection region where the impulsive SEPs are accelerated also provides the energy to drive out CME plasma, accounting for a strong, probably universal, impulsive SEP-CME association.

Table A2 lists properties of 111 Fe-rich impulsive SEP events 1995-2013

Element Abundances in Solar Energetic Particles and the Solar Corona **Review**

Donald V. **Reames**

E-print, June **2013, File**; Solar Phys. March **2014**, Volume 289, Issue 3, pp 977-993

This is a study of abundances of the elements He, C, N, O, Ne, Mg, Si, S, Ar, Ca, and Fe in solar energetic particles (SEPs) in the 2 - 15 MeV amu-1 region measured on the Wind spacecraft during 54 large SEP events occurring between November 1994 and June 2012. The origin of most of the temporal and spatial variations in abundances of the heavier elements lies in rigidity-dependent scattering during transport of the particles away from the site of acceleration at shock waves driven out from the Sun by coronal mass ejections (CMEs). Variation in the abundance of Fe is correlated with the Fe spectral index, as expected from scattering theory but not previously noted. Clustering of Fe abundances during the "reservoir" period, late in SEP events, is also newly reported. Transport-induced enhancements in one region are balanced by depletions in another, thus, averaging over these variations produces SEP abundances that are energy independent, confirms previous SEP abundances in this energy region, and provides a credible measure of element abundances in the solar corona. These SEP-determined coronal abundances differ from those in the solar photosphere by a well-known function that depends upon the first ionization potential (FIP) or ionization time of the element.

The Two Sources of Solar Energetic Particles **Review**

Donald V. **Reames**

E-print, June **2013**; Space Science Reviews, **2013,** 175:53–92**, File**

http://arxiv.org/abs/1306.3608

Evidence for two different physical mechanisms for acceleration of solar energetic particles (SEPs) arose 50 years ago with radio observations of type III bursts, produced by outward streaming electrons, and type II bursts from coronal and interplanetary shock waves. Since that time we have found that the former are related to “impulsive” SEP events from impulsive flares or jets. Here, resonant stochastic acceleration, related to magnetic reconnection involving open field lines, produces not only electrons but 1000-fold enhancements of 3He/4He and of (Z>50)/O. Alternatively, in “gradual” SEP events, shock waves, driven out from the Sun by coronal mass ejections (CMEs), more democratically sample ion abundances that are even used to measure the coronal abundances of the elements.

Gradual events produce by far the highest SEP intensities near Earth. Sometimes residual impulsive suprathermal ions contribute to the seed population for shock acceleration, complicating the abundance picture, but this process has now been modeled theoretically. Initially, impulsive events define a point source on the Sun, selectively filling few magnetic flux tubes, while gradual events show extensive acceleration that can fill half of the inner heliosphere, beginning when the shock reaches ∼2 solar radii. Shock acceleration occurs as ions are scattered back and forth across the shock by resonant Alfvén waves amplified by the accelerated protons themselves as they stream away. These waves also can produce a streaming-limited maximum SEP intensity and plateau region upstream of the shock. Behind the shock lies the large expanse of the "reservoir", a spatially extensive trapped volume of uniform SEP intensities with invariant energy-spectral shapes where overall intensities decrease with time as the enclosing "magnetic bottle" expands adiabatically. These reservoirs now explain the slow intensity decrease that defines gradual events and was once erroneously attributed solely to slow outward diffusion of the particles. At times the reservoir from one event can contribute its abundances and even its spectra as a seed population for acceleration by a second CME-driven shock wave. Confinement of particles to magnetic flux tubes that thread their source early in events is balanced at late times by slow velocity-dependent migration through a tangled network produced by field-line random walk that is probed by SEPs from both impulsive and gradual events and even by anomalous cosmic rays from the outer heliosphere. As a practical consequence, high-energy protons from gradual SEP events can be a significant radiation hazard to astronauts and equipment in space and to the passengers of high-altitude aircraft flying polar routes.

Spatial Distribution of Solar Energetic Particles in the Inner Heliosphere

Donald V. **Reames**1 , Chee K. Ng2, 3 and Allan J. Tylka

Solar Phys., July **2013**, Volume 285, Issue 1-2, pp 233-250

We study the spatial distribution of solar energetic particles (SEPs) throughout the inner heliosphere during six large SEP events from the period 1977 through 1979, as deduced from observations on the Helios 1 and 2, IMP 7 and 8, ISEE 3, and Voyager 1 and 2 spacecraft. Evidence of intensity maxima associated with the expanding shock wave is commonly seen along its central and western flanks, although the region of peak acceleration or "nose" of the shock is sometimes highly localized in longitude. In one event (1 January 1978) a sharp peak in 20 – 30 MeV proton intensities is seen more strongly by Voyager at ∼ 2 AU than it is by spacecraft at nearby longitudes at ∼ 1 AU. Large spatial regions, or **"reservoirs,"** often exist behind the shocks with spatially uniform SEP intensities and invariant spectra that decrease adiabatically with time as their containment volume expands. Reservoirs are seen to sweep past 0.3 AU and can extend out many AU. Boundaries of the reservoirs can vary with time and with particle velocity, rather than rigidity. In one case, a second shock wave from the Sun reaccelerates protons that retain the same hard spectrum as protons in the reservoir from the preceding SEP event. Thus reservoirs can provide not only seed particles but also a "seed spectrum" with a spectral shape that is unchanged by a weaker second shock.

19 and 24 September 1977, 1 January 1978, 28 April 1978, 23 September 1978

PARTICLE ENERGY SPECTRA AT TRAVELING INTERPLANETARY SHOCK WAVES

Donald V. **Reames**

2012 ApJ 757 93

We have searched for evidence of significant shock acceleration of He ions of ~1-10 MeV amu–1 in situ at 258 interplanetary traveling shock waves observed by the Wind spacecraft. We find that the probability of observing significant acceleration, and the particle intensity observed, depends strongly upon the shock speed and less strongly upon the shock compression ratio. For most of the 39 fast shocks with significant acceleration, the observed spectral index agrees with either that calculated from the shock compression ratio or with the spectral index of the upstream background, when the latter spectrum is harder, as expected from diffusive shock theory. In many events the spectra are observed to roll downward at higher energies, as expected from Ellison-Ramaty and from Lee shock-acceleration theories. The dearth of acceleration at ~85% of the shocks is explained by (1) a low shock speed, (2) a low shock compression ratio, and (3) a low value of the shock-normal angle with the magnetic field, which may cause the energy spectra that roll downward at energies below our observational threshold. Quasi-parallel shock waves are rarely able to produce measurable acceleration at 1 AU. The dependence of intensity on shock speed, seen here at local shocks, mirrors the dependence found previously for the peak intensities in large solar energetic-particle events upon speeds of the associated coronal mass ejections which drive the shocks.

Streaming-limited Intensities of Solar Energetic Particles on the Intensity Plateau

Donald V. **Reames** and Chee K. Ng

2010 ApJ 723 1286-1293

https://iopscience.iop.org/article/10.1088/0004-637X/723/2/1286/pdf

We examine the energy spectra of H, He, O, and Fe ions on the temporal intensity plateau region in large solar energetic-particle (SEP) events, where intensities may be "streaming limited." Upstream of shock waves near the

Sun, equilibrium may occur when outwardly streaming protons amplify resonant Alfvén waves that then scatter subsequent protons sufficiently to reduce the streaming. In the largest SEP events, the so-called ground-level events (GLEs), we find proton energy spectra that are peaked near ~10 MeV with the energy of similar peaks decreasing for heavier ions and for smaller events. These spectra contrast sharply with spectra near the time of shock passage which rise monotonically above the plateau spectra with decreasing energy. We suggest that strong suppression of upstream ion intensities near ~1 MeV amu–1 on the plateau occurs when those ions resonate with waves amplified earlier by streaming protons of ~10 MeV and above. GLEs with much lower intensities of 10-100 MeV protons on the plateau show spectra of ions that rise monotonically toward low energies with no peaking and no suppression of low-energy ions. Wave amplification by streaming protons and the pitch-angle dependence of the resonance condition are essential factors in our understanding of the limiting behavior.

A MULTI-SPACECRAFT VIEW OF SOLAR-ENERGETIC-PARTICLE ONSETS IN THE 1977 NOVEMBER 22 EVENT

Donald V. **Reames**1 and Nand Lal2

Astrophysical Journal, 723:550–554, **2010**

We examine the onset timing of solar energetic particles in the large ground-level event (GLE) of **1977 November 22** as observed from six spacecraft at four distinct solar longitudes. In most cases, it was possible to use velocity dispersion of the energetic protons to fix the solar particle release (SPR) time and the path length traveled by the initial particle burst from each solar longitude. We find that the SPR times do depend upon solar longitude, being earliest for spacecraft that are magnetically well connected to the source region, and later for longitudes on the flanks of the outward-driven shock wave. The earliest SPR time occurs well after peak photon emission from the associated H*α* flare. These observations are consistent with conclusions derived from single-longitude observations of different GLE events. They are consistent with shock acceleration over a broad spatial region with heights rising, and/or shock speeds falling, for longitudes on the flanks of the shock.

SOLAR ENERGETIC-PARTICLE RELEASE TIMES IN HISTORIC GROUND-LEVEL EVENTS

Donald V. **Reames**

Astrophysical Journal, 706:844–850, **2009** November, **File**

Ground-level events (GLEs) are large solar energetic-particle events with sufficiently hard spectra for GeV protons to be detected by neutron monitors at ground level. For each of 30 well-observed historic GLEs from four solar cycles, extending back to 1973, I have plotted onset times versus velocity−1 for particles observed on the *IMP-7* and *8*, *ISEE-3*, *Wind*, and *GOES* spacecraft and by neutron monitors. A linear fit on such a plot for each GLE determines the initial solar particle release (SPR) time, as the intercept, and the magnetic path length traversed, as the slope, of the fitted line. Magnetic path lengths and SPR times are well determined by the fits and cannot be used as adjustable parameters to make particle and photon emission times coincide. SPR times follow the onsets of shock-induced type II radio bursts and the coronal height of the coronal mass ejection (CME)-driven shock at SPR time can be determined for GLEs spanning an interval of solar longitude of ~140 deg. For a given GLE, all particle species and energies diverge from a single SPR point at a given coronal height and footpoint longitude of the field line to the Earth. These heights tend to increase with longitudinal distance away from the source, a pattern expected for shock acceleration. Acceleration for magnetically well connected large GLEs begins at ~2 solar radii, in contrast to non-GLEs that have been found to be strongly associated with shocks above ~3 solar radii. The higher densities and magnetic field strengths at lower altitudes may be responsible for the acceleration of higher-energy particles in GLEs, while those GLEs that begin above 3*R*S may compensate by having higher shock speeds. These results support the joint dependence of maximum particle energy on magnetic field strength, injected particle density, and shock speed, all predicted theoretically.

SOLAR RELEASE TIMES OF ENERGETIC PARTICLES IN GROUND-LEVEL EVENTS

Donald V. **Reames**

Astrophysical Journal, 693:812–821, **2009, File** March

We study the onset times of energetic particles of various species and velocities, *v*, in large solar energetic particle events with sufficiently hard spectra that are seen by neutron monitors at ground level. Observations of He, O, and Fe from the *Wind* spacecraft provide especially well-defined sequences of onset times, and data from *IMP-8*, *GOES*, and neutron monitors contribute importantly at higher energies. Plotting onset times versus v^{-1} yields a line with the initial solar particle release (SPR) time as the intercept and the magnetic path length as the slope.

We find consistent results for 13 of the 16 ground-level events that occurred from 1994 to 2007, in solar cycle 23. Path lengths vary from 1.1 to 2.2 AU in the 13 events. In *all* of the events, SPR times occur after the onset of the shock wave-induced type II radio emission. Events with well-defined SPR times are found over a wide span of solar longitude, suggesting that all ion species and energies are released together, even far from the source longitude, with no evidence of energy- or rigidity-dependent coronal transport. If the SPR time is converted to a radial distance of the source shock wave from the Sun and plotted against longitude, acceleration for well-connected events is found to begin at 2–4 solar radii over a longitude span of ~ 100° and to rise to greater heights only at longitudes more distant from the source, as would be expected from shock-acceleration models.

ANOMALOUS COSMIC RAYS AS PROBES OF MAGNETIC CLOUDS
D. V. **Reames**1, S. W. Kahler2, and A. J. Tylka3
Astrophysical Journal, 700:L196–L199, **2009**
We report, for the first time, the observation near the Earth of anomalous cosmic ray (ACR) particles throughout the interiors of interplanetary magnetic clouds (MCs) at the same intensity as outside the MCs. ACRs, accelerated in the outer heliosphere, have unique elemental abundances making their identity unambiguous as they probe these clouds from the outside. Thus,MCs, carried out from the Sun by coronal mass ejections (CMEs), are seen to contain no structures that are magnetically closed to the penetration of ions with energies above a few MeV amu^{-1}. As the MCs expand outward, they must fill their increasing volume with ACRs dynamically, to the same degree as neighboring “open” field lines. These observations cast doubt on conventional ideas about the closed field topologies
of MCs and the cross-field transport of energetic particles. The ACR observations conflict with some reports of significant exclusion from MCs of solar energetic particles (SEPs) of comparable energy and rigidity. A process that allows cross-field transport of ACRs may also allow similar transport of SEPs late in events, causing the large spatial extent and uniformity of SEPs in “invariant spectral regions” extending far behind CME-driven shock waves.

Heavy-Element Abundances in Solar Energetic Particle Events,
D. V. **Reames** and C. K. Ng,
Ap. J., 610, 510, **2007**.

Particle acceleration at the Sun and in the heliosphere **Review**
Donald V. **Reames**
Space Science Reviews volume 90, pages413–491 (**1999**)
https://link.springer.com/content/pdf/10.1023/A:1005105831781.pdf
https://doi.org/10.1023/A:1005105831781
Energetic particles are accelerated in rich profusion at sites throughout the heliosphere. They come from solar flares in the low corona, from shock waves driven outward by coronal mass ejections (CMEs), from planetary magnetospheres and bow shocks. They come from corotating interaction regions (CIRs) produced by high-speed streams in the solar wind, and from the heliospheric termination shock at the outer edge of the heliospheric cavity. We sample many populations near Earth, but can distinguish them readily by their element and isotope abundances, ionization states, energy spectra, angular distributions and time behavior. Remote spacecraft have probed the spatial distributions of the particles and examined new sources in situ. Most acceleration sources can be ‘seen’ only by direct observation of the particles; few photons are produced at these sites. Wave-particle interactions are an essential feature in acceleration sources and, for shock acceleration, new evidence of energetic-proton-generated waves has come from abundance variations and from local cross-field scattering. Element abundances often tell us the physics of the source plasma itself, prior to acceleration. By comparing different populations, we learn more about the sources, and about the physics of acceleration and transport, than we can possibly learn from one source alone.

Evolution of the Solar Flare Energetic Electrons in the Inhomogeneous Inner Heliosphere
Hamish A. S. **Reid**, Eduard P. Kontar
Solar Physics, July **2013**, Volume 285, Issue 1-2, pp 217-232
Solar flare accelerated electrons escaping into the interplanetary space and seen as type III solar radio bursts are often detected near the Earth. Using numerical simulations we consider the evolution of energetic electron spectrum in the inner heliosphere and near the Earth. The role of Langmuir wave generation, heliospheric plasma density fluctuations, and expansion of magnetic field lines on the electron peak flux and fluence spectra is studied to predict the electron properties as could be observed by Solar Orbiter and Solar Probe Plus. Considering various energy loss mechanisms we show that the substantial part of the initial energetic electron energy is lost via wave–plasma processes due to plasma inhomogeneity. For the parameters adopted, the results show that the electron spectrum changes mostly at the distances before $\sim 20\, R_\odot$. Further into the heliosphere, the electron flux spectrum of electrons forms a broken power law relatively similar to what is observed at 1 AU.

Solar Energetic Particle-Associated Coronal Mass Ejections Observed by the Mauna Loa Solar Observatory Mk3 and Mk4 Coronameters

I. G. **Richardson** , O. C. St Cyr, J. T. Burkepile , H. Xie , B. J. Thompson

Solar Phys. 298, Article number: 105 **2023**

https://arxiv.org/pdf/2308.10826.pdf

https://link.springer.com/content/pdf/10.1007/s11207-023-02192-9.pdf

We report on the first comprehensive study of the coronal mass ejections (CMEs) associated with ∼25 MeV solar energetic proton (SEP) events in 1980-2013 observed in the low/inner corona by the Mauna Loa Solar Observatory (MLSO) Mk3 and Mk4 coronameters. Where possible, these observations are combined with spacebased observations from the Solar Maximum Mission C/P, P78-1 SOLWIND or SOHO/LASCO coronagraphs. The aim of the study is to understand directly-measured (rather than inferred from proxies) CME motions in the low to middle corona and their association with SEP acceleration, and hence attempt to identify early signatures that are characteristic of SEP acceleration in ground-based CME observations that may be used to warn of impending SEP events. Although we find that SEP events are associated with CMEs that are on average faster and wider than typical CMEs observed by MLSO, a major challenge turns out to be determining reliable estimates of the CME dynamics in the low corona from the 3-minute cadence Mk3/4 observations since different analysis techniques can produce inconsistent results. This complicates the assessment of what early information on a possible SEP event is available from these low coronal observations**. 25 Mar 1981, 7 Nov 1987, 2-3 Nov 2003, June 16, 2005, September 7, 2005, 11 Jun-30 Jul 2012, June 13, 2022**

Table 1. MLSO Mk3 Coronameter CMEs Associated With ~ 25 MeV Solar Proton Events. 1980-1998

Table 2. MLSO Mk4 Coronameter CMEs Associated With ~ 25 MeV Solar Proton Events 1999-2013

Solar Energetic Particles Observed by the STEREO Spacecraft During Solar Cycle 24

I. G. **Richardson**

Presentation at the Fleishman's Webinar, 22 May **2019**

http://www.ioffe.ru/LEA/SF_AR/files/Richardson2019.pdf

February 12, 2000, August 14, 2010 , 18 Aug 2010, 4 Aug 2011, Nov. 3, 2011 , 31 Aug 2012, January 22 and February 12, 2018, May 3, 2018

Prediction of Solar Energetic Particle Event Peak Proton Intensity Using a Simple Algorithm Based on CME Speed and Direction and Observations of Associated Solar Phenomena

I. G. **Richardson** , M. L. Mays, B. J. Thompson

Space Weather **Volume16, Issue11** **2018** Pages 1862-1881

sci-hub.tw/10.1029/2018SW002032

We assess whether a formula obtained by Richardson et al. [2014] relating the peak intensity of 14-24 MeV protons in a solar energetic particle (SEP) event at 1 AU to the solar event location and the speed of the associated coronal mass ejection (CME), may be used in a scheme to predict the intensity of an SEP event at any location at this heliocentric distance. Starting with all 334 CMEs in the CCMC/SWRC DONKI database in October 2011 – July 2012, we use the CME speed and direction to predict the proton intensity at Earth and the two STEREO spacecraft using this formula. Since most (~85%) of these CMEs were not in fact associated with SEP events, many SEP events are predicted that are not actually observed. Such cases may be reduced by considering whether type II or type III radio emissions accompany the CMEs, or by selecting faster, wider CMEs. This method is also applied to predict the SEP intensities associated with ∼1100 CMEs observed by the SOHO LASCO coronagraphs during 1997–2006 in solar cycle 23. Various skill scores are calculated which assess different aspects of the skill of the SEP predictions. We conclude that the Richardson et al. [2014] formula has potential as a simple empirical SEP intensity prediction tool.

25 MeV Solar Proton Events in Cycle 24 and Previous Cycles **Review**

Ian G. **Richardson**, Tycho T. von Rosenvinge, Hilary V. Cane

Advances in Space Research Volume 60, Issue 4, 15 August **2017**, Pages 755-767

http://arxiv.org/pdf/1604.07873v1.pdf

http://sci-hub.cc/10.1016/j.asr.2016.07.035

We summarize observations of around a thousand solar energetic particle (SEP) events since 1967 that include ~25 MeV protons made by various near-Earth spacecraft (IMPs 4, 5, 7, 8, ISEE 3, SOHO), encompassing solar cycles 20 to the current cycle (24). We also discuss recent observations of similar SEP events in cycle 24 from the STEREO spacecraft. The observations show, for example, that the time distribution of 25 MeV proton events varies from cycle to cycle. In particular, the time evolution of the SEP occurrence rate in cycle 24 is strongly asymmetric between the northern and southern solar hemispheres, and tracks the sunspot number in each hemisphere, whereas cycle 23 was more symmetric. There was also an absence of 25 MeV proton events during the solar minimum preceding cycle 24 (other minima show occasional, often reasonably intense events), and, so far, there have been few exceptionally intense events in cycle 24 compared to cycles 22 and 23, though cycle 21 also apparently lacked such events. We note a correlation between the rate of intense 25 MeV proton events and "ground level events" observed by neutron monitors since 1967 and demonstrate that the GLE rate at Earth in cycle 24 to date appears to be significantly lower than expected based on the intense 25 MeV proton event rate. **February 8-14, 2000**.

North/south hemispheric periodicities in the >25 MeV solar proton event rate during the rising and peak phases of solar cycle 24

Ian **Richardson**, Tycho von Rosenvinge, Hilary Cane

Solar Phys. Volume 291, Issue 7, pp 2117–2134 **2016**

http://arxiv.org/pdf/1604.03141v1.pdf **File**

We present evidence that >25 MeV solar proton events show a clustering in time at intervals of ~6 months that persisted during the rising and peak phases of solar cycle 24. This phenomenon is most clearly demonstrated by considering events originating in the northern or southern solar hemispheres separately. We examine how these variations in the solar energetic particle (SEP) event rate are related to other phenomena, such as hemispheric sunspot numbers and areas, rates of coronal mass ejections, and the mean solar magnetic field. Most obviously, the SEP event rate closely follows the sunspot number and area in the same hemisphere. The ~6 month variations are associated with features in many of the other parameters we examine, indicating that they are just one signature of the episodic development of cycle 24. They may be related to the "~150 day" periodicities reported in various solar and interplanetary phenomena during previous solar cycles. The clear presence of ~6 month periodicities in cycle 24 that evolve independently in each hemisphere conflicts with a scenario suggested by McIntosh et al. (2015) for the variational time scales of solar magnetism.

The Properties of Solar Energetic Particle Event-Associated Coronal Mass Ejections Reported in Different CME Catalogs

Ian G. **Richardson**, Tycho T. von Rosenvinge, Hilary V. Cane

Solar Phys. Volume 290, Issue 6, pp 1741-1759 **2015 File**

http://arxiv.org/pdf/1505.03071v1.pdf

https://sci-hub.ru/10.1007/s11207-015-0701-4

We compare estimates of the speed and width of coronal mass ejections (CMEs) in several catalogs for the CMEs associated with ~200 solar energetic particle (SEP) events in 2006-2013 that included 25 MeV protons. The catalogs used are: CDAW, CACTUS, SEEDS and CORIMP, all derived from observations by the LASCO coronagraphs on the SOHO spacecraft, the CACTUS catalog derived from the COR2 coronagraphs on the STEREO-A and -B spacecraft, and the DONKI catalog, which uses observations from SOHO and the STEREO spacecraft. We illustrate how, for this set of events, CME parameters can differ considerably in each catalog. The well-known correlation between CME speed and proton event intensity is shown to be similar for most catalogs, but this is largely because it is determined by a few large particle events associated with fast CMEs, and small events associated with slow CMEs. Intermediate particle events "shuffle" in position when speeds from different catalogs are used. Quadrature spacecraft CME speeds do not improve the correlation. CME widths also vary widely between catalogs, and are influenced by plane of the sky projection and how the width is inferred from the coronagraph images. The high degree of association (~50%) between the 25 MeV proton events and "full halo" (360 deg.-width) CMEs as defined in the CDAW catalog is removed when other catalogs are considered. Using CME parameters from the quadrature spacecraft, the SEP intensity is correlated with CME width, which is also correlated with CME speed. **January 16, 2012, January 23, 2012, April 9, 2012, August 10, 2012, February 6, 2013**

,

Catalog

> 25 MeV Proton Events Observed by the High Energy Telescopes on the STEREO A and B Spacecraft and/or at Earth During the First ~ Seven Years of the STEREO Mission

I. G. **Richardson**, T. T. von Rosenvinge, H. V. Cane, E. R. Christian, C. M. S. Cohen, A. W. Labrador, R. A. Leske, R. A. Mewaldt, M. E. Wiedenbeck, E. C. Stone

Solar Phys., August **2014**, Volume 289, Issue 8, pp 3059-3107 **2014; File**

https://link.springer.com/content/pdf/10.1007%2Fs11207-014-0524-8.pdf

Using observations from the High Energy Telescopes (HETs) on the STEREO A and B spacecraft and similar observations from near-Earth spacecraft, we summarize the properties of more than 200 individual > 25 MeV solar

proton events, some detected by multiple spacecraft, that occurred from the beginning of the STEREO mission in October 2006 to December 2013, and provide a catalog of these events and their solar sources and associations. Longitudinal dependencies of the electron and proton peak intensities and delays to onset and peak intensity relative to the solar event have been examined for 25 three-spacecraft particle events. Expressed as Gaussians, peak intensities fall off with longitude with σ=47±14∘ for 0.7 – 4 MeV electrons, and σ=43±13∘ for 14 – 24 MeV protons. Several particle events are discussed in more detail, including one on **3 November 2011**, in which ∼ 25 MeV protons filled the inner heliosphere within 90 minutes of the solar event, and another on **7 March 2012**, in which we demonstrate that the first of two coronal mass ejections that erupted from an active region within ∼ 1 hour was associated with particle acceleration. Comparing the current Solar Cycle 24 with the previous cycle, the first > 25 MeV proton event was detected at Earth in the current solar cycle around one year after smoothed sunspot minimum, compared with a delay of only two months in Cycle 23. Otherwise, solar energetic particle event occurrence rates were reasonably similar during the rising phases of Cycles 23 and 24. However, the rate declined in 2013, reflecting the decline in sunspot number since the peak in the northern-hemisphere sunspot number in November 2011. Observations in late 2013 suggest that the rate may be rising again in association with an increase in the southern sunspot number.
Table 1 >25 MeV proton events at 1 AU during the STEREO mission.

Database of episode-integrated solar energetic proton fluences
Zachary D. **Robinson**1*, James H. Adams Jr.2, Michael A. Xapsos3 and Craig A. Stauffer
J. Space Weather Space Clim. **2018**, 8, A24
https://www.swsc-journal.org/articles/swsc/pdf/2018/01/swsc170061.pdf
A new database of proton episode-integrated fluences is described. This database contains data from two different instruments on multiple satellites. The data are from instruments on the Interplanetary Monitoring Platform-8 (IMP8) and the Geostationary Operational Environmental Satellites (GOES) series. A method to normalize one set of data to one another is presented to create a seamless database spanning 1973 to 2016. A discussion of some of the characteristics that episodes exhibit is presented, including episode duration and number of peaks. As an example of what can be understood about episodes, the **July 4, 2012** episode is examined in detail. The coronal mass ejections and solar flares that caused many of the fluctuations of the proton flux seen at Earth are associated with peaks in the proton flux during this episode. The reasoning for each choice is laid out to provide a reference for how CME and solar flares associations are made. **July 16, 2002, August 14, 2002, June 4, 2011**

New Probabilistic Model For Episode Integrated Fluences of Protons Using Episodes From 1973-2013
Zachary D. **Robinson**
Thesis (2015) **2017**
https://arxiv.org/pdf/1711.04391.pdf
A new probabilistic model for protons has been created using episode integrated fluences. This model will allow the user to choose a mission start date, mission duration, and confidence level to construct a mission-specific, bounding case spectrum for proton fluences at a distance of 1 AU from the sun. A new database of episode integrated fluences will be created for this model. The database will contain 29 channels that span the energy range 0.88-485 MeV. This database will cover the period from November 1, 1973 to December 31, 2013, making it the largest database on solar activity. **August 22, 2005, June 4, 2011, August 2, 2011, November 4, 2011, July 4, 2012, October 14, 2013,**

Global Muon Detector Network Used for Space Weather Applications
M. **Rockenbach**, A. Dal Lago, N. J. Schuch, K. Munakata, T. Kuwabara, A. G. Oliveira, E. Echer, C. R. Braga, R. R. S. Mendonça, C. Kato, … show all 19
Space Science Reviews, August **2014**, Volume 182, Issue 1-4, pp 1-18
In this work, we summarize the development and current status of the Global Muon Detector Network (GMDN). The GMDN started in 1992 with only two muon detectors. It has consisted of four detectors since the Kuwait-city muon hodoscope detector was installed in March 2006. The present network has a total of 60 directional channels with an improved coverage of the sunward Interplanetary Magnetic Field (IMF) orientation, making it possible to continuously monitor cosmic ray precursors of geomagnetic storms. The data analysis methods developed also permit precise calculation of the three dimensional cosmic ray anisotropy on an hourly basis free from the atmospheric temperature effect and analysis of the cosmic ray precursors free from the diurnal anisotropy of the cosmic ray intensity.

Neutrons and energetic charged particles in the inner heliosphere: Measurements of the MESSENGER Neutron Spectrometer from 0.3 to 0.85 AU

Douglas J. **Rodgers**1, David J. Lawrence1, William C. Feldman2 and Patrick N. Peplowski
JGR Volume 120, Issue 2, pages 841–854, February **2015**
Energetic charged particle and neutron data from the Neutron Spectrometer (NS) on board the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft have been acquired for solar distances ranging from 0.3 to 0.85 AU. The NS is sensitive to ions with energies greater than 120 MeV/nucleon and has made the first measurements of these energetic ions in the inner heliosphere since the mid-1970s. The high-energy ion measurements are well correlated with Earth-based neutron monitor measurements, which themselves provide a measure of the solar modulation of galactic cosmic rays (GCRs). These measurements provide an explicit demonstration of the expected GCR solar modulation for solar distances to 0.3 AU. These NS data also represent the first interplanetary neutron measurements in the inner heliosphere. The time variability of the neutron measurements are driven by two primary effects: time variable production of neutrons from GCRs interacting with local spacecraft material and small count rate changes due to temperature-driven gain changes in the NS instrument. When these time-dependent variations are removed from the neutron measurements, there is no statistically significant variation of neutron count rates versus solar distance. These data are used to derive an upper limit on solar neutron production of 1024 neutrons[0.5 < E < 9 MeV] sr−1 s−1 during quiescent periods.

Solar energetic particles injected inside and outside a magnetic cloud: The widespread solar energetic particle event on 2022 January 20

L. **Rodríguez-García**, R. Gómez-Herrero, N. Dresing, L. A. Balmaceda, +++
A&A **2024**
https://arxiv.org/pdf/2409.04564
Context. On **2022 January 20**, the Energetic Particle Detector (EPD) on board Solar Orbiter measured a solar energetic particle (SEP) event showing unusual first arriving particles from the anti-Sun direction. Near-Earth spacecraft separated 17° in longitude to the west from Solar Orbiter measured classic antisunward-directed fluxes. STEREO-A and MAVEN, separated 18° to the east and 143° to the west from Solar Orbiter respectively, also observed the event, suggesting that particles spread over at least 160° in the heliosphere.
Results. Solar Orbiter was embedded in a MC erupting on 16 January from the same active region as the one related to the SEP event on 20 January. The SEP event is related to a M5.5 flare and a fast CME-driven shock of 1433 km/s, which injected particles within and outside the MC. The hard SEP spectra, the presence of a Type II radio burst, and the co-temporal Type III radio bursts being observed from 80 MHz that seems to emanate from the Type II, points to the shock as the relevant accelerator of the particles.
Conclusions. The detailed analysis of the SEP event strongly suggest that the energetic particles are injected mainly by a CME-driven shock into and outside of a previous MC present in the heliosphere at the time of the particle onset. The sunward propagating SEPs measured by Solar Orbiter are produced by the injection of particles along the longer (western) leg of the MC still connected to the Sun at the time of the release of the particles. The determined electron propagation path length inside the MC is around 30% longer than the estimated length of the loop leg of the MC itself (based on the graduated cylindrical shell model) consistent with a low number of field line rotations.

RADIAL DEPENDENCE OF THE PEAK INTENSITY OF SOLAR ENERGETIC ELECTRON EVENTS IN THE INNER HELIOSPHERE

Laura **Rodríguez-García**1, Alexander Kollhoff2, and the Solar Orbiter/EPD team
Solar Orbiter nugget #2 **2023**
https://www.cosmos.esa.int/web/solar-orbiter/science-nuggets/radial-dependence-of-the-peak-intensity-of-solar-energetic-electron-events-in-the-inner-heliosphere

Solar activity relations in energetic electron events measured by the MESSENGER mission

L. **Rodríguez-García**, L. A. Balmaceda, R. Gómez-Herrero, A. Kouloumvakos, N. Dresing, D. Lario, I. Zouganelis, A. Fedeli, F. Espinosa Lara, I. Cernuda, G. C. Ho, R. F. Wimmer-Schweingruber, J. Rodríguez-Pacheco
A&A 674, A145 (**2023**)
https://arxiv.org/pdf/2212.01592.pdf
https://www.aanda.org/articles/aa/pdf/2023/06/aa45604-22.pdf
Aims. We perform a statistical study of the relations between the properties of solar energetic electron (SEE) events measured by the MESSENGER mission from **2010 to 2015** and the parameters of the respective parent solar activity phenomena to identify the potential correlations between them. During the time of analysis MESSENGER heliocentric distance varied between 0.31 and 0.47 au.
Conclusions. (1) In this particular sample of events, with a majority of SEE events being widespread in heliolongitude and displaying relativistic electron intensity enhancements, a shock-related acceleration mechanism might be more relevant than a flare-related process in the acceleration of near-relativistic electrons. This result is mainly based on the stronger and more significant correlation found between the SEE peak intensities and the shock speed in comparison to the flare intensity; and on the asymmetry to the east of the range of connection angles (CAs)

for which the SEE events present higher peak intensities and higher correlations with the solar activity, which might be related to the evolution of the magnetic field connection to the shock front. We note that the CA is the angular distance between the footpoint of the magnetic field connecting to the spacecraft and the longitude of the source region. (2) The correlations between the peak intensity of the SEE event and the shock speed or the flare intensity are stronger than in previous studies using measurements by spacecraft near 1 au.

Solar energetic electron events measured by MESSENGER and Solar Orbiter. Peak intensity and energy spectrum radial dependences: statistical analysis

L. **Rodríguez-García**, R. Gómez-Herrero, N. Dresing, D. Lario, I. Zouganelis, L. A. Balmaceda, A. Kouloumvakos, A. Fedeli, F. Espinosa Lara, I. Cernuda, G. C. Ho, R. F. Wimmer-Schweingruber, J. Rodríguez-Pacheco

A&A 670, A51 **2023**
https://arxiv.org/pdf/2211.11054.pdf
https://www.aanda.org/articles/aa/pdf/2023/02/aa44553-22.pdf

Context/Aims: We present a list of 61 solar energetic electron (SEE) events measured by the MESSENGER mission and the radial dependences of the electron peak intensity and the peak-intensity energy spectrum. The analysis comprises the period from 2010 to 2015, when MESSENGER heliocentric distance varied between 0.31 and 0.47 au. We also show the radial dependencies for a shorter list of 12 SEE events measured in February and March 2022 by spacecraft near 1 au and by Solar Orbiter around its first close perihelion at 0.32 au.
Results: Due to the elevated background intensity level of the particle instrument on board MESSENGER, the SEE events measured by this mission are necessarily large and intense; most of them accompanied by a CME-driven shock, being widespread in heliolongitude, and displaying relativistic (∼1 MeV) electron intensity enhancements. The two main conclusions derived from the analysis of the large SEE events measured by MESSENGER, which are generally supported by Solar Orbiter's data results, are: (1) There is a wide variability in the radial dependence of the electron peak intensity between ∼0.3 au and ∼1 au, but the peak intensities of the energetic electrons decrease with radial distance from the Sun in 27 out of 28 events. On average and within the uncertainties, we find a radial dependence consistent with R−3. (2) The electron spectral index found in the energy range around 200 keV (δ200) of the backward-scattered population near 0.3 au measured by MESSENGER is harder in 19 out of 20 (15 out of 18) events by a median factor of ∼20% (∼10%) when comparing to the anti-sunward propagating beam (backward-scattered population) near 1 au. **19-20 Aug 2013, 1 Feb-22 Mar 2022**
Table 1. Solar energetic electron events measured by the MESSENGER mission 2010-2015
Table 4. Solar energetic electron events measured by Solar Orbiter near its first close perihelion 2022
SolOrb nuggets **2023** https://www.cosmos.esa.int/web/solar-orbiter/science-nuggets/radial-dependence-of-the-peak-intensity-of-solar-energetic-electron-events-in-the-inner-heliosphere

The unusual widespread solar energetic particle event on 2013 August 19. *Solar origin and particle longitudinal distribution*

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A&A 653, A137 **2021**
https://arxiv.org/pdf/2107.10257.pdf
https://doi.org/10.1051/0004-6361/202039960
https://www.aanda.org/articles/aa/pdf/2021/09/aa39960-20.pdf

Context: Late on **2013 August 19**, STEREO-A, STEREO-B, MESSENGER, Mars Odyssey, and the L1 spacecraft, spanning a longitudinal range of 222° in the ecliptic plane, observed an energetic particle flux increase. The widespread solar energetic particle (SEP) event was associated with a coronal mass ejection (CME) that came from a region located near the far-side central meridian from Earth's perspective. The CME erupted in two stages, and was accompanied by a late M-class flare observed as a post-eruptive arcade, persisting low-frequency (interplanetary) type II and groups of shock-accelerated type III radio bursts, all of them making this SEP event unusual.
Aims: There are two main objectives of this study, disentangling the reasons for the different intensity-time profiles observed by the spacecraft, especially at MESSENGER and STEREO-A locations, longitudinally separated by only 15°, and unravelling the single solar source related with the widespread SEP event.
Results: The solar source associated with the widespread SEP event is the shock driven by the CME, as the flare observed as a post-eruptive arcade is too late to explain the estimated particle onset. The different intensity-time profiles observed by STEREO-A, located at 0.97 au, and MESSENGER, at 0.33 au, can be interpreted as enhanced particle scattering beyond Mercury's orbit. The longitudinal extent of the shock does not explain by itself the wide spread of particles in the heliosphere. The particle increase observed at L1 may be attributed to cross-field diffusion

transport, and this is also the case for STEREO-B, at least until the spacecraft is eventually magnetically connected to the shock when it reaches ~0.6 au.

Validation of the effect of cross-calibrated GOES solar proton effective energies on derived integral fluxes by comparison with STEREO observations

J. V. **Rodriguez**, I. Sandberg, R. A. Mewaldt, I. A. Daglis, P. Jiggens

Space Weather Volume 15, Issue 2 February **2017** Pages 290–309

http://onlinelibrary.wiley.com/doi/10.1002/2016SW001533/full

The derivation of integral fluxes from instrument coincidence rates requires accurate knowledge of their effective energies. Recent cross calibrations of GOES with the high-energy-resolution Interplanetary Monitoring Platform (IMP) 8 Goddard Medium Energy Experiment (GME) (Sandberg et al., *Geophys. Res. Lett*, *41*, 4435, 2014a) gave significantly lower effective energies than those currently used by the NOAA Space Weather Prediction Center to calculate solar proton integral fluxes from GOES rates. This implie s systematically lower integral fluxes than currently produced. This paper quantifies the differences between the current and the cross-calibrated GOES integral fluxes and validates the latter. Care is taken to rule out the spectral resolution of the measurements or different integration algorithms as major contributors to differences in the magnitudes of the derived integral fluxes. The lower effective energies are validated by comparison with the independent, high-resolution observations by the STEREO Low-Energy Telescope (LET) and High-Energy Telescope (HET) during the December 2006 solar proton events. The current GOES product is similar to the >10 MeV integral fluxes recalculated by using the *Sandberg et al*. [**2014a**] effective energies but is substantially greater at higher energies. (The median ratios of the current to the recalculated fluxes are 1.1 at >10 MeV, 1.7 at >30 MeV, 2.1 at >60 MeV, and 2.9 at >100 MeV.) By virtue of this validation, the cross-calibrated GOES integral fluxes should be considered more accurate than the current NOAA product. The results of this study also demonstrate good consistency between the two long-term IMP 8 GME and STEREO LET and HET solar proton data sets. **06–15 December 2006**

Variation of proton flux profiles with the observer's latitude in simulated gradual SEP events

R. **Rodríguez-Gasén**, A. Aran, B. Sanahuja, C. Jacobs, S. Poedts

E-print, Oct **2013,** http://arxiv.org/pdf/1310.4651v1.pdf; Solar Phys. **2014**, V. 289, Issue 5, pp 1745-1762

We study the variation of the shape of the proton intensity-time profiles in simulated gradual Solar Energetic Particle (SEP) events with the relative observer's position in space with respect to the main direction of propagation of an interplanetary (IP) shock. Using a three-dimensional (3D) magnetohydrodynamic (MHD) code to simulate such a shock, we determine the evolution of the downstream-to-upstream ratios of the plasma variables at its front. Under the assumption of an existing relation between the normalized ratio in speed across the shock front and the injection rate of shock-accelerated particles, we model the transport of the particles and we obtain the proton flux profiles to be measured by a grid of 18 virtual observers located at 0.4 and 1.0 AU, with different latitudes and longitudes with respect to the shock nose. The differences among flux profiles are the result of the way each observer establishes a magnetic connection with the shock front, and we find that changes in the observer's latitude may result in intensity changes of up to one order of magnitude at both radial distances considered here. The peak intensity variation with the radial distance for the pair of observers located at the same angular position is also derived. This is the first time that the latitudinal dependence of the peak intensity with the observer's heliocentric radial distance has been quantified within the framework of gradual SEP event simulations.

The Energetic Particle Detector (EPD)

Energetic particle instrument suite for the Solar Orbiter mission

J. **Rodríguez-Pacheco**1 , R. F. Wimmer-Schweingruber2 , G. M. Mason3 , G. C. Ho3 , S. Sánchez-Prieto1 , M. Prieto1 ...

A&A 642, A7 (**2020**)

https://www.aanda.org/articles/aa/pdf/forth/aa35287-19.pdf

https://doi.org/10.1051/0004-6361/201935287

https://www.aanda.org/articles/aa/pdf/2020/10/aa35287-19.pdf

After decades of observations of solar energetic particles (SEP) from space-based observatories, relevant questions on particle injection, transport, and acceleration remain open. To address these scientific topics, accurate measurements of the particle properties in the inner heliosphere are needed. In this paper we describe the Energetic Particle Detector (EPD), an instrument suite that is part of the scientific payload aboard the Solar Orbiter mission. Solar Orbiter will approach the Sun as close as 0.28 au and will provide extra-ecliptic measurements beyond ∼ 30◦ heliographic latitude during the later stages of the mission. The EPD will measure electrons, protons, and heavy ions with high temporal resolution over a wide energy range, from suprathermal energies up to several hundreds of megaelectronvolts/nucleons. For this purpose, EPD is composed of four units: the SupraThermal Electrons and Protons (STEP), the Electron Proton Telescope (EPT), the Suprathermal Ion Spectrograph (SIS), and the High-Energy Telescope (HET) plus the Instrument Control Unit (ICU) that serves as power and data interface with the spacecraft. The low-energy population of electrons and ions will be covered by STEP and EPT, while the high-energy range will be measured by HET. Elemental and isotopic ion composition measurements will be performed by SIS and HET, allowing full particle identification from a few kiloelectronvolts up to several hundreds of megaelectronvolts/nucleons. Angular information will be provided by the separate look directions from different sensor heads, on the ecliptic plane along the Parker spiral magnetic field both forward and backwards, and out of the ecliptic plane observing both northern and southern hemispheres. The unparalleled observations of EPD will provide key insights into long-open and crucial questions about the processes that govern energetic particles in the inner heliosphere.

2. Science objectives of the Energetic Particle Detector (Injection, Acceleration mechanisms, Transport, Additional science targets)

Energetic Particles Measured in and out of the Ecliptic Plane During the Last Gnevyshev Gap

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Solar Physics, November **2012**, Volume 281, Issue 1, pp 491-499

We analyzed the temporal variation of energetic particles measured by the Low Energy Telescope (LET), the Kiel Electron Telescope (KET), and the High Energy Telescope (HET) instruments aboard Ulysses and the Electron Proton Helium Instrument (EPHIN) aboard SOHO during the last solar magnetic field polarity reversal in 2001. We have found two periods with anomalous low fluxes during that time that are present both at low and high heliolatitudes. We compared the energetic particle fluxes with solar energetic phenomena that traditionally have been associated with solar energetic particle (SEP) events at 1 AU. Our results show that these periods are related to relative minima in the number of X-ray flares and CMEs. Since Ulysses scanned the whole latitude range from 80 °S to 80 °N, we conclude that this process affects the inner three-dimensional heliosphere globally.

Why should the latitude of the observer be considered when modeling gradual proton events? An insight using the concept of cobpoint

R. **Rodríguez-Gasén**a, , , A. Aranb, B. Sanahujaa, C. Jacobsc and S. Poedts

Advances in Space Research, Volume 47, Issue 12, 15 June **2011**, Pages 2140-2151

The shape of flux profiles of gradual solar energetic particle (SEP) events depends on several not well-understood factors, such as the strength of the associated shock, the relative position of the observer in space with respect to the traveling shock, the existence of a background seed particle population, the interplanetary conditions for particle transport, as well as the particle energy. Here, we focus on two of these factors: the influence of the shock strength and the relative position of the observer. We performed a 3D simulation of the propagation of a coronal/interplanetary CME-driven shock in the framework of ideal MHD modeling. We analyze the passage of this shock by nine spacecraft located at 0.4 AU (Mercury's orbit) and at different longitudes and latitudes. We study the evolution of the plasma conditions in the shock front region magnetically connected to each spacecraft, that is the region of the shock front scanned by the "cobpoint" (Heras et al., 1995), as the shock propagates away from the Sun. Particularly, we discuss the influence of the latitude of the observer on the injection rate of shock-accelerated particles and, hence, on the resulting proton flux profiles to be detected by each spacecraft.

Improving the twilight model for polar cap absorption nowcasts

N. C. **Rogers**, A. Kero, F. Honary, P. T. Verronen, E. M. Warrington, D. W. Danski

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http://onlinelibrary.wiley.com/doi/10.1002/2016SW001527/pdf

During solar proton events (SPE), energetic protons ionize the polar mesosphere causing HF radio wave attenuation, more strongly on the dayside where the effective recombination coefficient, αeff, is low. Polar cap absorption models predict the 30 MHz cosmic noise absorption, A, measured by riometers, based on real-time measurements of the integrated proton flux-energy spectrum, J. However, empirical models in common use cannot account for regional and day-to-day variations in the daytime and nighttime profiles of αeff(z) or the related sensitivity parameter, . Large prediction errors occur during twilight when m changes rapidly, and due to errors locating the rigidity cutoff latitude. Modeling the twilight change in m as a linear or Gauss error-function transition over a range of solar-zenith angles (χl < χ < χu) provides a better fit to measurements than selecting day or night αeff profiles based on the Earth-shadow height. Optimal model parameters were determined for several polar cap riometers for large SPEs in 1998–2005. The optimal χl parameter was found to be most variable, with smaller values (as low as 60°) postsunrise compared with presunset and with positive correlation between riometers over a wide area. Day and night values of m exhibited higher correlation for closely spaced riometers. A nowcast simulation is presented in which rigidity boundary latitude and twilight model parameters are optimized by assimilating age-weighted measurements from 25 riometers. The technique reduces model bias, and root-mean-square errors are reduced by up to 30% compared with a model employing no riometer data assimilation.

Assimilation of real-time riometer measurements into models of 30 MHz polar cap absorption

Neil Christopher **Rogers*** and Farideh Honary

J. Space Weather Space Clim., 5, A8 (**2015**)

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140045.pdf

Space weather events may adversely affect high frequency (HF) radio propagation, hence the ability to provide nowcasting and forecasting of HF radio absorption is key for industries that rely on HF communications. This paper presents methods of assimilating 30 MHz radio absorption measurements into two types of ionospheric polar cap absorption (PCA) model to improve their performance as nowcasting tools. Type 1 models calculate absorption as m times the square root of the flux of solar protons above an energy threshold, Et. Measurements from 14 riometers during 94 solar proton events (1995–2010) are assimilated by optimising the day and night values of m by linear regression. Further non-linear optimisations are demonstrated in which parameters such as Et are also optimised and additional terms characterise local time and seasonal variations. These optimisations reduce RMS errors by up to 36%. Type 2 models incorporate altitude profiles of electron and neutral densities and electron temperatures. Here the scale height of the effective recombination coefficient profile in the D-region is optimised by regression. Furthermore, two published models of the rigidity cut-off latitude (CL) are assessed by comparison with riometer measurements. A small improvement in performance is observed by introducing a 3-h lag in the geomagnetic index Kp in the CL models. Assimilating data from a single riometer in the polar cap reduces RMS errors below 1 dB with less than 0.2 dB bias. However, many high-latitude riometers now provide absorption measurements in near-real time and we demonstrate how these data may be assimilated by fitting a low-order spherical harmonic function to both the measurements and a PCA model with optimised parameters.

Table 8. Thirteen large, multi-day SPE events in the period 1995–2005 (following the selection of Akmaev 2010).

Precise and Accurate Short-term Forecasting of Solar Energetic Particle Events with Multivariate Time Series Classifiers

Sumanth A. **Rotti**, Berkay Aydin, Petrus C. Martens

2024 *ApJ* **974** 188

https://arxiv.org/pdf/2408.05590

https://iopscience.iop.org/article/10.3847/1538-4357/ad6d57/pdf

Solar energetic particle (SEP) events are one of the most crucial aspects of space weather that require continuous monitoring and forecasting using robust methods. We demonstrate a proof of concept of using a data-driven supervised classification framework on a multivariate time series data set covering solar cycles 22, 23, and 24. We implement ensemble modeling that merges the results from three proton channels (E≥10 MeV, 50 MeV, and 100 MeV) and the long band X-ray flux (1-8Å) channel from the Geostationary Operational Environmental Satellite missions. Our task is binary classification, such that the aim of the model is to distinguish strong SEP events from nonevents. Here, strong SEP events are those crossing the Space Weather Prediction Center's "S1" threshold of solar radiation storm and proton fluxes below that are weak SEP events. In addition, we consider periods of non-occurrence of SEPs following a flare with magnitudes ≥C6.0 to maintain a natural imbalance of sample distribution. In our data set, there are 244 strong SEP events comprising the positive class. There are 189 weak events and 2,460 "SEP-quiet" periods for the negative class. We experiment with summary statistic classifier, one-nearest neighbor and supervised time series forest (STSF), and compare their performances to validate our methods for prediction windows from 5 min up to 60 min. We find STSF to perform better under all circumstances. For an optimal classification threshold of ≈0.3 and a 60 min prediction window, we obtain: TSS = 0.850, HSS = 0.878, GSS = 0.783.

Short-term Classification of Strong Solar Energetic Particle Events using Multivariate Time Series Classifiers

Sumanth A. **Rotti**, Berkay Aydin, Petrus C. Martens

ApJ **966** 165 **2024**

https://arxiv.org/pdf/2403.17418.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ad374e/pdf

Solar energetic particle (SEP) events are one of the most crucial aspects of space weather that require continuous monitoring and forecasting. Their prediction depends on various factors including source eruptions. In the present work, we use the Geostationary Solar Energetic Particle (GSEP) data set covering solar cycles 22, 23, and 24. We develop a framework using time series-based machine learning (ML) models with the aim of developing robust short-term forecasts by classifying SEP events. For this purpose, we introduce an ensemble learning approach that merges the results from univariate time series of three proton channels (10 MeV, 50 MeV, and 100 MeV) and the long band X-ray flux channel from the Geostationary Operational Environmental Satellite (GOES) missions and analyze their performance. We consider three models, namely, time series forest (TSF), supervised time series forest (STSF) and bag of SFA symbols (BOSS). Our study also focuses on understanding and developing confidence in the predictive capabilities of our models. Therefore, we utilize multiple evaluation techniques and metrics. Based on that, we find STSF to perform well in all scenarios. The summary of metrics for the STSF model is as follows: AUC = 0.981; F1-score = 0.960; TSS = 0.919; HSS = 0.920; GSS = 0.852; and MCC = 0.920. The Brier score loss of the STSF model is 0.077. This work lays the foundation for building near-real-time (NRT) short-term SEP event predictions using robust ML methods. **4-5 Sep 2017**

Analysis of SEP Events and Their Possible Precursors Based on the GSEP Catalog

Sumanth **Rotti**1 and Petrus C. Martens1

2023 ApJS 267 40

https://arxiv.org/pdf/2306.11318.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/acdace/pdf

Solar energetic particle (SEP) events are one of the most crucial aspects of space weather. Their prediction depends on various factors including the source solar eruptions such as flares and coronal mass ejections (CMEs). The Geostationary Solar Energetic Particle (GSEP) events catalog was developed as an extensive data set toward this effort for solar cycles 22, 23, and 24. In the present work, we review and extend the GSEP data set by (1) adding "weak" SEP events that have proton enhancements from 0.5 to 10 pfu in the E >10 MeV channel and (2) improving the associated solar source eruptions information. We analyze and discuss spatiotemporal properties such as flare magnitudes, locations, rise times, and speeds and widths of CMEs. We check for the correlation of these parameters with peak proton fluxes and event fluences. Our study also focuses on understanding feature importance toward the optimal performance of machine-learning (ML) models for SEP event forecasting. We implement random forest, extreme gradient boosting, logistic regression, and support vector machine classifiers in a binary classification schema. Based on the evaluation of our best models, we find both the flare and CME parameters are requisites to predict the occurrence of an SEP event. This work is a foundation for our further efforts on SEP event forecasting using robust ML methods. **2011 August 9, 2014-04-18**

Integrated Geostationary Solar Energetic Particle Events Catalog: GSEP

Sumanth **Rotti**, Berkay Aydin, Manolis K. Georgoulis, Petrus C. Martens

ApJS **262** 29 **2022**

https://arxiv.org/ftp/arxiv/papers/2204/2204.12021.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/ac87ac/pdf **File**

We present a catalog of solar energetic particle (SEP) events covering solar cycles 22, 23 and 24. We correlate and integrate three existing catalogs based on Geostationary Operational Environmental Satellite (GOES) integral proton flux data. We visually verified and labeled each event in the catalog to provide a homogenized data set. We have identified a total of 342 SEP events of which 246 cross the space weather prediction center (SWPC) threshold of a significant proton event. The metadata consists of physical parameters and observables concerning the possible source solar eruptions, namely flares and coronal mass ejections for each event. The sliced time series data of each event, along with intensity profiles of proton fluxes in several energy bands, have been made publicly available. This data set enables researchers in machine learning (ML) and statistical analysis to understand the SEPs and the source eruption characteristics useful for space weather prediction.

GSEP Dataset

https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/DZYLHK

Deriving the properties of coronal pressure fronts in 3-D: application to the 17 May 2012 ground level enhancement

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2016 ApJ 833 45

http://arxiv.org/pdf/1605.05208v1.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/833/1/45/pdf

We study the link between an expanding coronal shock and the energetic particles measured near Earth during the Ground Level Enhancement (GLE) of 17 May 2012. We developed a new technique based on multipoint imaging to triangulate the 3-D expansion of the shock forming in the corona. It uses images from three vantage points by mapping the outermost extent of the coronal region perturbed by the pressure front. We derive for the first time the 3-D velocity vector and the distribution of Mach numbers, M_FM, of the entire front as a function of time. Our approach uses magnetic field reconstructions of the coronal field, full magneto-hydrodynamic simulations and imaging inversion techniques. We find that the highest M_FM values appear along the coronal neutral line within a few minutes of the CME eruption; this neutral line is usually associated with the source of the heliospheric and plasma sheet. We can also estimate the time evolution of the shock speed, shock geometry and Mach number along different modeled magnetic field lines. Despite the level of uncertainty in deriving the shock Mach numbers, all employed reconstruction techniques show that the release time of GeV particles occurs when the coronal shock becomes super-critical (M_FM>3) near the tip of helmet streamers. Combining in-situ measurements with heliospheric imagery, we also demonstrate that magnetic connectivity between the accelerator (the coronal shock of 17 May 2012) and the near-Earth environment is established via a magnetic cloud that erupted from the same active region roughly five days earlier. This analysis also shows that the derivation of magnetic connectivity between the coronal shock and a probe must result from a full analysis of the interplanetary medium extending back in time by at least five days before the event of interest.

Table B1. Characteristics of WL CMEs and in situ measurements during GLE events

THE LONGITUDINAL PROPERTIES OF A SOLAR ENERGETIC PARTICLE EVENT INVESTIGATED USING MODERN SOLAR IMAGING

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2012 ApJ 752 44, **File**

https://iopscience.iop.org/article/10.1088/0004-637X/752/1/44/pdf

We use combined high-cadence, high-resolution, and multi-point imaging by the Solar-Terrestrial Relations Observatory (STEREO) and the Solar and Heliospheric Observatory to investigate the hour-long eruption of a fast and wide coronal mass ejection (CME) on **2011 March 21** when the twin STEREO spacecraft were located beyond the solar limbs. We analyze the relation between the eruption of the CME, the evolution of an Extreme Ultraviolet (EUV) wave, and the onset of a solar energetic particle (SEP) event measured in situ by the STEREO and near-Earth orbiting spacecraft. Combined ultraviolet and white-light images of the lower corona reveal that in an initial CME lateral "expansion phase," the EUV disturbance tracks the laterally expanding flanks of the CME, both moving parallel to the solar surface with speeds of ~450 km s–1. When the lateral expansion of the ejecta ceases, the EUV disturbance carries on propagating parallel to the solar surface but devolves rapidly into a less coherent structure. Multi-point tracking of the CME leading edge and the effects of the launched compression waves (e.g., pushed streamers) give anti-sunward speeds that initially exceed 900 km s–1 at all measured position angles. We combine our analysis of ultraviolet and white-light images with a comprehensive study of the velocity dispersion of energetic particles measured in situ by particle detectors located at STEREO-A (STA) and first Lagrange point (L1), to demonstrate that the delayed solar particle release times at STA and L1 are consistent with the time required (30-40 minutes) for the CME to perturb the corona over a wide range of longitudes. This study finds an association between the longitudinal extent of the perturbed corona (in EUV and white light) and the longitudinal extent of the SEP event in the heliosphere.

INTERPRETING THE PROPERTIES OF SOLAR ENERGETIC PARTICLE EVENTS BY USING COMBINED IMAGING AND MODELING OF INTERPLANETARY SHOCKS

A. P. **Rouillard**1,2, D. Odstrčil1,2, N. R. Sheeley3, A. Tylka3, A. Vourlidas3, G. Mason4, C.-C. Wu3, N. P. Savani5, B. E. Wood3, C. K. Ng1,3, G. Stenborg6, A. Szabo2 and O. C. St. Cy

2011 ApJ 735 7

Images of the solar corona obtained by the Solar-Terrestrial Relations Observatory (STEREO) provide high-cadence, high-resolution observations of a compression wave forming ahead of a fast (940 km s–1) coronal mass ejection (CME) that erupted at ~9:00 UT on 2010 April 03. The passage of this wave at 1 AU is detected in situ by the Advanced Composition Explorer and Wind spacecraft at 08:00 UT on April 05 as a shock followed by a turbulent and heated sheath. These unprecedented and complementary observations of a shock-sheath region from the Sun to 1 AU are used to investigate the onset of a Solar Energetic Particle (SEP) event measured at the first Lagrange point (L1) and at STEREO-Behind (STB). The spatial extent, radial coordinates, and speed of the ejection are measured from STEREO observations and used as inputs to a numerical simulation of the CME propagation in the background solar wind. The simulated magnetic and plasma properties of the shock and sheath region at L1 agree very well with the in situ measurements. These simulation results reveal that L1 and STB are magnetically connected to the western and eastern edges of the driven shock, respectively. They also show that the 12 hr delay between the eruption time of the ejection and the SEP onset at L1 corresponds to the time required for the bow shock to reach the magnetic field lines connected with L1. The simulated shock compression ratio increases along these magnetic field lines until the maximum flux of high-energy particles is observed.

THE VERY UNUSUAL INTERPLANETARY CORONAL MASS EJECTION OF 2012 JULY 23: A BLAST WAVE MEDIATED BY SOLAR ENERGETIC PARTICLES

C. T. **Russell**1, R. A. Mewaldt2, J. G. Luhmann3, G. M. Mason4, T. T. von Rosenvinge5, C. M. S. Cohen2, R. A. Leske2, R. Gomez-Herrero6, A. Klassen7, A. B. Galvin8, and K. D. C. Simunac
2013 ApJ 770 38; **File**
The giant, superfast, interplanetary coronal mass ejection, detected by STEREO A on **2012 July 23**, well away from Earth, appears to have reached 1 AU with an unusual set of leading bow waves resembling in some ways a subsonic interaction, possibly due to the high pressures present in the very energetic particles produced in this event. Eventually, a front of record high-speed flow reached STEREO. The unusual behavior of this event is illustrated using the magnetic field, plasma, and energetic ion observations obtained by STEREO. Had the Earth been at the location of STEREO, the large southward-oriented magnetic field component in the event, combined with its high speed, would have produced a record storm.

On The Solar Origins of Open Magnetic Fields in the Heliosphere
Rust, D.M., Haggerty, D.K., Georgoulis, M.K., Sheeley, N.R., Wang, Y.-M., DeRosa, M.L., Schriver, C.J.
E-print, Oct 2008; ApJ, v. 687, 635–645, **2008**
http://www.journals.uchicago.edu/doi/abs/10.1086/592017
A combination of heliospheric and solar data was used to identify open magnetic fields stretching from the lower corona to Earth orbit. 35 near-relativistic electron beams detected at the ACE spacecraft ??labeled?? the heliospheric segments of the open fields. An X-ray flare occurred<20 minutes before injection of the electrons in 25 events. These flares labeled the solar segment of the open fields. The flares occurred in western-hemisphere active regions (ARs) with *coronal holes whose polarity agreed with the polarity of the beam-carrying interplanetary fields in 23 of the 25 events*. We conclude that electron beams reach 1 AU from open AR fields adjacent to flare sites. The Wang & Sheeley implementation of the potential-field source-surface model successfully identified the open fields in 36% of cases. Success meant that the open fields reached the source surface within 3 heliographic deg of the interplanetary magnetic field connected to ACE at 1 AU. Inclusion of five near misses improves the success rate to 56%. The success rate for the Schrijver & DeRosa PFSS implementation was 50%. Our results suggest that, even if the input magnetic data are updated frequently, the PFSS models succeed in only 50% of cases to identify the coronal segment of open fields. Development of other techniques is in its infancy.

The U.S. and global neutron monitor network for heliophysics and space weather.
Ryan, J., Bindi, V., Clem, J., Evenson, P., Mangeard, P. -S., Seunarine, S., et al.
(**2022**). Available at: https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033

Prediction of Solar Proton Events with Machine Learning: Comparison with Operational Forecasts and "All-Clear" Perspectives
Viacheslav **Sadykov**, Alexander Kosovichev, Irina Kitiashvili, Vincent Oria, Gelu M Nita, Egor Illarionov, Patrick O'Keefe, Yucheng Jiang, Sheldon Fereira, Aatiya Ali
ApJ **2021**
https://arxiv.org/pdf/2107.03911.pdf
Solar Energetic Particle events (SEPs) are among the most dangerous transient phenomena of solar activity. As hazardous radiation, SEPs may affect the health of astronauts in outer space and adversely impact current and future space exploration. In this paper, we consider the problem of daily prediction of Solar Proton Events (SPEs) based on the characteristics of the magnetic fields in solar Active Regions (ARs), preceding soft X-ray and proton fluxes, and statistics of solar radio bursts. The machine learning (ML) algorithm uses an artificial neural network of custom architecture designed for whole-Sun input. The predictions of the ML model are compared with the SWPC NOAA operational forecasts of SPEs. Our preliminary results indicate that 1) for the AR-based predictions, it is necessary to take into account ARs at the western limb and on the far side of the Sun; 2) characteristics of the preceding proton flux represent the most valuable input for prediction; 3) daily median characteristics of ARs and the counts of type II, III, and IV radio bursts may be excluded from the forecast without performance loss; and 4) ML-based forecasts outperform SWPC NOAA forecasts in situations in which missing SPE events is very undesirable. The introduced approach indicates the possibility of developing robust "all-clear" SPE forecasts by employing machine learning methods.
See :
Predicting Solar Proton Events of Solar Cycles 22-24 using GOES Proton & Soft X-Ray Flux Statistics

Aatiya **Ali**, Viacheslav Sadykov, Alexander Kosovichev, Irina N. Kitiashvili, Vincent Oria, Gelu M. Nita, Egor Illarionov, Patrick M. O'Keefe, Fraila Francis, Chun-Jie Chong, Paul Kosovich, Russell D. Marroquin
ApJ **2023**
https://arxiv.org/pdf/2303.05446.pdf

Solar Energetic Particles: Acceleration and Observations
Takashi **Sako** **A review**
2010, In: Gopalswamy, N., Hasan, S.S., Ambastha, A. (eds.)
Heliophysical Processes, Astrophysics and Space Science Proceedings, Springer, Berlin, Chap. 4, 73-81, **File**.
Research of solar energetic particles (SEPs) is important in understanding particle acceleration, transport and interactions taking place in the universe. The importance of space weather to modern human life is also increasing. In this lecture, I introduce a selected subset of SEP observations together with observation techniques and future plans. The aim is to connect these SEP observations with associated particle acceleration mechanisms and the subsequent transport and interaction processes. Because the observational properties are determined by different processes, a wide range of observations is necessary in order to fully understand the phenomena taking place. I will also give an overview of the role of the SEP studies in general astrophysics.

Coronal mass ejection-related particle acceleration regions during a simple eruptive event
Carolina **Salas-Matamoros**1,5, Karl-Ludwig Klein1,2 and Alexis P. Rouillard3
A&A 590, A135 (**2016**) **File**
http://www.aanda.org/articles/aa/pdf/2016/06/aa28015-15.pdf
An intriguing feature of many solar energetic particle (SEP) events is the detection of particles over a very extended range of longitudes in the heliosphere. This may be due to peculiarities of the magnetic field in the corona, to a broad accelerator, to cross-field transport of the particles, or to a combination of these processes. The eruptive flare on **26 April 2008** provided an opportunity to study relevant processes under particularly favourable conditions since it occurred in a very quiet solar and interplanetary environment. This enabled us to investigate the physical link between a single well-identified coronal mass ejection (CME), electron acceleration as traced by radio emission, and the production of SEPs. We conduct a detailed analysis, which combines radio observations (Nançay Radio Heliograph and Nançay Decametre Array, Wind/Waves spectrograph) with remote-sensing observations of the corona in extreme ultraviolet (EUV) and white light, as well as in situ measurements of energetic particles near 1AU (SoHO and STEREO spacecraft). By combining images taken from multiple vantage points, we were able to derive the time-dependent evolution of the 3D pressure front that was developing around the erupting CME. Magnetic reconnection in the post-CME current sheet accelerated electrons, which remained confined in closed magnetic fields in the corona, while the acceleration of escaping particles can be attributed to the pressure front ahead of the expanding CME. The CME accelerated electrons remotely from the parent active region, owing to the interaction of its laterally expanding flank, which was traced by an EUV wave, with the ambient corona. SEPs detected at one STEREO spacecraft and SoHO were accelerated later, when the frontal shock of the CME intercepted the spacecraft-connected interplanetary magnetic field line. The injection regions into the heliosphere inferred from the radio and SEP observations are separated in longitude by about 140°. The observations for this event show that it is misleading to interpret multi-spacecraft SEP measurements in terms of one acceleration region in the corona. The different acceleration regions are linked to different vantage points in the interplanetary space.

Hard X-Ray Spectral Evolution and Production of Solar Energetic Particle Events during the January 2005 X-Class Flares
R. **Saldanha**, Sam Krucker, and R. P. Lin
The Astrophysical Journal, Vol. 673, No. 2: 1169-1173, **2008**; **File**
http://www.journals.uchicago.edu/doi/pdf/10.1086/524929
High-resolution hard X-ray observations provided by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) are used to study the spectral evolution of _50Y200 keV nonthermal electron bremsstrahlung emissions of five X-class flares observed during the January 2005 solar storm events. Four of these flares show progressive spectral hardening during at least some hard X-ray peaks, while only one event shows the otherwise more commonly observed soft-hard-soft behavior. Imaging observations reveal that_50Y100 keV nonthermal electron bremsstrahlung emissions originate from footpoints of flare loops at all times, including during times of progressive spectral hardening, indicating that the spectral hardening component is produced by precipitating electrons, and not

by electrons trapped in the corona. The four flares with progressive spectral hardening are all related to solar energetic particle (SEP) events, while the only X-class flare with soft-hard-soft behavior is not. This finding is consistent with earlier studies, suggesting that electron acceleration and transport in flares is somehow linked to the production of SEPs escaping into interplanetary space.

Catalogue of in situ observed solar energetic electrons from ACE/EPAM instrument

Susan W **Samwel**, Rositsa Miteva

MNRAS, Volume 505, Issue 4, August **2021**, Pages 5212–5227,

https://doi.org/10.1093/mnras/stab1564

We present the first comprehensive catalogue of in situ observed solar energetic electron (SEE) events that covers solar cycles [SCs] 23 and 24 in the energy range 103–315 keV. The electron enhancements are detected by the Electron, Proton, and Alpha Monitor − Deflected Electrons instrument [EPAM-DE] aboard the ACE spacecraft. Onset time, peak time, background-subtracted peak electron intensity, and onset-to-peak fluence have been analysed for each event where possible. We describe the utilized procedure to identify the electron events and the criteria of their association to their solar origin: solar flares (SFs) and coronal mass ejections (CMEs). A statistical study between the peak electron intensity/fluence and the SF/CME properties, also with respect to the SC, is presented. In addition, we investigated the properties of the SEEs that are accompanied with solar energetic protons. Furthermore, the correlation between the intensity and fluence of the SEEs and those of the solar energetic protons are examined with respect to the SCs. The SEE catalogue is generated and posted on-line and will be updated whenever data are available. The purpose of this catalogue is to provide a publicly available service to solar and space physics communities. In addition, such catalogues are considered as a novel tool that can be used in real-time particle forecasting systems which are also relied upon to mitigate against harmful space weather effects due to particle events.

Solar Energetic Particle Events Detected in the Housekeeping Data of the European Space Agency's Spacecraft Flotilla in the Solar System

Beatriz **Sánchez-Cano**, Olivier Witasse, Elise W. Knutsen, Dikshita Meggi, +++

Space Weather Volume21, Issue8 August **2023** e2023SW003540

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003540

Despite the growing importance of planetary Space Weather forecasting and radiation protection for science and robotic exploration and the need for accurate Space Weather monitoring and predictions, only a limited number of spacecraft have dedicated instrumentation for this purpose. However, every spacecraft (planetary or astronomical) has hundreds of housekeeping sensors distributed across the spacecraft, some of which can be useful to detect radiation hazards produced by solar particle events. In particular, energetic particles that impact detectors and subsystems on a spacecraft can be identified by certain housekeeping sensors, such as the Error Detection and Correction (EDAC) memory counters, and their effects can be assessed. These counters typically have a sudden large increase in a short time in their error counts that generally match the arrival of energetic particles to the spacecraft. We investigate these engineering datasets for scientific purposes and perform a feasibility study of solar energetic particle event detections using EDAC counters from seven European Space Agency Solar System missions: Venus Express, Mars Express, ExoMars-Trace Gas Orbiter, Rosetta, BepiColombo, Solar Orbiter, and Gaia. Six cases studies, in which the same event was observed by different missions at different locations in the inner Solar System are analyzed. The results of this study show how engineering sensors, for example, EDAC counters, can be used to infer information about the solar particle environment at each spacecraft location. Therefore, we demonstrate the potential of the various EDAC to provide a network of solar particle detections at locations where no scientific observations of this kind are available. **17-22 Jan 2005, 5 December 2006, 7 March 2012, 18 Jun-3 Jul 2015, 10 September 2017, 28 Oct 2021, 15 February 2022, 5 September 2022**

In-flight calibration of NOAA POES proton detectors—Derivation of the MEPED correction factors

Marit Irene **Sandanger**, Linn-Kristine Glesnes Ødegaard, Hilde Nesse Tyssøy, Johan Stadsnes, Finn Søraas, Kjellmar Oksavi, Aarsnes

JGR Volume 120, Issue 11 November **2015** Pages 9578–9593

The MEPED instruments on board the NOAA POES and MetOp satellites have been continuously measuring energetic particles in the magnetosphere since 1978. However, degradation of the proton detectors over time leads to an increase in the energy thresholds of the instrument and imposes great challenges to studies of long-term variability in the near-Earth space environment as well as a general quantification of the proton fluxes. By comparing monthly mean accumulated integral flux from a new and an old satellite at the same magnetic local time (MLT) and time period, we estimate the change in energy thresholds. The first 12 monthly energy spectra of the new satellite are used as a reference, and the derived monthly correction factors over a year for an old satellite show a small spread, indicating a robust calibration procedure. The method enables us to determine for the first time the correction factors also for the highest-energy channels of the proton detector. In addition, we make use of the newest satellite in orbit (MetOp-01) to find correction factors for 2013 for the NOAA 17 and MetOp-02 satellites. Without taking into account the level of degradation, the proton data from one satellite cannot be used quantitatively for more than 2 to 3 years after launch. As the electron detectors are vulnerable to contamination from energetic protons, the corrected proton measurements will be of value for electron flux measurements too. Thus, the correction factors ensure the correctness of both the proton and electron measurements.

Persistent Behavior in Solar Energetic Particle Time Series

N. V. **Sarlis**1, G. Livadiotis1, D. J. McComas1, M. E. Cuesta1, L. Y. Khoo1, C. M. S. Cohen2, D. G. Mitchell3, and N. A. Schwadron4

2024 ApJ 969 64

https://iopscience.iop.org/article/10.3847/1538-4357/ad479d/pdf

We investigate the long-term persistence of solar energetic particle (SEP) time series by means of four different methods: Hurst rescaled range R/S analysis, detrended fluctuation analysis, centered moving average analysis, and the fluctuation of natural time under the time reversal method. For these analyses, we use data sets from the Integrated Science Investigation of the Sun instrument suite on board NASA's Parker Solar Probe. Background systematic noise is modeled using cross-correlation analysis between different SEP energy channels and subtracted from the original data. The use of these four methods for deriving the time-series persistence allows us to (i) differentiate between quiet- and active-Sun periods based on the values of the corresponding self-similarity exponents alone; (ii) identify the onset of an ongoing activity well before it reaches its maximum SEP flux; (iii) reveal an interesting fine structure when activity is observed; and (iv) provide, for the first time, an estimate of the maximum SEP flux of a future storm based on the entropy change of natural time under time reversal.

Nowcast and forecast of galactic cosmic ray (GCR) and solar energetic particle (SEP) fluxes in magnetosphere and ionosphere – Extension of WASAVIES to Earth orbit

Tatsuhiko **Sato**, Ryuho Kataoka, Daikou Shiota, Yûki Kubo, Mamoru Ishii, Hiroshi Yasuda, Shoko Miyake, Yoshizumi Miyoshi, Haruka Ueno and Aiko Nagamatsu

J. Space Weather Space Clim. **2019**, 9, A9

https://www.swsc-journal.org/articles/swsc/pdf/2019/01/swsc180058.pdf

Real-time estimation of cosmic-ray fluxes on satellite orbits is one of the greatest challenges in space weather research. Therefore, we develop a system for nowcasting and forecasting the galactic cosmic ray (GCR) and solar energetic particle (SEP) fluxes at any location in the magnetosphere and ionosphere during ground-level enhancement (GLE) events. It is an extended version of the WArning System for AVIation Exposure to SEP (WASAVIES), which can determine event profiles by using real-time data of the count rates of several neutron monitors (NMs) at the ground level and high-energy proton fluxes observed by Geostationary Operational Environmental Satellites (GOES) satellites. The extended version, called WASAVIES-EO, can calculate the GCR and SEP fluxes outside a satellite based on its two-line element (TLE) data. Moreover, organ absorbed-dose and dose-equivalent rates of astronauts in the International Space Station (ISS) can be estimated using the system, considering its shielding effect. The accuracy of WASAVIES-EO was validated based on the dose rates measured in ISS, as well as based on high-energy proton fluxes observed by POES satellites during large GLEs that have occurred in the 21st century. Agreement between the nowcast and forecast dose rates in ISS, especially in terms of their temporal structures, indicates the usefulness of the developed system for future mission operations. **2001/4/15, 2005/1/20, 2006/12/13, 2012/5/17, 2017/9/10**

Correction J. Space Weather Space Clim., 9 (2019) A10

Composition of the Solar Corona, Solar Wind, and Solar Energetic Particles

J.T. **Schmelz**, D.V. Reames, R. von Steiger, S. Basu

E-print, 8 June **2012**; ApJ **2012** ApJ 755 33

Along with temperature and density, the elemental abundance is a basic parameter required by astronomers to understand and model any physical system. The abundances of the solar corona are known to differ from those of the solar photosphere via a mechanism related to the first ionization potential of the element, but the normalization of these values with respect to hydrogen is challenging. Here we show that the values used by solar physicists for over a decade and currently referred to as the ``coronal abundances'' do not agree with the data themselves. As a result, recent analysis and interpretation of solar data involving coronal abundances may need to be revised. We use observations from coronal spectroscopy, the solar wind, and solar energetic particles as well as the latest abundances of the solar photosphere to establish a new set of abundances that reflect our current understanding of the coronal plasma.

Low geo-effectiveness of fast halo CMEs related to the 12 X-class flares in 2002

B. **Schmieder**, R.S. Kim, B. Grison, K. Bocchialini, R.Y. Kwon, S. Poedts, P. Démoulin
2020
https://arxiv.org/pdf/2003.10777.pdf
It is generally accepted that extreme space weather events tend to be related to strong flares and fast halo coronal mass ejections CMEs. In the present paper, we carefully identify the chain of events from the Sun to the Earth induced by all 12 X-class flares that occurred in 2002. In this small sample, we find an unusual high rate (58\%) of solar sources with a longitude larger than 74 degrees. Yet, all 12 X-class flares are associated with at least one CME. The fast halo CMEs (50\%) are related to interplanetary CMEs (ICMEs) at L1 and weak Dst minimum values (>−51nT); while 5 (41\%) of the 12 X-class flares are related to solar proton events (SPE). We conclude that: (i) All twelve analyzed solar events, even those associated with fast halo CMEs originating from the central disk region, and those ICMEs and SPEs were not very geo-effective. This unexpected result demonstrates that the suggested events in the chain (fast halo CME, X-class flares, central disk region, ICME, SPE) are not infallible proxies for geo-effectiveness. (ii) The low value of integrated and normalized southward component of the IMF (B∗z) may explain the low geo-effectiveness for this small sample. In fact, B∗z is well correlated to the weak Dst and low auroral electrojet (AE) activity. Hence, the only space weather impact at Earth in 2002 we can explain is based on B∗z at L1. **2002: Apr-21, May-20, Jul-03, Jul-15, Jul-18, Jul-20, Jul-23, Aug-03, Aug-21, Aug-24, Aug-30, Oct-31**
Table 1. Properties of the 12 X-class ares in 2002 and their related phenomena.

Energetic Particles from Quasi-Separatrix Layers and Current Sheets at the Sun
Nathan A. **Schwadron**, Ronald M. Caplan, Jon A. Linker, Erika Palmerio, Matthew A. Young
ApJ **2024**
https://arxiv.org/pdf/2410.07420
Quasi-separatrix layers (QSLs) at the Sun are created from regions where channels of open magnetic flux have footpoints near regions of large-scale closed magnetic flux. These regions are particularly prone to magnetic reconnection at the Sun. In recent simulations of coronal mass ejections (CMEs) with the Magnetohydrodynamic Algorithm outside a Sphere (MAS) model coupled to the Energetic Particle Radiation Environment Module (EPREM) model, common sources of energetic particles were discovered over broad longitudinal distributions in the background solar wind, far from the sites of particle acceleration driven by compressions and shocks in front of CMEs. Further investigation revealed these to be accelerated energetic particles from the QSLs and current sheets. The energy released from magnetic reconnection near the QSL drives reconnection exhausts and field-aligned flows, which in turn accelerate energetic particles. The reconnection process also releases material previously contained within closed magnetic field structures, which are often rich in heavy ions and 3He ions, as corroborated by recent PSP observations. Therefore, the seed populations produced by QSLs are expected to be rich in 3He and heavy ions. Thus, we present the first global model of energetic particles accelerated from QSLs and above current sheets from the Sun. Our results provide a plausible source for seed populations near the Sun, which likely have 3He and heavy ion enhancements. These results aid in the development of predictive solar energetic particle models. **11/29/2020**

Parker Solar Probe Observations of Energetic Particles in the Flank of a Coronal Mass Ejection Close to the Sun
N. A. **Schwadron**1,2, Stuart D. Bale3,4, J. Bonnell5, A. Case6, M. Shen2, E. R. Christian7, C. M. S. Cohen8, A. J. Davis8, M. I. Desai9, K. Goetz10Show full author list
2024 ApJ 970 98
https://iopscience.iop.org/article/10.3847/1538-4357/ad527f/pdf
We present an event observed by Parker Solar Probe (PSP) at ∼0.2 au on **2022 March 2** in which imaging and in situ measurements coincide. During this event, PSP passed through structures on the flank of a streamer blowout coronal mass ejection (CME) including an isolated flux tube in front of the CME, a turbulent sheath, and the CME itself. Imaging observations and in situ helicity and principal variance signatures consistently show the presence of flux ropes internal to the CME. In both the sheath and the CME interval, the distributions are more isotropic, the spectra are softer, and the abundance ratios of Fe/O and He/H are lower than those in the isolated flux tube, and yet elevated relative to typical plasma and solar energetic particle abundances. These signatures in the sheath and the CME indicate that both flare populations and those from the plasma are accelerated to form the observed energetic particle enhancements. In contrast, the isolated flux tube shows large streaming, hard spectra, and large Fe/O and He/H ratios, indicating flare sources. Energetic particle fluxes are most enhanced within the CME interval from suprathermal through energetic particle energies (∼keV to >10 MeV), indicating particle acceleration, as well as confinement local to the closed magnetic structure. The flux-rope morphology of the CME helps to enable local modulation and trapping of energetic particles, in particular along helicity channels and other plasma boundaries. Thus, the CME acts to build up energetic particle populations, allowing them to be fed into subsequent higher-energy particle acceleration throughout the inner heliosphere where a compression or shock forms on the CME front.

Seed Population Pre-Conditioning and Acceleration Observed by Parker Solar Probe

N. A. **Schwadron**, S. Bale, J. Bonnell, A. Case, E. R. Christian, C. M. S. Cohen, ...

ApJS Volume 246, Issue 2, id.33 **2020**

https://arxiv.org/pdf/1912.02888.pdf

https://iopscience.iop.org/article/10.3847/1538-4365/ab5527/pdf

A series of solar energetic particle (SEP) events were observed at Parker Solar Probe (PSP) by the Integrated Science Investigation of the Sun (\ISOIS) during the period from **April 18, 2019 through April 24, 2019**. The PSP spacecraft was located near 0.48 au from the Sun on Parker spiral field lines that projected out to 1 au within ∼25∘ of near Earth spacecraft. These SEP events, though small compared to historically large SEP events, were amongst the largest observed thus far in the PSP mission and provide critical information about the space environment inside 1 au during SEP events. During this period the Sun released multiple coronal mass ejections (CMEs). One of these CMEs observed was initiated on **April 20, 2019** at 01:25 UTC, and the interplanetary CME (ICME) propagated out and passed over the PSP spacecraft. Observations by the Electromagnetic Fields Investigation (FIELDS) show that the magnetic field structure was mostly radial throughout the passage of the compression region and the plasma that followed, indicating that PSP did not directly observe a flux rope internal to the ICME, consistent with the location of PSP on the ICME flank. Analysis using relativistic electrons observed near Earth by the Electron, Proton and Alpha Monitor (EPAM) on the Advanced Composition Explorer (ACE) demonstrates the presence of electron seed populations (40--300 keV) during the events observed. The energy spectrum of the \ISOIS~ observed proton seed population below 1 MeV is close to the limit of possible stationary state plasma distributions out of equilibrium. \ISOIS~ observations reveal the \revise{enhancement} of seed populations during the passage of the ICME, which \revise{likely indicates a key part} of the pre-acceleration process that occurs close to the Sun.

Particle Radiation Sources, Propagation and Interactions in Deep Space, at Earth, the Moon, Mars, and Beyond: Examples of Radiation Interactions and Effects Review

Schwadron, N.A., Cooper, J.F., Desai, M. et al.

Space Sci Rev Volume 212, Issue 3–4, pp 1069–1106 (**2017**). doi:10.1007/s11214-017-0381-5

Part of the following topical collections:

The Scientific Foundation of Space Weather

https://link.springer.com/content/pdf/10.1007%2Fs11214-017-0381-5.pdf

Particle radiation has significant effects for astronauts, satellites and planetary bodies throughout the Solar System. Acute space radiation hazards pose risks to human and robotic exploration. This radiation also naturally weathers the exposed surface regolith of the Moon, the two moons of Mars, and other airless bodies, and contributes to chemical evolution of planetary atmospheres at Earth, Mars, Venus, Titan, and Pluto. We provide a select review of recent areas of research covering the origin of SEPs from coronal mass ejections low in the corona, propagation of events through the solar system during the anomalously weak solar cycle 24 and important examples of radiation interactions for Earth, other planets and airless bodies such as the Moon. **July 23, 2012**

PARTICLE ACCELERATION AT LOW CORONAL COMPRESSION REGIONS AND SHOCKS

N. A. **Schwadron**1, M. A. Lee1, M Gorby1, N. Lugaz1, H. E. Spence1, M. Desai2, T. Török3, C. Downs3,J. Linker3, R. Lionello

2015 ApJ 810 97

We present a study on particle acceleration in the low corona associated with the expansion and acceleration of coronal mass ejections (CMEs). Because CME expansion regions low in the corona are effective accelerators over a finite spatial region, we show that there is a rigidity regime where particles effectively diffuse away and escape from the acceleration sites using analytic solutions to the Parker transport equation. This leads to the formation of broken power-law distributions. Based on our analytic solutions, we find a natural ordering of the break energy and second power-law slope (above the break energy) as a function of the scattering characteristics. These relations provide testable predictions for the particle acceleration from low in the corona. Our initial analysis of solar energetic particle observations suggests a range of shock compression ratios and rigidity dependencies that give rise to the solar energetic particle (SEP) events studied. The wide range of characteristics inferred suggests competing mechanisms at work in SEP acceleration. Thus, CME expansion and acceleration in the low corona may naturally give rise to rapid particle acceleration and broken power-law distributions in large SEP events.

Synthesis of 3-D Coronal- Solar Wind Energetic Particle Acceleration Modules

Nathan A. **Schwadron**, Matt Gorby, Tibor Torok, Cooper Downs, Jon Linker, Roberto Lionello, Zoran Mikic, Pete Riley, Joe Giacalone, Ben Chandran, Kai Germaschewski, Phil A. Isenberg, Martin A. Lee, Noe Lugaz, Sonya Smith, Harlan E. Spence, Mihir Desai, Justin Kasper, Kamen Kozarev, Kelly Korreck, Mike Stevens, John Cooper, and Peter MacNeice
Space Weather Quarterly, Volume 11, Issue 2, JUL **2014**
http://onlinelibrary.wiley.com/doi/10.1002/SWQv11i002/pdf

Halo Coronal Mass Ejections during Solar Cycle 24: reconstruction of the global scenario and geoeffectiveness

Camilla **Scolini**, Mauro Messerotti, Stefaan Poedts, Luciano Rodriguez
Journal of Space Weather and Space Climate 2017
https://arxiv.org/pdf/1712.05847.pdf **File**
In this study we present a statistical analysis of 53 fast Earth-directed halo CMEs observed by the SOHO/LASCO instrument during the period Jan. 2009-Sep. 2015, and we use this CME sample to test the capabilities of a Sun-to-Earth prediction scheme for CME geoeffectiveness. First, we investigate the CME association with other solar activity features by means of multi-instrument observations of the solar magnetic and plasma properties. Second, using coronagraphic images to derive the CME kinematical properties at 0.1 AU, we propagate the events to 1 AU by means of the WSA-ENLIL+Cone model. Simulation results at Earth are compared with in-situ observations at L1. By applying the pressure balance condition at the magnetopause and a solar wind-Kp index coupling function, we estimate the expected magnetospheric compression and geomagnetic activity level, and compare them with global data records. The analysis indicates that 82% of the CMEs arrived at Earth in the next 4 days. Almost the totality of them compressed the magnetopause below geosynchronous orbits and triggered a geomagnetic storm. Complex sunspot-rich active regions associated with energetic flares result the most favourable configurations from which geoeffective CMEs originate. The analysis of related SEP events shows that 74% of the CMEs associated with major SEPs were geoeffective. Moreover, the SEP production is enhanced in the case of fast and interacting CMEs. In this work we present a first attempt at applying a Sun-to-Earth geoeffectiveness prediction scheme - based on 3D simulations and solar wind-geomagnetic activity coupling functions - to a statistical set of potentially geoeffective halo CMEs. The results of the prediction scheme are in good agreement with geomagnetic activity data records, although further studies performing a fine-tuning of such scheme are needed. **5-13 March 2012, 18-27 June 2015**,
Table 1. Complete list of the selected CME events.

DROPOUTS IN SOLAR ENERGETIC PARTICLES: ASSOCIATED WITH LOCAL TRAPPING BOUNDARIES OR CURRENT SHEETS?

A. **Seripienlert**[1,2], D. Ruffolo[1,2], W. H. Matthaeus[3], and P. Chuychai[2,4]
Astrophysical Journal, 711:980–989, **2010** March
In recent observations by the *Advanced Composition Explorer*, the intensity of solar energetic particles exhibits sudden, large changes known as dropouts. These have been explained in terms of turbulence or a flux tube structure in the solar wind. Dropouts are believed to indicate filamentary magnetic connection to a localized particle source near the solar surface, and computer simulations of a random-phase model of magnetic turbulence have indicated a spatial association between dropout features and local trapping boundaries (LTBs) defined for a two-dimensional (2D) + slab model of turbulence. Previous observations have shown that dropout features are not well associated with sharp magnetic field changes, as might be expected in the flux tube model. Random-phase turbulence models do not properly treat sharp changes in the magnetic field, such as current sheets, and thus cannot be tested in this way. Here, we explore the properties of a more realistic magnetohydrodynamic (MHD) turbulence model (2D MHD), in which current sheets develop and the current and magnetic field have characteristic non-Gaussian statistical properties. For this model, computer simulations that trace field lines to determine magnetic connection from a localized particle source indicate that sharp particle gradients should frequently be associated with LTBs, sometimes with strong 2D magnetic fluctuations, and infrequently with current sheets. Thus, the 2D MHD + slab model of turbulent fluctuations includes some realistic features of the flux tube view and is consistent with the lack of an observed association between dropouts and intense magnetic fields or currents.

Perpendicular Diffusion of Energetic Particles: A Complete Analytical Theory

Andreas **Shalchi**
ApJ **923** 209 **2021**
https://arxiv.org/pdf/2109.07574.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac2363/pdf
https://doi.org/10.3847/1538-4357/ac2363
Over the past two decades scientists have achieved a significant improvement of our understanding of the transport of energetic particles across a mean magnetic field. Due to test-particle simulations as well as powerful non-linear

analytical tools our understanding of this type of transport is almost complete. However, previously developed non-linear analytical theories do not always agree perfectly with simulations. Therefore, a correction factor a2 was incorporated into such theories with the aim to balance out inaccuracies. In this paper a new analytical theory for perpendicular transport is presented. This theory contains the previously developed unified non-linear transport theory, the most advanced theory to date, in the limit of small Kubo number turbulence. For two-dimensional turbulence new results are obtained. In this case the new theory describes perpendicular diffusion as a process which is sub-diffusive while particles follow magnetic field lines. Diffusion is restored as soon as the turbulence transverse complexity becomes important. For long parallel mean free paths one finds that the perpendicular diffusion coefficient is a reduced field line random walk limit. For short parallel mean free paths, on the other hand, one gets a hybrid diffusion coefficient which is a mixture of collisionless Rechester & Rosenbluth and fluid limits. Overall the new analytical theory developed in the current paper is in agreement with heuristic arguments. Furthermore, the new theory agrees almost perfectly with previously performed test-particle simulations without the need of the aforementioned correction factor a2 or any other free parameter.

Perpendicular Transport of Energetic Particles in Magnetic Turbulence **Review**

Andreas **Shalchi**

Space Science Reviews **volume 216**, Article number: 23 (**2020**)

https://link.springer.com/content/pdf/10.1007/s11214-020-0644-4.pdf

Scientists have explored how energetic particles such as solar energetic particles and cosmic rays move through a magnetized plasma such as the interplanetary and interstellar medium since more than five decades. From a theoretical point of view, this topic is difficult because the particles experience complicated interactions with turbulent magnetic fields. Besides turbulent fields, there are also large scale or mean magnetic fields breaking the symmetry in such systems and one has to distinguish between transport of particles parallel and perpendicular with respect to such mean fields. In standard descriptions of transport phenomena, one often assumes that the transport in both directions is normal diffusive but non-diffusive transport was found in more recent work. This is in particular true for early and intermediate times where the diffusive regime is not yet reached. In recent years researchers employed advanced numerical tools in order to simulate the motion of those particles through the aforementioned systems. Nevertheless, the analytical description of the problem discussed here is of utmost importance since analytical forms of particle transport parameters need to be known in several applications such as solar modulation studies or investigations of shock acceleration. The latter process is directly linked to the question of what the sources of high energy cosmic rays are, a problem which is considered to be one of the most important problems of the sciences of the 21st century. The present review article discusses analytical theories developed for describing particle transport across a large scale magnetic field as well as field line random walk. A heuristic approach explaining the basic physics of perpendicular transport is also presented. Simple analytical forms for the perpendicular diffusion coefficient are proposed which can easily be incorporated in numerical codes for solar modulation or shock acceleration studies. Test-particle simulations are also discussed together with a comparison with analytical results. Several applications such as cosmic ray propagation and diffusive shock acceleration are also part of this review.

Interacting CMEs and their associated flare and SEP activities

A.**Shanmugaraju**, S.Prasanna Subramanian

2014

http://arxiv.org/pdf/1405.6316v1.pdf

We have analyzed a set of 25 interacting events which are associated with the DH type II bursts. These events are selected from the Coronal Mass Ejections observed during the period 1997-2010 in SOHO/LASCO and DH type IIs in Wind/WAVES. Their pre and primary CMEs from nearby active regions are identified using LASCO and EIT images and their height-time diagrams. Their interacting time and height are obtained, and their associated activities, such as, flares and solar energetic particles (>10pfu) are also investigated. Results from the analysis are: primary CMEs are much faster than the pre-CMEs, their X-ray flares are also stronger (X and M class) compared to the flares (C and M class) of pre-CMEs. Most of the events occurred during the period 2000-2006. From the observed width and speed of pre and primary CMEs, the pre-CMEs are found to be less energetic than the primary CMEs. While the primary CMEs are tracked up to the end of LASCO field of view, most of the pre-CMEs are tracked up to < 26Rs. The SEP intensity is found to be related with the integrated flux of the X-ray flares associated with the primary CMEs for nine events originating from the western region.

Table 1: Data corresponding to all the pre and primary CMEs observed during the period 1997 – 2010

1997 Nov 06, 2000 July 22, 2001 Jan 20, 2001 Apr 02, 2002 Apr 14, 2003 Mar 18, 2003 Nov 18, 2003 Dec 2, 2004 July 23, 2004 July 25, 2004 Nov 06, 2004 Nov 07, 2004 Dec 29, 2004 Dec 30, 2005 Jan 17, 2005 Jan 20, 2005 June 03, 2005 July 07, 2005 July 13, 2005 July 14, 2005 July 30, 2005 Sep 13, 2007 June 03, 2010 Aug 18

Characteristics of Sustained >100 γ-ray Emission Associated with Solar Flares

G. H. **Share**, R. J. Murphy, A. K. Tolbert, B. R. Dennis, S. M. White, R. A. Schwartz, and A. J. Tylka
ApJ Supplement **2017**
http://www.astro.umd.edu/~share/publications/share_2017.pdf **File**
We characterize and provide a catalog of thirty >100 MeV sustained γ-ray emission (SGRE) events observed by Fermi LAT. These events are temporally and spectrally distinct from the associated solar flares. Their spectra are consistent with decay of pions produced by >300 MeV protons and are not consistent with electron bremsstrahlung. SGRE start times range from CME onset to two hours later. Their durations range from about four minutes to twenty hours and appear to be correlated with durations of >100 MeV SEP proton events. The >300 MeV protons producing SGRE have spectra that can be fit with power laws with a mean index of ∼4 and RMS spread of 1.8. γ-ray line measurements indicate that SGRE proton spectra are steeper above 300 MeV than they are below 300 MeV. The number of SGRE protons >500 MeV is on average about ten times more than the number in the associated flare and about fifty to one hundred times less than the number in the accompanying SEP. SGRE can extend tens of degrees from the flare site. Sustained bremsstrahlung from MeV electrons was observed in one SGRE event. Flare >100 keV X-ray emission appears to be associated with SGRE and with intense SEPs. From this observation, we provide arguments that lead us to propose that sub-MeV to MeV protons escaping from the flare contribute to the seed population that is accelerated by shocks onto open field lines to produce SEPs and onto field lines returning to the Sun to produce SGRE. **3 June 1983?, 2011-02-24, 2011 March 7, 2011-05-29, 2011-06-02, 2011-06-07, 2011-08-04, 2011-08-09, 2011-09-06, 2011-09-07, 2011-09-24, 22-Jan-12, 2012-01-23, 2012-01-27, 2012-03-04, 2012-03-05, 06-Mar-12, 2012 March 7, 2012-03-09, 2012-03-10, 2012-03-13, 2012-05-17, 2012-06-03, 2012-07-06, 2012-10-23, 2012-11-27, 2013-04-11, 2013-05-13, 2013-05-14, 2013-05-15, 2013-10-11, 2013-10-25, 2013-10-28, 2014 February 25, 2014-09-01, 2015-06-21**
Table 1. LAT Sustained >100 MeV Emission (SGRE) Events from June 2008 to December 2016
Table 4. Onset Times of CMEs, Type II Radio, and SGREs
Table A1. Solar Eruptive Events from June 2008 to May 2012
Table C2. Spectral Characteristics of Sustained-Emission Events
Table E3. Radio Bursts from LAT Sustained >100 MeV Events

Comment on ``Detection and characterization of 0.5--8 MeV neutrons near Mercury: Evidence for a solar origin"

Gerald H. **Share**, Ronald J. Murphy, Allan J. Tylka, Brian R. Dennis, and James M. Ryan
E-print, Sept **2014**; JGR, **2014**
We argue that the hour-long neutron transient detected by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Neutron Spectrometer beginning at 15:45 UT on **2011 June 4** is due to secondary neutrons from energetic protons interacting in the spacecraft. The protons were probably accelerated by a shock that passed the spacecraft about thirty minutes earlier. We reach this conclusion after a study of data from the MESSENGER neutron spectrometer, gamma-ray spectrometer, X-ray Spectrometer, and Energetic Particle Spectrometer, and from the particle spectrometers on STEREO A. Our conclusion differs markedly from that given by **Lawrence et al. (2014}** who claimed that there is "strong evidence" that the neutrons were produced by the interaction of ions in the solar atmosphere. We identify significant faults with the authors' arguments that led them to that conclusion.

Physics of Solar Neutron Production: Questionable Detection of Neutrons from the 2007 December 31 Flare

Gerald H. **Share**, Ronald J. Murphy, Allan J. Tylka, Benz Kozlovsky, James M. Ryan, and Chul Gwon
E-print Dec 2010; JGR, Vol. 116, No. A3, A03102, **2011**
Spacecraft observations in the inner heliosphere offer the first opportunity to measure 1--10 MeV solar neutrons. We discuss the cross sections for neutron production in solar flares and calculate the escaping neutron spectra for mono-energetic and power-law particle spectra at the Sun and at the distance (0.48 AU) and observation angle of MESSENGER at the time of its reported detection of low-energy solar neutrons associated with the **2007 December 31** solar flare. We detail solar physics concerns about this detection: 1. the inferred number of accelerated protons at the Sun for this modest M2-class flare would have been 10 times larger than any flare observed to date and 2. the implied energy in accelerated ions would have been 50 to 10^4 times what we would expect based on the observed energy in non-thermal electrons and the energy in the thermal X-ray plasma. We find that there is no compelling evidence for a high electron/proton ratio in the solar energetic particle (SEP) event raising concerns that the neutron counts came mostly from SEP ion interactions in the spacecraft; this concern is supported by the similarity of the SEP and neutron count rates. The MESSENGER team made detailed calculations of neutron production from SEP protons. However, if interactions <30 MeV had been included in their calculations and the carbon spacecraft structure were a significant source of secondary neutrons we estimate that SEP proton and alpha-particle interactions could account for the observed fast neutron rate. This is due to 13C that has a 3 MeV proton threshold for neutron production and is exothermic for alpha-particle interactions.

Relationship Between Flares and GLEs
Gerald **Share**1,2, Ronald Murphy2
Presentation at "Ground Level Enhancement (GLE)"
Comparative Data Analysis Workshop (CDAW), LMSAL, Jan 6-9, **2009**

Re-examination of the First Five Ground-Level Events
Shea, M. A.; Smart, D.
36th International Cosmic Ray Conference (ICRC2019), held July 24th-August 1st, 2019 in Madison, WI, U.S.A. Online at https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=358, id.1149, **2019**
https://pos.sissa.it/358/1149/pdf
28 Feb 1942, 7 Mar 1942, 25 Jul 1946, 19 Nov 1949, 23 Feb 1956

Space Weather and the Ground-Level Solar Proton Events of the 23rd Solar Cycle
Shea, M. A.; Smart, D. F. **Review**
Space Sci. Rev., 171, Numbers 1-4, 161-188, **2012, File**
Solar proton events can adversely affect space and ground-based systems. Ground-level events are a subset of solar proton events that have a harder spectrum than average solar proton events and are detectable on Earth's surface by cosmic radiation ionization chambers, muon detectors, and neutron monitors. This paper summarizes the space weather effects associated with ground-level solar proton events during the 23rd solar cycle. These effects include communication and navigation systems, spacecraft electronics and operations, space power systems, manned space missions, and commercial aircraft operations. The major effect of ground-level events that affect manned spacecraft operations is increased radiation exposure. The primary effect on commercial aircraft operations is the loss of high frequency communication and, at extreme polar latitudes, an increase in the radiation exposure above that experienced from the background galactic cosmic radiation. Calculations of the maximum potential aircraft polar route exposure for each ground-level event of the 23rd solar cycle are presented. The space weather effects in October and November 2003 are highlighted together with on-going efforts to utilize cosmic ray neutron monitors to predict high energy solar proton events, thus providing an alert so that system operators can possibly make adjustments to vulnerable spacecraft operations and polar aircraft routes.

A Study of Variations of Galactic Cosmic-Ray Intensity Based on a Hybrid Data-processing Method
Zhenning **Shen**1,2, Gang Qin3, Pingbing Zuo1,2, Fengsi Wei1, and Xiaojun Xu2
2020 ApJ 900 143
https://doi.org/10.3847/1538-4357/abac60
The low-energy cosmic-ray (CR) fluxes measured by space-borne instruments are generally considered to consist of gradually changing galactic CRs (GCRs) and short-lived solar energetic particles (SEPs). The SEP events cause sharp and ephemeral increases in the time profile of CR observations, with a higher occurrence rate in solar maximum. It is necessary to eliminate such spikes and obtain the pure GCR component while studying the modulation of GCRs in both short and long timescales. A hybrid data-processing method based on spike detection and time series analysis techniques is developed to remove the spikes and decompose the GCR data observed by the Interplanetary Monitoring Platform 8 into the long-term variation trend and the 27 day variation components. With the hybrid data-processing method, the 11 yr and 27 day variations in the intensity of low-energy GCRs can be studied systematically. Using the fitted trend component, the time lag in the solar modulation of low-energy GCRs is studied, and the results show that the time lag is both epoch and energy dependent. The obtained 27 day variation component is anticorrelated with the changes in solar wind velocity even during solar maximum. Implementing the running Fourier series fit procedure, the 27 day variation amplitude of the proton flux is computed. It is found that the yearly averaged values clearly show 11 and 22 yr variation cycles. In addition, the energy spectrum of the 27 day variation amplitude is softer in the A < 0 solar minimum than that in the A > 0 solar minimum.

Why the Shock-ICME Complex Structure is Important: Learning From the Early 2017 September CMEs
Chenglong **Shen**, Mengjiao Xu, Yuming Wang, Yutian Chi, Bingxian Luo
2018
https://arxiv.org/pdf/1805.05763.pdf **File**
In the early days of 2017 September, an exceptionally energetic solar active region AR12673 aroused great interest in the solar physics community. It produced four X class flares, more than 20 CMEs and an intense geomagnetic storm, for which the peak value of the Dst index reached up to -142nT at 2017 September 8 02:00 UT. In this work, we check the interplanetary and solar source of this intense geomagnetic storm. We find that this geomagnetic storm was mainly caused by a shock-ICME complex structure, which was formed by a shock driven by the **2017**

September 6 CME propagating into a previous ICME which was the interplanetary counterpart of the **2017 September 4** CME. To better understand the role of this structure, we conduct the quantitative analysis about the enhancement of ICME's geoeffectiveness induced by the shock compression. The analysis shows that the shock compression enhanced the intensity of this geomagnetic storm by a factor of two. Without shock compression, there would be only a moderate geomagnetic storm with a peak Dst value of -79 nT. In addition, the analysis of the proton flux signature inside the shock-ICME complex structure shows that this structure also enhanced the solar energetic particles (SEPs) intensity by a factor of ~ 5. These findings illustrate that the shock-ICME complex structure is a very important factor in solar physics study and space weather forecast.
See STEP Team at USTC (University of Science and Technology of China) http://space.ustc.edu.cn/dreams/

A study of cosmic ray flux based on the noise in raw CCD data from solar images

Z.-N. **Shen**, G. Qin
JGR Vol: 121, Pages: 10,712–10,727 **2016**
Raw solar images from CCDs are often contaminated with single-pixel noise which is thought to be made by cosmic ray hits. The cosmic ray-affected pixels are usually outstanding when compared with the perimeter zone. In this work, we use a method based on the median filtering algorithm to identify and count the cosmic ray traces from SOHO/EIT solar images to estimate the cosmic ray (CR) flux. With such cosmic ray flux, we study the transient variations associated with the violent solar activities, such as the solar proton events (SPEs), which show good similarity with the observations of GOES 11 P6 channel with an energy interval 80–165 MeV. Further, using SPE list observed by SOHO/ERNE proton channels with more narrow energy intervals, it is found that CRs in the energy range 118–140 MeV affect the SOHO/EIT images the most. In addition, by using a robust automatic despiking method, we get the background of the cosmic ray flux from solar images, which is considered to be the galactic cosmic ray (GCR) flux. The GCR flux from solar images shows an 11 year period due to the solar modulation, similar to the SOHO/ERNE GCR flux and Newark neutron monitor count rates. Furthermore, GCRs from solar images have a 27 day period and show good anticorrelation with the changes of solar wind velocity.

COMPOUND TWIN CORONAL MASS EJECTIONS IN THE 2012 MAY 17 GLE EVENT

C. **Shen**1,2, G. Li3, X. Kong3,4, J. Hu3, X. D. Sun2, L. Ding5, Y. Chen4, Yuming Wang1, and L. Xia
2013 ApJ 763 114
http://iopscience.iop.org/0004-637X/763/2/114/pdf/0004-637X_763_2_114.pdf
We report a multiple spacecraft observation of the **2012 May 17** GLE event. Using the coronagraph observations by SOHO/LASCO, STEREO-A/COR1, and STEREO-B/COR1, we identify two eruptions resulting in two coronal mass ejections (CMEs) that occurred in the same active region and close in time (~2 minutes) in the 2012 May 17 GLE event. Both CMEs were fast. Complicated radio emissions, with multiple type II episodes, were observed from ground-based stations: Learmonth and BIRS, as well as the WAVES instrument on board the Wind spacecraft. High time-resolution SDO/AIA imaging data and SDO/HMI vector magnetic field data were also examined. A complicated pre-eruption magnetic field configuration, consisting of twisted flux-tube structure, is reconstructed. Solar energetic particles (SEPs) up to several hundred MeV nucleon–1 were detected in this event. Although the eruption source region was near the west limb, the event led to ground-level enhancement. The existence of two fast CMEs and the observation of high-energy particles with ground-level enhancement agrees well with a recently proposed "twin CME" scenario.

Enhancement of Solar Energetic Particles During a Shock –Magnetic Cloud Interacting Complex Structure

Chenglong **Shen** · Yuming Wang · Pinzhong Ye · S. Wang
Solar Phys (**2008**) 252: 409–418, DOI 10.1007/s11207-008-9268-7
http://www.springerlink.com/content/58g4814844610p91/fulltext.pdf
The behavior of solar energetic particles (SEPs) in a shock – magnetic cloud interacting complex structure observed by the *Advanced Composition Explorer* (ACE) spacecraft on **5 November 2001** is analyzed. A strong shock causing magnetic field strength and solar wind speed increases of about 41 nT and 300 km s^{-1}, respectively, propagated within a preceding magnetic cloud (MC). It is found that an extraordinary SEP enhancement appeared at the high-energy (≥10 MeV) proton intensities and extended over and only over the entire period of the shock –MC structure passing through the spacecraft. Such SEP behavior is much different from the usual picture that the SEPs are depressed in MCs. The comparison of this event with other top SEP events of solar cycle 23 (**2000 Bastille Day and 2003 Halloween events**) shows that such an enhancement resulted from the effects of the shock –MC complex structure leading to the highest ≥10 MeV proton intensity of solar cycle 23. Our analysis suggests that the relatively isolated magnetic field configuration of MCs combined with an embedded strong shock could significantly enhance the SEP intensity; SEPs are accelerated by the shock and confined into the MC. Further, we find that the SEP enhancement at lower energies happened not only within the shock –MC structure but also after it, probably owing to the presence of a following MC-like structure. This is consistent with the

picture that SEP fluxes could be enhanced in the magnetic topology between two MCs, which was proposed based on numerical simulations by Kallenrode and Cliver (*Proc. 27th ICRC* **8**, 3318, 2001b).

STRENGTH OF CORONAL MASS EJECTION-DRIVEN SHOCKS NEAR THE SUN AND THEIR IMPORTANCE IN PREDICTING SOLAR ENERGETIC PARTICLE EVENTS

Chenglong **Shen**, Yuming Wang, Pinzhong Ye, X. P. Zhao, Bin Gui, and S. Wang

The Astrophysical Journal, 670:849–856, **2007** November 20

Coronal shocks are important structures, but there are no direct observations of them in solar and space physics. The strength of shocks plays a key role in shock-related phenomena, such as radio bursts and solar energetic particle (SEP) generation. This paper presents an improved method of calculating Alfve´n speed and shock strength near the Sun. This method is based on using as many observations as possible, rather than one-dimensional global models. Two events, a relatively slow CME on **2001 September 15** and a very fast CME on **2000 June 15**, are selected to illustrate the calculation process. The calculation results suggest that the slow CME drove a strong shock, with Mach number of 3.43–4.18, while the fast CME drove a relatively weak shock, with Mach number of 1.90–3.21. This is consistent with the radio observations, which find a stronger and longer decameter-hectometric (DH) type II radio burst during the first event, and a short DH type II radio burst during the second event. In particular, the calculation results explain the observational fact that the slow CME produced a major solar energetic particle (SEP) event, while the fast CME did not. Through a comparison of the two events, the importance of shock strength in predicting SEP events is addressed.

On the Role of Interplanetary Shocks in Accelerating MeV Electrons

N. Talebpour **Sheshvan**, N. Dresing, R. Vainio, A. Afanasiev, D. E. Morosan

A&A 674, A133 **2023**

https://arxiv.org/pdf/2301.05587.pdf

https://www.aanda.org/articles/aa/pdf/2023/06/aa45908-23.pdf

One of the sources of solar energetic particle (SEP) events is shocks that are driven by fast coronal mass ejections (CMEs). They can accelerate SEPs up to relativistic energies and are attributed to the largest SEP events. New studies suggest that CME-driven shocks can potentially accelerate electrons to MeV energies in the vicinity of the Sun. We focus on relativistic electrons associated with strong IP shocks between 2007 and 2019 to determine whether the shocks can keep accelerating such electrons up to 1 AU distance. We have analyzed High Energy Telescope (HET) observations aboard the STEREO spacecraft of potential electron energetic storm particle (ESP) events, characterized by intensity time series that peak at the time of, or close to, the associated CME-driven shock crossing. We present a new filtering method to assess the statistical significance of particle intensity increases and apply it to MeV electron observations in the vicinity of interplanetary shocks. We identified 27 candidate events by visual inspection from a STEREO in-situ shock list. Our method identified nine clear cases, where a significant increase of MeV electrons was found in association with a shock. Typically, the highest statistical significance was observed in the highest HET energy channel of electrons. All nine cases were associated with shocks driven by interplanetary CMEs that showed large transit speeds, in excess of 900 km/s. In several cases multiple shocks were observed within one day of the shock related to the electron increase. Although electron ESP events at MeV energies are found to be rare at 1 AU our filtering method is not designed to identify a potential interplanetary shock contribution from distances closer to the Sun. Future observations taken during closer approaches to the Sun will likely provide clarity on interplanetary shock acceleration of electrons. **4-5 Jun 2011, 29 January 2012, 7 Mar 2012, 27 May 2012, 23 July 2012, 6 Nov 2013, 8 Nov 2013, 25 Sep 2014, 24 Sep 2017, 19 Sep 2017**

Table 1: Parameters of the nine electron ESP events 2011-2017

Proton and Helium Heating by Cascading Turbulence in a Low-beta Plasma

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2022 ApJ 941 39

https://iopscience.iop.org/article/10.3847/1538-4357/ac9fd7/pdf

How ions are energized and heated is a fundamental problem in the study of energy dissipation in magnetized plasmas. In particular, the heating of heavy ions (including 4He2+, 3He2+, and others) has been a constant concern for understanding the microphysics of impulsive solar flares. In this article, via two-dimensional hybrid-kinetic particle-in-cell simulations, we study the heating of helium ions (4He2+) by turbulence driven by cascading waves launched at large scales from the left-handed polarized helium ion cyclotron wave branch of a multi-ion plasma composed of electrons, protons, and helium ions. We find significant parallel (to the background magnetic field) heating for both helium ions and protons due to the formation of beams and plateaus in their velocity distribution functions along the background magnetic field. The heating of helium ions in the direction perpendicular to the magnetic field starts with a lower rate than that in the parallel direction, but overtakes the parallel heating after a few hundreds of the proton gyro-periods due to cyclotron resonances with mainly obliquely propagating waves induced by the cascade of injected helium ion cyclotron waves at large scales. There is, however, little evidence for proton heating in the perpendicular direction due to the absence of left-handed polarized cyclotron waves near the proton cyclotron frequency. Our results are useful for understanding the preferential heating of 3He and other heavy ions in the 3He-rich solar energetic particle events, in which helium ions play a crucial role as a species of background ions regulating the kinetic plasma behavior.

RHESSI OBSERVATIONS OF THE PROPORTIONAL ACCELERATION OF RELATIVISTIC >0.3 MeV ELECTRONS AND >30 MeV PROTONS IN SOLAR FLARES

A. Y. **Shih**1, R. P. Lin1, and D.M. Smith2

Astrophysical Journal, 698:L152–L157, **2009, File**

http://www.iop.org:80/EJ/toc/-alert=43191/1538-4357/698/2

We analyze all *RHESSI* measurements from 2002 to 2005 (29 flare events) of the 2.223 MeV neutroncapture γ -ray line and >0.3 MeV electron bremsstrahlung continuum emissions, produced by >30 MeV accelerated protons (depending on assumptions) and >0.3 MeV accelerated electrons, respectively. We find a close proportionality between the two emissions over >3 orders of magnitude in fluence, from the largest flares down to the limits of detectability. This implies that the processes in flares that accelerate electrons above 0.3 MeV and protons above 30 MeV are closely related, and that the relative acceleration of these two populations is roughly independent of flare size. We find an overall weak correlation between the 2.223 MeV fluence and the peak *GOES* 1–8 Å soft X-ray (SXR) flux, but with a close proportionality for flares with 2.223 MeV fluence above a threshold of 50 ph cm^{-2} (equivalent to ~2 Ч 10^{31} protons >30 MeV). Below this threshold the flares usually have large (M-class or higher) but generally uncorrelated excess SXR emission. Thus, above this threshold it appears that flares reach a maximum efficiency for >30 MeV proton and relativistic (>0.3 MeV) electron acceleration, with proportionate amounts of energy going to flare SXR thermal emission and to >50 keV electrons. Finally, we find that the electron-to-proton ratios—J_e(0.5 MeV)/J_p (10 MeV)— in these flares, obtained from the γ -ray observations, are about 2 orders of magnitude larger than the ratios in gradual solar energetic particle (SEP) events, but are comparable with ratios in impulsive SEP events.

Rigidity Dependence of the Long-Term Variations of Galactic Cosmic-Ray Intensity in Relation to the Interplanetary Magnetic-Field Turbulence: 1968 – 2002

M. **Siluszyk**, K. Iskra, M. V. Alania

Solar Phys., Volume 289, Issue 11, pp 4297-4308, **2014**

http://download.springer.com/static/pdf/143/art%253A10.1007%252Fs11207-014-0573-z.pdf?auth66=1409647301_dbf55b825794d964d3beece684d821f5&ext=.pdf

We studied the relationship between the power-law exponent γ on the rigidity R of the spectrum of galactic cosmic-ray (GCR) intensity variation ($\delta D(R)/D(R)\propto R^{-\gamma}$) and the exponents ν_y and ν_z of the power spectral density (PSD) of the B_y and B_z components of the interplanetary magnetic field (IMF) turbulence (PSD~$f^{-\nu}$, where f is the frequency). We used the data from neutron monitors and IMF for the period of 1968 – 2002. The exponents ν_y and ν_z were calculated in the frequency interval $\Delta f=f_2-f_1=3\times10^{-6}$ Hz of the resonant frequencies ($f_1=1\times10^{-6}$ Hz, $f_2=4\times10^{-6}$ Hz) that are responsible for the scattering of GCR particles with the rigidity range detected by neutron monitors. We found clear inverse correlations between γ and ν_y or ν_z when the time variations of the resonant frequencies were derived from in situ measurements of the solar wind velocity U_{sw} and IMF strength B during 1968 – 2002. We argue that these inverse relations are a fundamental feature in the GCR modulation that is not restricted to the analyzed years of 1968 – 2002.

Enerdetic Particles in the Heliosphere Book

Simnett G.M.

Astrophysics and Space Science Library V. 438 **2017**

Energetic neutral atoms from the Sun: an alternative interpretation of a unique event⋆

G. M. **Simnett**

A&A 531, A46 (**2011**)

The high temperature of the solar corona results in virtually complete ionization of the light elements and a high degree of ionization of the heavier elements. Therefore it is not expected that many neutral atoms should be emitted from the Sun, and certainly not with high kinetic energy. A particle event associated with the first major flare of the current solar cycle, on **5 December 2006**, has been interpreted as containing energetic neutral hydrogen atoms (ENA) of at least a few MeV. The ENAs were identified as such on account of their arrival direction at 1 AU, which was from the solar direction; the lack of atoms heavier than hydrogen; and the timing of their arrival, which was consistent with emission at the time of the flare X-ray burst. The observations were made from the two STEREO spacecraft which were near the Earth at the time. However, the EPAM instrument on the ACE spacecraft, which is in orbit around the L1 Lagrangian point some 1.5 × 106 km away from the Earth towards the Sun, observed a pulse, or precursor, of electrons of energies of at least 50 keV but approximately one hour earlier than the pulse of ENAs at STEREO. Later ACE and STEREO detected a major charged particle event which is presumably associated with the 5 December flare. The relative times of the onsets of the energetic particles in both the precursor and the main solar energetic particle event at the STEREO spacecraft and ACE were consistent with corotation of the interplanetary magnetic field if the particles were the same population propagating, and probably trapped, within the field. The precursor proton intensity detected by STEREO was below the threshold of the ACE/EPAM detectors. We conclude that the interpretation of the particles seen by STEREO as energetic neutral atoms is suspect.

On the timescale and location of ^{3}He acceleration:

G. M. **Simnett**

A&A 507 (**2009**) 469-480

We present a novel explanation for the ^{3}He-rich solar energetic particle events. We suggest that at low latitudes the coronal magnetic field is largely closed out to several solar radii. Quasi-continuous magnetic reconnection provides conditions suitable for resonant acceleration of ^{3}He which essentially accelerates all the ambient ions up to energies around 1 MeV/nucleon, which are largely trapped in the closed field. Electrons are also accelerated together with a relatively small number of ions which also satisfy the resonance condition. Ultra-heavy ions may also be accelerated, although details of how this is achieved are not known at this time. Reconnection in the outer region of the closed magnetic field injects the trapped particles from time to time into the interplanetary medium as impulsive events, while leakage provides a dribble of ions into the interplanetary medium, to provide the quiet time background. The trapped ions may also be seed particles for acceleration in a chromospheric flare. The flare acceleration does not preferentially accelerate ^{3}He nor ultra-heavy ions.

Erratum: The timing of relativistic proton acceleration in the 20 January 2005 flare, and other papers:

G. M. **Simnett**

A&A 472 (**2007**) 309-310

In 2006 a timing error was discovered in the EPAM data from the ACE spacecraft, which has since been corrected. There are two publications where the interpretation of the data needs some revision on account of the error (Simnett 2006, A&A, 445, 715; Simnett et al. 2005, A&A, 440, 759). Here we publish the correct versions of the data and indicate where the discussion in the above papers needs modifying.

A NOVEL TECHNIQUE TO INFER IONIC CHARGE STATES OF SOLAR ENERGETIC PARTICLES

L. S. **Sollitt,**1 E. C. Stone,2 R. A. Mewaldt,2 C. M. S. Cohen,2 A. C. Cummings,2
R. A. Leske,2 M. E. Wiedenbeck,3 and T. T. von Rosenvinge4

The Astrophysical Journal, 679:910-919, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/587121

In some large solar energetic particle (SEP) events, the intensities of higher energy SEPs decay more rapidly than at lower energies. This energy dependence varies with particle species, as would be expected if the decay timescale depended on a rigidity-dependent diffusion mean free path. By comparing the decay timescales of carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron, mean charge states are inferred for these (and other) elements in three SEP events between 1997 and 2002 at energies between 10 and 200 MeV nucleon$_{-1}$. In a fourth event, upper limits for the charge states are inferred. The charge states of many different particle species are all consistent with a single source temperature; in two events in 1997 and 2002, the best-fit temperature is much higher than that of the corona, which could imply a contribution from solar flare material. However, comparison with lower energy iron charge states for the 1997 event implies that the observed high-energy charge state could also be understood as the result of stripping during shock acceleration in the corona.

Variation in Path Lengths of Turbulent Magnetic Field Lines and Solar Energetic Particles

Wirin **Sonsrettee** (1), Piyanate Chuychai, Achara Seripienlert (2), Paisan Tooprakai (3), Alejandro Sáiz (4), David Ruffolo (4), William H. Matthaeus (5 and 6), Rohit Chhiber

ApJ **967** 97 **2024**

https://arxiv.org/pdf/2404.14718.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ad3d58/pdf

Modeling of time profiles of solar energetic particle (SEP) observations often considers transport along a large-scale magnetic field with a fixed path length from the source to the observer. Here we point out that variability in the turbulent field line path length can affect the fits to SEP data and the inferred mean free path and injection profile. To explore such variability, we perform Monte Carlo simulations in representations of homogeneous 2D MHD + slab turbulence adapted to spherical geometry and trace trajectories of field lines and full particle orbits, considering proton injection from a narrow or wide angular region near the Sun, corresponding to an impulsive or gradual solar event, respectively. We analyze our simulation results in terms of field line and particle path length statistics for 1∘×1∘ pixels in heliolatitude and heliolongitude at 0.35 and 1 AU from the Sun, for different values of the turbulence amplitude b/B0 and turbulence geometry as expressed by the slab fraction fs. Maps of the most probable path lengths of field lines and particles at each pixel exhibit systematic patterns that reflect the fluctuation amplitudes experienced by the field lines, which in turn relate to the local topology of 2D turbulence. We describe the effects of such path length variations on SEP time profiles, both in terms of path length variability at specific locations and motion of the observer with respect to turbulence topology during the course of the observations.

Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing GLE Alert Plus

G. **Souvatzoglou**, A. Papaioannou, H. Mavromichalaki, J. Dimitroulakos and C. Sarlanis

Space Weather, Volume 12, Issue 11, pages 633–649, November **2014**

http://sci-hub.cc/10.1002/2014SW001102

http://cosray.phys.uoa.gr/publications/D106.pdf

Whenever a significant intensity increase is being recorded by at least three neutron monitor stations in real-time mode, a ground level enhancement (GLE) event is marked and an automated alert is issued. Although, the physical concept of the algorithm is solid and has efficiently worked in a number of cases, the availability of real-time data is still an open issue and makes timely GLE alerts quite challenging. In this work we present the optimization of the GLE alert that has been set into operation since 2006 at the Athens Neutron Monitor Station. This upgrade has led to *GLE Alert Plus*, which is currently based upon the Neutron Monitor Database (NMDB). We have determined the critical values per station allowing us to issue reliable GLE alerts close to the initiation of the event while at the same time we keep the false alert rate at low levels. Furthermore, we have managed to treat the problem of data availability, introducing the Go-Back-N algorithm. A total of 13 GLE events have been marked from January 2000 to December 2012. *GLE Alert Plus* issued an alert for 12 events. These alert times are compared to the alert times of GOES Space Weather Prediction Center and Solar Energetic Particle forecaster of the University of Málaga (UMASEP). In all cases GLE Alert Plus precedes the GOES alert by ≈8–52 min. The comparison with UMASEP demonstrated a remarkably good agreement. Real-time GLE alerts by *GLE Alert Plus* may be retrieved by **http://cosray.phys.uoa.gr/gle_alert_plus.html**, **http://www.nmdb.eu**, **nd** **http://swe.ssa.esa.int/web/guest/space-radiation.** An automated GLE alert email notification system is also available to interested users.

Table 1. Parent Solar Events for the Selected GLE Events From 2000 to 2012 and Comparison of the *General Alert* Issued by GLE Alert Plus to the GLE Onset

Investigating the heliosphere, magnetosphere, atmosphere, and properties of cosmic rays during the 2018 Aug 25-26 strong geomagnetic storm

Starodubtsev, S ; Kovalev, I ; Gololobov, P ; Grigoryev, V ; Kravtsova, M ; Krymsky, G ; Olemskoy, S ; Sdobnov, V

ADVANCES IN SPACE RESEARCH Volume 73 Issue 8 Page 4363-4377 **2024**

DOI 10.1016/j.asr.2024.01.027

https://www.webofscience.com/wos/woscc/full-record/WOS:001215744800001

We investigated the conditions of the heliosphere, magnetosphere, and atmosphere from cosmic ray (CR) observations during the **2018 Aug 25-26** strong geomagnetic storm. The analysis involved the global survey (GS) and the spectrographic global survey (SGS) methods created and developed at the Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy of the Siberian Branch of the Russian Academy of Sciences (ShICRA SB RAS) and at the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences (ISTP SB RAS). Also, in our analysis, we used the data on direct measurements of the interplanetary medium parameters from the known OMNI database, CR measurements at the GOES geostationary satellites, from the global network of neutron monitors and muon detectors, from the Sayan spectrograph, and from the A.I. Kuzmin Yakutsk spectrograph of CR. When analyzing this event, the SGS enabled to obtain the data on the orientation of the mean interplanetary magnetic field, on the geomagnetic cutoff rigidity and its variations during the geomagnetic storm. Also, this method allowed us to estimate the bulk temperature over the point of recording CR, the ring current and the magnetopause current, as well as their contributions to the Dst-index, and also to establish differential rigidity spectra of CR at different stages of the magnetic storm evolution. Through the GS method, we determined the value and the directions for the first two spherical harmonics of CR distribution, and the direction to their anisotropy source. The results obtained through two different global survey methods are shown to be agree and mutually supplement each other. Using the Yakutsk spectrograph records enabled to determine the index for the power energy spectrum of variations in CR intensity during the investigated event.

New Aspects of a Lid-removal Mechanism in the Onset of an Eruption Sequence that Produced a Large Solar Energetic Particle (SEP) Event

Alphonse C. **Sterling**1, Ronald L. Moore1,2, David A. Falconer1,2,3, and Javon M. Knox

2014 ApJ 788 L20

We examine a sequence of two ejective eruptions from a single active region on **2012 January 23**, using magnetograms and EUV images from the Solar Dynamics Observatory's (SDO) Helioseismic and Magnetic Imager (HMI) and Atmospheric and Imaging Assembly (AIA), and EUV images from STEREO/EUVI. This sequence produced two coronal mass ejections (CMEs) and a strong solar energetic particle event (SEP); here we focus on the magnetic onset of this important space weather episode. Cheng et al. showed that the first eruption's ("Eruption 1") flux rope was apparent only in "hotter" AIA channels, and that it removed overlying field that allowed the second eruption ("Eruption 2") to begin via ideal MHD instability; here we say that Eruption 2 began via a "lid removal" mechanism. We show that during Eruption 1's onset, its flux rope underwent a "tether weakening" (TW) reconnection with field that arched from the eruption-source active region to an adjacent active region. Standard flare loops from Eruption 1 developed over Eruption 2's flux rope and enclosed filament, but these overarching new loops were unable to confine that flux rope/filament. Eruption 1's flare loops, from both TW reconnection and standard-flare-model internal reconnection, were much cooler than Eruption 2's flare loops (GOES thermal temperatures of ~7.5 MK and 9 MK, compared to ~14 MK). The corresponding three sequential GOES flares were, respectively, due to TW reconnection plus earlier phase Eruption 1 tether-cutting reconnection, Eruption 1 later-phase tether-cutting reconnection, and Eruption 2 tether-cutting reconnection.

The soft X-ray Neupert effect as a proxy for solar energetic particle injection
A proof-of-concept physics-based forecasting model

Ruhann **Steyn**1*, Du Toit Strauss1, Frederic Effenberger2,3 and Daniel Pacheco4

J. Space Weather Space Clim. **2020**, 10, 64

https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200079.pdf

The acceleration and injection of solar energetic particles (SEPs) near the Sun is one of the major unsolved problems in contemporary SEP transport modeling efforts. Here, we establish a new approach to the injection problem by utilizing a correlation between the soft X-ray thermal emission in solar flares, and their hard X-ray counterpart, the so-called Neupert effect, which is indicative of the presence of non-thermal particles. We show that the resulting injection function, in the initial phase of the flare, is similar to those inferred from inverting the transport problem based on in-situ observations. For few cases, we find early injections with no in-situ correspondence, that can be caused by particles accelerated before there is a magnetic connection between the source and the spacecraft. **The method has limitations for long-duration injections, since it is not applicable to the decay phase of the flare** where particle trapping might play a role. For a sample of SEP events in 1980, observed with the Helios-1 and IMP8 spacecraft, we show the results of a 2D SEP transport model based on this approach. We discuss that, with this method, a physics-based, real-time operational SEP now-cast model for the heliosphere is feasible. **28 May 1980**

On the onset delays of solar energetic electrons and protons: Evidence for a common accelerator

R.D. **Strauss**, N. Dresing, I.G. Richardson, J.P. van den Berg, P.J. Steyn

ApJ **951** 2 **2023**

https://arxiv.org/pdf/2305.05347.pdf

The processes responsible for the acceleration of solar energetic particles (SEPs) are still not well understood, including whether SEP electrons and protons are accelerated by common or separate processes. Using a numerical particle transport model that includes both pitch-angle and perpendicular spatial diffusion, we simulate, amongst other quantities, the onset delay for MeV electrons and protons and compare the results to observations of SEPs from widely-separated spacecraft. Such observations have previously been interpreted, in a simple scenario assuming no perpendicular diffusion, as evidence for different electron and proton sources. We show that, by assuming a common particle source together with perpendicular diffusion, we are able to simultaneously reproduce the onset delays for both electrons and protons. We argue that this points towards a common accelerator for these particles. Moreover, a relatively broad particle source is required in the model to correctly describe the observations. This is suggestive of diffusive shock acceleration occurring at large shock structures playing a significant role in the acceleration of these SEPs.

The mini-neutron monitor: a new approach in neutron monitor design

Du Toit **Strauss**1*, Stepan Poluianov2,3, Cobus van der Merwe1, Hendrik Krüger1, Corrie Diedericks1, Helena Krüger1, Ilya Usoskin2,3, Bernd Heber4, Rendani Nndanganeni5, Juanjo Blanco-Ávalos6, Ignacio García-Tejedor6, Konstantin Herbst4, Rogelio Caballero-Lopez7, Katlego Moloto1, Alejandro Lara7, Michael Walter8, Nigussie Mezgebe Giday9 and Rita Traversi10
J. Space Weather Space Clim. **2020**, 10, 39
https://www.swsc-journal.org/articles/swsc/pdf/2020/01/swsc200035.pdf
The near-Earth cosmic ray flux has been monitored for more than 70 years by a network of ground-based neutron monitors (NMs). With the ever-increasing importance of quantifying the radiation risk and effects of cosmic rays for, e.g., air and space-travel, it is essential to continue operating the existing NM stations, while expanding this crucial network. In this paper, we discuss a smaller and cost-effective version of the traditional NM, the mini-NM. These monitors can be deployed with ease, even to extremely remote locations, where they operate in a semi-autonomous fashion. We believe that the mini-NM, therefore, offers the opportunity to increase the sensitivity and expand the coverage of the existing NM network, making this network more suitable to near-real-time monitoring for space weather applications. In this paper, we present the technical details of the mini-NM's design and operation, and present a summary of the initial tests and science results.

On the Shape of SEP Electron Spectra: The Role of Interplanetary Transport

R. D. **Strauss**1, N. Dresing2, A. Kollhoff2, and M. Brüdern2
2020 ApJ 897 24
sci-hub.tw/10.3847/1538-4357/ab91b0
We address the effect of particle scattering on the energy spectra of solar energetic electron events using (i) an observational and (ii) a modeling approach. (i) We statistically study observations of the STEREO spacecraft, using directional electron measurements made with the Solar Electron and Proton Telescope in the range of 45–425 keV. We compare the energy spectra of the anti-Sunward propagating beam with that of the backward-scattered population and find that, on average, the backward-scattered population shows a harder spectrum with the effect being stronger at higher energies. (ii) We use a numerical solar energetic particle (SEP) transport model to simulate the effect of particle scattering (both in terms of pitch angle and perpendicular to the mean field) on the spectrum. We find that pitch-angle scattering can lead to spectral changes at higher energies (E > 100 keV) and further away from the Sun (r > 1 au), which are also often observed. At lower energies, and closer to the Sun, the effect of pitch-angle scattering is much more reduced, so that the simulated energy spectra still resemble the injected power-law functions. When examining pitch-angle-dependent spectra, we find, in agreement with the observational results, that the spectra of the backward-propagating electrons are harder than that of the forward (from the Sun) propagating population. We conclude that Solar Orbiter and Parker Solar Probe will be able to observe the unmodulated omnidirectional SEP electron spectrum close to the Sun at higher energies, giving a direct indication of the accelerated spectrum. **2011 July 26**

Solar Energetic Particle Propagation in Wave Turbulence and the Possibility of Wave Generation

R. D. **Strauss**1,2 and J. A. le Roux3
2019 ApJ 872 125
sci-hub.tw/10.3847/1538-4357/aafe02
A complete theory for the complex interaction between solar energetic particles (SEPs) and the turbulent interplanetary magnetic field remains elusive. In this work we aim to contribute to such a theory by modeling the propagation of SEP electrons in plasma wave turbulence. We specify a background turbulence spectrum, as constrained through observations, calculate the transport coefficients from first principles, and simulate the propagation of these electrons in the inner heliosphere. We have also, for the first time, included dynamical effects into the perpendicular diffusion coefficient. We show that such a "physics-first" approach can lead to reasonable results, when compared qualitatively to observations. In addition, we include the effect of wave growth/damping due to streaming electrons and show that these particles can significantly alter the turbulence levels close to the Sun for the largest events.

On the Pulse Shape of Ground Level Enhancements

R.D. **Strauss**, O. Ogunjobi, H. Moraal, K.G. McCracken, R.A. Caballero-Lopez
Solar Phys. 292:51 **2017**
https://arxiv.org/pdf/1703.05906.pdf
http://link.springer.com/content/pdf/10.1007%2Fs11207-017-1086-3.pdf
We study the temporal intensity profile, or pulse shape, of cosmic ray ground level enhancements (GLEs) by calculating the rise (τr) and decay (τd) times for a small subset of all available events. Although these quantities show very large inter-event variability, a linear dependence of τd≈3.5τr is found. We interpret these observational findings in terms of an interplanetary transport model, thereby including the effects of scattering (in pitch-angle) as these particles propagate from (near) the Sun to Earth. It is shown that such a model can account for the observed

trends in the pulse shape, illustrating that interplanetary transport must be taken into account when studying GLE events, especially their temporal profiles. Furthermore, depending on the model parameters, the pulse shape of GLEs may be determined entirely by interplanetary scattering, obscuring all information regarding the initial acceleration process, and hence making a classification between impulsive and gradual events, as is traditionally done, superfluous.

Table 1. A summary of the GLE events selected for this study.

Perpendicular Diffusion of Solar Energetic Particles: Model Results and Implications for Electrons

R. Du Toit **Strauss**1,2, Nina Dresing3, and N. Eugene Engelbrecht1

2017 ApJ 837 43

The processes responsible for the effective longitudinal transport of solar energetic particles (SEPs) are still not completely understood. We address this issue by simulating SEP electron propagation using a spatially 2D transport model that includes perpendicular diffusion. By implementing, as far as possible, the most reasonable estimates of the transport (diffusion) coefficients, we compare our results, in a qualitative manner, to recent observations at energies of 55–105 keV, focusing on the longitudinal distribution of the peak intensity, the maximum anisotropy, and the onset time. By using transport coefficients that are derived from first principles, we limit the number of free parameters in the model to (i) the probability of SEPs following diffusing magnetic field lines, quantified by , and (ii) the broadness of the Gaussian injection function. It is found that the model solutions are extremely sensitive to the magnitude of the perpendicular diffusion coefficient and relatively insensitive to the form of the injection function as long as a reasonable value of a = 0.2 is used. We illustrate the effects of perpendicular diffusion on the model solutions and discuss the viability of this process as a dominant mechanism by which SEPs are transported in longitude. Lastly, we try to quantity the effectiveness of perpendicular diffusion as an interplay between the magnitude of the relevant diffusion coefficient and the SEP intensity gradient driving the diffusion process. It follows that perpendicular diffusion is extremely effective early in an SEP event when large intensity gradients are present, while the effectiveness quickly decreases with time thereafter.

On Aspects Pertaining to the Perpendicular Diffusion of Solar Energetic Particles

R. D. **Strauss**1,2 and H. Fichtner

2015 ApJ 801 29

https://arxiv.org/pdf/1804.03689.pdf

The multitude of recent multi-point spacecraft observations of solar energetic particle (SEP) events has made it possible to study the longitudinal distribution of SEPs in great detail. SEPs, even those accelerated during impulsive events, show a much wider than expected longitudinal extent, bringing into question the processes responsible for their transport perpendicular to the local magnetic field. In this paper, we examine some aspects of perpendicular transport by including perpendicular diffusion in a numerical SEP transport model that simulates the propagation of impulsively accelerated SEP electrons in the ecliptic plane. We find that (1) the pitch-angle dependence of the perpendicular diffusion coefficient is an important, and currently mainly overlooked, transport parameter. (2) SEP intensities are generally asymmetric in longitude, being enhanced toward the west of the optimal magnetic connection to the acceleration region. (3) The maximum SEP intensity may also be shifted (parameter dependently) away from the longitude of best magnetic connectivity at 1 AU. We also calculate the maximum intensity, the time of maximum intensity, the onset time, and the maximum anisotropy as a function of longitude at Earth's orbit and compare the results, in a qualitative fashion, to recent spacecraft observations.

Modeling ground and space based cosmic ray observations

R.D. **Strauss** ⇑, M.S. Potgieter, S.E.S. Ferreira

Advances in Space Research 49 (**2012**) 392–407 **Review**

After entering our local astrosphere (called the heliosphere), galactic cosmic rays, as charged particles, are affected by the Sun’s turbulent magnetic field. This causes their intensities to decrease towards the inner heliosphere, a process referred to as modulation. Over the years, cosmic ray modulation has been studied extensively at Earth, utilizing both ground and space based observations. Moreover, modelling cosmic ray modulation and comparing results with observations, insight can be gained into the transport of these particles, as well as offering explanations for observed features. We review some of the most prominent cosmic ray observations made near Earth, how these observations can be modelled and what main insights are gained from this modelling approach. Furthermore, a discussion on drifts, as one of the main modulation processes, are given as well as how drift effects manifest in near Earth observations. We conclude by discussing the contemporary challenges, fuelled by observations, which are presently being investigated. A main challenge is explaining observations made during the past unusual solar minimum.

Criteria for Forecasting Proton Events by Real-Time Solar Observations

Struminsky, AB ; Sadovskii, AM ; Grigorieva, IY

Geomagnetism and Aeronomy, **2024**, Vol. 64, No. 2, pp. 139–149. 2024 **File**
The sequence for overcoming the threshold values of a number of physical characteristics for proton event forecasting in real time is discussed. Each characteristic adds a new physical meaning that refines the forecast. To take into account all the characteristics, the following continuous patrol observations are necessary: (1) the magnetic field of the active region (ascent of the flux) and the total magnetic field of the Sun, which can predict the onset of flare activity several days prior to main events; (2) soft X-ray radiation in two channels to calculate the temperature (T) and emission measure of plasma, which can show preheating to T > 10 MK required to begin proton acceleration (the first few minutes before the start of hard X-ray (HXR) radiation with energies >100 keV); (3) HXR radiation >100 keV or microwave radiation (>3 GHz), which indicates the intensity and duration of operation of the electron accelerator (a few to tens of minutes before the arrival of protons with energies >100 MeV); (4) radio emission at plasma frequencies (<1000 MHz), showing the development of the flare process upward into the corona and leading to a coronal mass ejection (CME) several minutes before the onset of type II and IV radio bursts (the first tens of minutes before the appearance of a CME in the field of view of the coronagraph); (5) the direction and velocity of CME propagation, which determine the conditions to release accelerated protons into the heliosphere. These stages of solar proton flares are illustrated by observations of proton events on **August 2–9, 2011**. To quantitatively predict the onset time, maximum and magnitude of the proton flux, as well as its fluence, it is necessary to create statistical regression models based on all of the listed characteristics of past solar proton events.

Sources of Solar Protons in the Events of February 24-25 and July 16-17, 2023

Struminsky, AB ; Sadovskii, AM ; Grigorieva, IY
Cosmic Research Volume 62 Issue 2 Page 133-146 **2024 File**
DOI 10.1134/S0010952523600300
From the beginning of January 2021 to the end of August 2023, the radiation monitor of the Spektr-RG spacecraft registered three enhancements in the count rate, which exceed the background variations during the solar activity cycle and have a comparable maximum value. These enhancements are associated with solar proton events (SPEs) from the flares X1.0 on October 28, 2021; M6.3 on February 25, 2023; and M5.7 on July 17, 2023. Using the example of these events, as well as smaller SPEs from the flares M3.7 on **February 24, 2023**, and M4.0 on **July 16, 2023**, threshold criteria for "proton" flares are discussed. In powerful SPEs, the contribution of solar protons to the radiation dose can exceed the total contribution of galactic cosmic rays (GCR) over a sufficiently long period of time. Therefore, such SPEs are sources of increased radiation hazard and require prediction based on real-time observations. It was shown that, in these five flares, thresholds were overcome according to three criteria: plasma temperature >12 MK (soft X-ray source), duration (>5 min) of microwave or hard X-ray (HXR) radiation (electron acceleration >100 keV), and height of flare development process >60 Mm (radio emission at plasma frequencies <610 MHz). The arrival of the first solar protons >100 MeV to the Earth's orbit was expected no earlier than 10 min relative to the beginning of HXR or microwave radiation, i.e., could have been predicted in advance. To study the relationship between solar flares and SPEs, we used data from the anticoincidence shield of the spectrometer on INTEGRAL (ACS SPI), which is an effective but uncalibrated detector of HXR >100 keV and protons >100 MeV, as well as patrol observations of radio emission at fixed frequencies (Radio Solar Telescope Network). It is noted that the X2.2 (N25E64) flare on **February 17, 2023** satisfied all three "protonity" criteria and could become the source of a powerful SPE near the Earth in a case of favorable location on the Sun. In the M8.6 (N27W29) flare on **February 28, 2023**, the third criterion was not met, and it did not lead to an SPE as expected (it developed in a plasma with a density >2.5 x 10(10) cm(-3) and plasma frequency >1415 MHz).

Solar Electrons and Protons in the Events of September 4–10, 2017 and Related Phenomena

A. B. **Struminskii**, I. Yu. Grigor'eva, Yu. I. Logachev & A. M. Sadovskii
Plasma Physics Reports volume 46, pages174–188(**2020**)
sci-hub.si/10.1134/S1063780X20020130
https://link.springer.com/content/pdf/10.1134/S1063780X20020130.pdf
Russian Text © The Author(s), 2020, published in Fizika Plazmy, **2020**, Vol. 46, No. 2, pp. 139–153.
The solar proton events on **September 4–10, 2017** motivated us to reconsider the hypothesis of the presence of two phases of acceleration of charged particles in solar flares in which nonrelativistic electrons are accelerated in the first phase, while relativistic electrons and protons are accelerated during the second phase. According to the data of SOHO/EPHIN (relativistic electrons) and ACS SPI (hard X-rays and protons with energy of >100 MeV), the populations of electrons and protons accelerated at the first and second phases of a flare could be separated in these events near the Earth. The data of observations are indicative of the realization of a stochastic mechanism of acceleration in flares according to which protons and electrons gain energy in many elementary acts, whose duration is much shorter than that of the flare itself. To reconcile the stochastic acceleration process with the existence of two phases in solar flares, it is necessary taking into account the gyrosynchrotron radiation losses of electrons that can be neglected at the first phase. The energy of accelerated protons at the first phase is too low for their detection in the Sun. However, in the second phase, it can reach levels sufficient for detection of nuclear and pion decay gamma

lines. In this case, the role of coronal mass ejection consists in (1) involvement of an increasingly larger number of loops in the flare process at altitudes ranging from the chromosphere to the corona; (2) return of the accelerated particles into the flare region; (3) additional acceleration of particles at the shock front; (4) creation of conditions for escaping of particles into the interplanetary space in a wide spatial angle.

"SOL2017-09-04 (M5.5) 2017 as a Source of Relativistic Electrons and Protons,"

Alexei **Struminsky**:
RHESSI Nuggets #373 March **2020**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/SOL2017-09-04_(M5.5)_2017_as_a_Source_of_Relativistic_Electrons_and_Protons
Flare-accelerated particles, rather than SEPs, energize sustained gamma-ray emission.
The observational data do not contradict the scenario of stochastic acceleration in which protons and electrons simultaneously gain energy in elementary actions, whose duration is much shorter than the duration of the flare itself.
The proposed scenario combines two, at first sight irreconcilable, approaches, namely, acceleration both in the flares and in the CME shock waves as well.
The acceleration rate at the flare site should be greater than that at the shock front. Flare-accelerated protons, rather than shock-accelerated SEPS (Ref. [4]) would produce the sustained γ-ray -emission.

Gamma-Ray Solar Flares and In Situ Particle Acceleration

Alexei **Struminsky**
Proceedings IAU Symposium No. 335, 2017 C. Foullon & O.E. Malandraki, eds.
Volume 13, Symposium #335 (Space Weather of the Heliosphere: Processes and Forecasts)
July 2017 , pp. 43-48,   **2018**
DOI: https://doi.org/10.1017/S1743921317008067
https://www.cambridge.org/core/services/aop-cambridge-core/content/view/0EE03E87AABB0AA197D8D9E0BF23CC4D/S1743921317008067a.pdf/gammaray_solar_flares_and_in_situ_particle_acceleration.pdf
At present two concurrent paradigms of solar energetic particle (SEP) origin exist: acceleration directly in the flare site or by the shock wave of coronal mass ejection (CME). Active discussions on a relative role of flares and coronal mass ejections for SEP acceleration and propagation are continuous until now. In my opinion only future observations of solar high energy γ–emission with better spectral, spatial and temporal resolution may clarify this issue. In my report I discuss possible signatures of the flare and shock acceleration processes. What is a picture provided by the current instruments? What can we expect to observe with a perfect instrument in high energy gamma rays in one or another case on a time scale of impulsive and long decay flare phases?

Observation of solar high energy gamma and X-ray emission and solar energetic particles

Alexei **Struminsky**, Weiqun Gan
24th European Cosmic Ray Symposium, Kiel, September 2014,   **2015**
We considered 18 solar flares observed between June 2010 and July 2012, in which high energy >100 MeV {\gamma}-emission was registered by the Large Area Telescope (LAT) aboard FermiGRO. We examined for these {\gamma}-events soft X-ray observations by GOES, hard X-ray observations by the Anti-Coincidence Shield of the SPectrometer aboard INTEGRAL (ACS SPI) and the Gamma-Ray burst Monitor (GBM) aboard FermiGRO. Hard X-ray and {\pi}0-decay {\gamma}-ray emissions are used as tracers of electron and proton acceleration, respectively. Bursts of hard X-ray were observed by ACS SPI during impulsive phase of 13 events. Bursts of hard X-ray >100 keV were not found during time intervals, when prolonged hard {\gamma}-emission was registered by LAT/FermiGRO. Those events showing prolonged high-energy gamma-ray emission not accompanied by >100 keV hard X-ray emission are interpreted as an indication of either different acceleration processes for protons and electrons or as the presence of a proton population accelerated during the impulsive phase of the flare and subsequently trapped by some magnetic structure. In-situ energetic particle measurements by GOES and STEREO (High Energy Telescope, HET) shows that five of these {\gamma}-events were not accompanied by SEP events at 1 AU, even when multi-point measurements including STEREO are taken into account. Therefore accelerated protons are not always released into the heliosphere. A longer delay between the maximum temperature and the maximum emission measure characterises flares with prolonged high energy {\gamma}-emission and solar proton events.
Table 1. The Fermi LAT high energy γ-events [7] and solar HXR bursts
Table 2. Solar proton events (http://umbra.nascom.nasa.gov/SEP/) and their parent X-ray event.

2010Jun12 2011Mar7 2011Jun2 2011Jun7 2011Aug4 **2011Aug9** **2011Sep6** 2011Sep7
2011Sep24 2012Jan23 2012Jan27 2012Mar5 2012Mar7 2012Mar9 2012Mar10 2012May17

2012Jun3 2012Jul6

Large SEP events of 2012: proton onset and source function

Alexei **Struminsky**

2013 J. Phys.: Conf. Ser. 409 012148

http://iopscience.iop.org/1742-6596/409/1/012148/pdf/1742-6596_409_1_012148.pdf

Studying the solar proton events of **2012 on January 27 and May 17** we apply methods elaborated previously. The results are compared with those obtained for the events of **2006 December 13 and 14**. The onset of microwave emission at 15.4 GHz has been chosen as a zero time moment for each parent solar flare. Emission measure of flare plasma started its exponential increase at zero time. The onsets of 100 MeV solar protons in these four events have been registered by the GOES detector after 30-35 min after to the zero time. Temporal profiles of ~100 MeV proton intensities can be fitted by the diffusion propagation model with mean free path of ~0.1 a.u. and prolonged source functions with several episodes of different injection rate into the heliosphere. These methods are not applicable for poor connected SEP events as the event on March 7, 2012.

Energetic particles in the heliosphere and GCR modulation: Reviewing of SH-posters

Alexei **Struminsky**

2013 J. Phys.: Conf. Ser. 409 012018

This rapporteur paper addresses the SH poster session titled "Energetic particles in the heliosphere (solar and anomalous CRs, GCR modulation)" of the 23rd European Cosmic Ray Symposium (ECRS) and the 32nd Russian Cosmic Ray Conference (RCRC). The 65 posters presented are tentatively divided into five sections: Instruments and Methods; Solar Energetic Particles; Short Term Variations; Long Term Variations; Heliosphere.

Prolonged Release of 100 MeV Solar Protons in the GLE Events of 1997-2002

Struminsky, Alexei

Proceedings of the 28th ICRC July 31-August 7, 2003. Tsukuba, Japan. Editors: T. Kajita, Y. Asaoka, A. Kawachi, Y. Matsubara and M. Sasaki, p. 3317–3320, **2003**

http://www-rccn.icrr.u-tokyo.ac.jp/icrc2003/PROCEEDINGS/PDF/817.pdf

The solar proton events of 1991 June 11 and 15 provide evidence that > 100 MeV protons interacting in the solar atmosphere and escaping into the interplanetary space are from the same population. Events of 1997-2002 accompanied by ground level enhancements are considered. The model of diffusion propagation assuming prolonged and multiple release of solar protons fits quite well proton intensity measured within 84-200 MeV energy band. The number of protons in the solar source is estimated for different time moments by using the propagation model. The obtained numbers of interacting protons suggest that the relevant instrument should observe prolonged γ -emission with a significant contribution from π 0 -decay in many of the considered events. Apparently a notation of local radiation belts of the Sun should be intro duced. **06.11.1997, 02.05.1998, 06.05.1998, 24.08.1998, 14.07.2000, 08.11.2000, 15.04.2001, 18.04.2001, 04.11.2001, 26.12.2001, 24.08.2002**

Table 1. Possible source functions for 84–200 MeV protons:

Predicting the energetic proton flux with a machine learning regression algorithm
Mirko **Stumpo**, Monica Laurenza, Simone Benella, Maria Federica Marcucci
ApJ **975** 8 **2024**
https://arxiv.org/pdf/2406.12730
https://iopscience.iop.org/article/10.3847/1538-4357/ad7734/pdf
The need of real-time of monitoring and alerting systems for Space Weather hazards has grown significantly in the last two decades. One of the most important challenge for space mission operations and planning is the prediction of solar proton events (SPEs). In this context, artificial intelligence and machine learning techniques have opened a new frontier, providing a new paradigm for statistical forecasting algorithms. The great majority of these models aim to predict the occurrence of a SPE, i.e., they are based on the classification approach. In this work we present a simple and efficient machine learning regression algorithm which is able to forecast the energetic proton flux up to 1 hour ahead by exploiting features derived from the electron flux only. This approach could be helpful to improve monitoring systems of the radiation risk in both deep space and near-Earth environments. The model is very relevant for mission operations and planning, especially when flare characteristics and source location are not available in real time, as at Mars distance. **October 25, 2000**
Table

Open issues in statistical forecasting of solar proton events: a Machine Learning perspective
Mirko **Stumpo**, Simone Benella, Monica Laurenza, Tommaso Alberti, Giuseppe Consolini, Maria Federica Marcucci
Space Weather **Volume19, Issue10** e2021SW002794 **2021**
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002794
https://doi.org/10.1029/2021SW002794
Several techniques have been developed in the last two decades to forecast the occurrence of Solar Proton Events (SPEs), mainly based on the statistical association between the >10 MeV proton flux and precursor parameters. The Empirical model for Solar Proton Events Real Time Alert (ESPERTA; Laurenza et al., 2009) provides a quite good and timely prediction of SPEs after the occurrence of $\geq$M2 soft x-ray (SXR) bursts, by using as input parameters the flare heliolongitude, the SXR and the ~1 MHz radio fluence. Here, we reinterpret the ESPERTA model in the framework of machine learning and perform a cross validation, leading to a comparable performance. Moreover, we find that, by applying a cut-off on the ≥M2 flares heliolongitude, the False Alarm Rate (FAR) is reduced. The cut-off is set to E20° where the cumulative distribution of ≥M2 flares associated with SPEs shows a break which reflects the poor magnetic connection between the Earth and eastern hemisphere flares. The best performance is obtained by using the SMOTE algorithm, leading to probability of detection of 0.83 and a FAR of 0.39. Nevertheless, we demonstrate that a relevant FAR on the predictions is a natural consequence of the sample base rates. From a Bayesian point of view, we find that the FAR explicitly contains the prior knowledge about the class distributions. This is a critical issue of any statistical approach, which requires to perform the model validation by preserving the class distributions within the training and test datasets.
Table SPE flare list (1995-2017)

Specification of > 2 MeV electron flux as a function of local time and geomagnetic activity at geosynchronous orbit
Yi-Jiun **Su***, Jack M. Quinn, W. Robert
Johnston, James P. McCollough andMichael J. Starks
Space Weather, **2014**
An algorithm has been developed for specifying > 2 MeV electron flux everywhere along geosynchronous orbit for use in operational products. The statistics of integrated electron fluxes from four GOESs for more than a solar cycle clearly indicate that the local time variation can be represented by a Gaussian distribution as a function of geomagnetic Kp index, which empirically determines the center and the half width of the Gaussian distribution. Using the most current estimated 3 h Kp value as an input, the prediction scheme requires the most recent electron flux measurements from available GOES(s) to determine the maximum and minimum for a Gaussian fit and to provide estimated electron fluxes at geosynchronous orbit with the time resolution of the instrument. In balancing between sufficient data for statistics and the change of geomagnetic configuration, the optimal length of data accumulation time for nowcasting is 6 h when one or two satellites are available. The prediction efficiency (PE) is independent of local time and solar cycle. We found that the PE values are greater than 0.5 when Kp < 5 and independent of Kp at low and moderate values; however, PE decreases dramatically with increasing Kp when Kp ≥ 5. Although the PE varies from year to year and with the choice of the test satellite, our finding resulted in a PE > 0.6 in 67.6% of the cases and PE > 0.8 more than 23.5% of the time based on our analysis from four GOESs between 1998 and 2009. Moreover, skill scores from our newly developed algorithm are ~90% of the time better

than those resulting from a simpler algorithm based on a table provided by O'Brien (2009), indicating a dramatic improvement in predictive capability.

Forbush decreases and turbulence levels at CME fronts

Prasad **Subramanian**, H. M. Antia, S. R. Dugad, U. D. Goswami, S. K. Gupta, Y. Hayashi, N. Ito, S. Kawakami, H. Kojima, P. K. Mohanty, P. K. Nayak, T. Nonaka, A. Oshima, K. Sivaprasad, H. Tanaka, S. C. Tonwar

E-print, Oct 2008; A&A 494, 1107–1118 (**2009**); **File**

http://solar.physics.montana.edu/cgi-bin/eprint/index.pl?entry=8571

We seek to estimate the average level of MHD turbulence near coronal mass ejection (CME) fronts as they propagate from the Sun to the Earth. We examine the cosmic ray data from the GRAPES-3 tracking muon telescope at Ooty, together with the data from other sources for three well observed Forbush decrease events. Each of these events are associated with frontside halo Coronal Mass Ejections (CMEs) and near-Earth magnetic clouds. In each case, we estimate the magnitude of the Forbush decrease using a simple model for the diffusion of high energy protons through the largely closed field lines enclosing the CME as it expands and propagates from the Sun to the Earth. We use estimates of the cross-field diffusion coefficient D_{perp} derived from published results of extensive Monte Carlo simulations of cosmic rays propagating through turbulent magnetic fields. Our method helps constrain the ratio of energy density in the turbulent magnetic fields to that in the mean magnetic fields near the CME fronts. This ratio is found to be sim 2% for the **11 April 2001** Forbush decrease event, sim 6% for **the 20 November 2003** Forbush decrease event and sim 249% for the much more energetic event of **29 October 2003**.

Magnetic Configuration of Active Regions Associated with GLE Events

Regina A. **Suleymanova**, Leonty I. Miroshnichenko, Valentina I. Abramenko

Solar Phys. Volume 299, article number 7, (**2024**)

https://doi.org/10.1007/s11207-023-02248-w

https://arxiv.org/pdf/2404.06877.pdf

Charged particles, generated in solar flares, sometimes can attain extremely high energy, above the 500-MeV level, and produce abrupt ground-level enhancements (GLEs) on the ground-based detectors of cosmic rays. The initial flares are strong eruptions and they could originate from active regions (ARs). A list of GLE events and associated flares was initially available, and our aim was to find the hosting AR for each GLE event. Moreover, we aimed to classify the revealed ARs using the magnetomorphological classification (MMC: Abramenko, 2021). We have shown that in 94% of cases such ARs belong to the most complex morphological classes, namely, ��, ��, ��, ��� classes by the Hale classification and B2, B3 classes by the MMC. We also found that the GLE-associated ARs are the ARs with the total unsigned magnetic flux much stronger than the common ARs of the same complexity. The set of GLE-related ARs only partially overlaps with the set of SARs (superactive regions). These ARs seem to be a manifestation of nonlinearities in the regular process of the global mean-field dynamo, the key ingredient to maintain fluctuations and to create critical conditions in different aspects of the solar activity.

BIDIRECTIONAL FLUXES OF NEARLY RELATIVISTIC ELECTRONS DURING THE ONSET OF SOLAR ENERGETIC PARTICLE EVENTS

L. P. **Sun**1 and C. Li

E-print, May **2013**; **2013** ApJ 765 99

We report intensity and anisotropy measurements of energetic electrons in the energy range of ~27-~500 keV as observed with the Wind and Advanced Composition Explorer (ACE) spacecraft in 2000 June for several solar energetic particle (SEP) events. The solar sources of the SEP events are inferred from observations from the Solar and Heliospheric Observatory spacecraft. All of the events originate from the western limb active regions (ARs), which are well connected by interplanetary magnetic field (IMF) lines linking the Sun to near-Earth space. The observations on board Wind show bimodal pitch angle distributions (PADs), whereas ACE shows PADs with one peak, as is usually observed for impulsive injection of electrons at the Sun. During the time of observations, Wind was located, upstream of the Earth's bow shock in the dawn-noon sector, at distances of ~40-~80 RE from the Earth, and we infer that it was magnetically connected to the quasi-parallel bow shock. Meanwhile, ACE, orbiting the Sun-Earth libration point L1, was not connected to the bow shock. The electron intensity-time profiles and the energy spectra show that the backstreaming electrons observed at Wind are not of magnetospheric origin. The observations suggest rather that the bidirectional electron fluxes are due to reflection or scattering by an obstacle located at a distance of less than ~150 RE in the anti-sunward direction, which is compatible with the obstacle being the Earth's bow shock or magnetosheath.

Particle acceleration in the process of eruptive opening and reconnection of magnetic fields
Svestka, Z., Martin, S.F., & Kopp, R.A.
1980, in: Solar and Interplanetary Dynamics, ed. M. Dryer & E. Tandberg-Hanssen (Dordrecht : Reidel), 217 **File**
In: Solar and interplanetary dynamics; Proceedings of the Symposium, Cambridge, Mass., August 27-31, 1979. (A81-27626 11-92) Dordrecht, D. Reidel Publishing Co., 1980, p. 217-221.
Noted that nearly all large SEP events were well associated with two-ribbon Ha flares, which are part of the **magnetically reconnecting loop arcades**, envisioned energetic particles escaping upward, perhaps to be further accelerated in the CME-driven shock.

Type II radio bursts and particle acceleration
Z. **Švestka** & L. F Svestka, Martin, & Kopp (1980), noting that nearly all large SEP events were well associated with two-ribbon Ha Ñares, which are part of the magnetically reconnecting loop arcades, envisioned energetic particles escaping upward, perhaps to be further accelerated in the CME-driven shock.ritzová-Švestková
Solar Physics volume 36, pages 417–431(**1974**)
https://link.springer.com/content/pdf/10.1007/BF00151211.pdf
328 particle events recorded during 30 months from January 1, 1966 to June 30, 1968 (taken from the new Catalog of Solar Particle Events, 1955–1969) are compared with the occurrence of 166 type II radio bursts during the same period. The results of this comparison give a convincing evidence that proton acceleration to higher energies in flares (the 'second acceleration step') is closely connected with the type II burst occurrence. The shock wave appears to originate near the time when the impulsive burst occurs, and the second acceleration step follows immediately the first one; in some cases the second step sets in while the first step is still in progress.
A detailed analysis indicates that we may need even three different acceleration mechanisms in flares: The first one gives rise to electrons which produce the microwave and hard X-ray bursts (and it probably also accelerates protons to low energies); the second, which sometimes coincides (but mostly does not coincide) with the first one, produces beams of electrons which give rise to type III bursts; and the third one, characterized by the type II burst-producing shock wave, accelerates (on some, rather rare occasions) the particles, preaccelerated by the first mechanism, to higher energies.

Solar Energetic Particle Forecasting Algorithms and Associated False Alarms
Bill **Swalwell**, Silvia Dalla, Robert Walsh
Solar Phys. 292:173 **2017** **File**
https://arxiv.org/pdf/1710.08156.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1196-y.pdf
Solar energetic particle (SEP) events are known to occur following solar flares and coronal mass ejections (CMEs). However some high-energy solar events do not result in SEPs being detected at Earth, and it is these types of event which may be termed "false alarms".
We define two simple SEP forecasting algorithms based upon the occurrence of a magnetically well-connected CME with a speed in excess of 1500 km/s ("a fast CME") or a well-connected X-class flare and analyse them with respect to historical data sets. We compare the parameters of those solar events which produced an enhancement of >40 MeV protons at Earth ("an SEP event") and the false alarms. We find that an SEP forecasting algorithm based solely upon the occurrence of a well-connected fast CME produces fewer false alarms (28.8%) than one based solely upon a well-connected X-class flare (50.6%). Both algorithms fail to forecast a relatively high percentage of SEP events (53.2% and 50.6% respectively). Our analysis of the historical data sets shows that false alarm X-class flares were either not associated with any CME, or were associated with a CME slower than 500 km/s; false alarm fast CMEs tended to be associated with flares of class less than M3.
A better approach to forecasting would be an algorithm which takes as its base the occurrence of both CMEs and flares. We define a new forecasting algorithm which uses a combination of CME and flare parameters and show that the false alarm ratio is similar to that for the algorithm based upon fast CMEs (29.6%), but the percentage of SEP events not forecast is reduced to 32.4%. Lists of the solar events which gave rise to >40 MeV protons and the false alarms have been derived and are made available to aid further study.
Table 5. List of fast CMEs between 1 January 1996 and 31 March 2013 which were false alarms.
Table 6. List of X-class flares between 1 January 1996 and 31 March 2013 which were false alarms. C
Table 7. List of X-class flares between 1 April 1980 and 31 December 1995 which were false alarms

Scaling Relations in Coronal Mass Ejections and Energetic Proton Events associated with Solar Superflares

Takuya **Takahashi**, Yoshiyuki Mizuno, Kazunari Shibata

ApJL **833** L8 **2016**

https://arxiv.org/pdf/1611.06015v1.pdf

https://iopscience.iop.org/article/10.3847/2041-8205/833/1/L8/pdf

In order to discuss the potential impact of solar 'superflares' on space weather, we investigated statistical relations among energetic proton peak flux with energy higher than 10MeV (Fp), CME speed near the Sun (VCME) obtained by {\it SOHO}/LASCO coronagraph and flare soft X-ray peak flux in 1-8\AA band (FSXR) during 110 major solar proton events (SPEs) recorded from 1996 to 2014. The linear regression fit results in the scaling relations VCME∝F^{α}SXR, Fp∝F^{β}SXR and Fp∝V^{γ}CME with α=0.30±0.04, β=1.19±0.08 and γ=4.35±0.50, respectively. On the basis of simple physical assumptions, on the other hand, we derive scaling relations expressing CME mass (MCME), CME speed and energetic proton flux in terms of total flare energy (Eflare) as, MCME∝E2/3 flare, VCME∝E1/6 flare and Fp∝E5/6flare ∝ V5CME, respectively. We then combine the derived scaling relations with observation, and estimated the upper limit of VCME and Fp to be associated with possible solar superflares.

See Major SEP Events http://cdaw.gsfc.nasa.gov/CME_list/sepe/

The Instantaneous Response of the Geomagnetic Field, Near-Earth IMF, and Cosmic-Ray Intensity to Solar Flares.

Takalo, J.

Sol Phys 299, 16 (**2024**).

https://doi.org/10.1007/s11207-024-02257-3

https://link.springer.com/content/pdf/10.1007/s11207-024-02257-3.pdf

We show using superposed epoch analysis (SEA) that the most energetic protons (>60 MeV) in the near-Earth interplanetary magnetic field (IMF) have a peak almost immediately (less than a day) after the peak in solar-flare index (SFI), while protons greater than 10 MeV peak one day after the SFI and protons greater than 1 MeV peak two days after the SFI.

The geomagnetic indices AU, -AL, PC, Ap, and -Dst peak after two to three days in SEAs after the peak in SFI. The auroral electrojet indices AU and -AL, however, have only low peaks. In particular, the response of the eastward electrojet, AU, to SFI is negligible compared to other geomagnetic indices.

The SEAs of the SFI and cosmic-ray counts (CR) show that the deepest decline in the CR intensity also follows with a 2 – 3-day lag the maximum of the SFI for Solar Cycles 20 – 24. The depths of the declines are related to the SFI strength of each cycle, i.e., the average decline is about 5% for Cycles 21 and 22, but only 3% for Cycle 24. The strongest Cycle 19, however, differs from the other cycles such that it has a double-peaked decline and lasts longer than the decline of the other cycles.

The double-superposed epoch analyses show that the response of IMF Bv2, which is about two days, and CR to SFI are quite simultaneous, but sometimes Bv2 may peak somewhat earlier than the decline existing in CR.

Ne/O and Fe/O Characteristics of Large Solar Energetic Particle Events during Solar Cycles 23 and 24

Lun C. **Tan**1,2 and Olga E. Malandraki3

2021 ApJ 920 136

https://iopscience.iop.org/article/10.3847/1538-4357/ac1587/pdf

https://doi.org/10.3847/1538-4357/ac1587

We have examined the Ne/O and Fe/O characteristics of large solar energetic particle (SEP) events at the ion energy range of 3–40 MeV nucleon−1 during solar cycles 23 and 24. In each cycle, the solar activity displays an ∼3 yr rising phase and a longer declining phase. While Fe-poor events only appeared in the declining phase of cycle 23, the properties of Fe-rich events were similar in the rising phases of both cycles. Also, very few Fe-rich events were seen in the declining phase of cycle 24. In addition, the Ne/O data in the corona, solar wind, and SEP events consistently reveal that the characteristics of SEP events are mainly governed by the solar wind turbulence status that exhibits a significant difference between slow and fast streams. During the rising phase of the solar cycles, slow streams are dominated by the two-dimensional turbulence component, which significantly reduces the injection energy of the quasi-perpendicular (Q-Perp) shock acceleration. Also, slow streams have an increased Ne/O ratio and hence enhanced temperature of coronal suprathermals, favoring the occurrence of Fe-rich events. In contrast, in the declining phase of the solar cycles, the fast streams are dominated by the slab turbulence component, which could significantly increase the injection energy of the Q-Perp shock acceleration. Consequently, in fast streams, most Fe-rich events originate from jet suprathermals. The coronal suprathermals may produce the Fe-poor events having abnormally low Ne/O ratios provided the speed of the associated coronal mass ejection is large enough.

An Alternative Interpretation of Impulsive SEP Events Occurring on 1999 January 9–10

Lun C. **Tan**1,2

2020 ApJ 901 120
https://doi.org/10.3847/1538-4357/abb086

We have examined two impulsive solar energetic particle events that occurred on 1999 January 9–10 (earlier event A and later event B). Both events showed earlier velocity dispersion and later intensity dropout of ions. In particular, in event A, the dropout repeated five times. Through the onset time analysis of solar particles, we find that only at higher energies (>0.2 MeV nucleon−1 for heavy ions and >2.8 keV for electrons) can the analysis provide a consistent path length of ions and electrons. The path length in event A is larger than that in event B. In contrast, at lower energies, the analysis fails to predict the distribution of first arrival of solar particles. The divergence between observation and prediction would increase if the interplanetary scattering of ions were taken into account. We then focus on the lower-energy region, where a negative correlation of ion intensities with plasma β is displayed. We have found that the repeated dropout of ions can be caused by the magnetic reconnection acceleration in the solar wind. In addition, we have discovered an isolated proton dropout event in which a sharply anisotropic pitch-angle distribution of low-energy electrons is also seen. Our observation is consistent with the prediction of Tautz et al. that a minimum power spectral density component parallel to the magnetic field can reduce the magnetic mirroring effect, preventing electron scattering through 90°.

Influence of Magnetic Reconnection-accelerated Electrons in Solar Wind on Onset Time Analysis of Impulsive Electron Events

Lun C. **Tan**

2019 ApJ 882 143
https://doi.org/10.3847/1538-4357/ab3580

Observations have shown that type III radio bursts (RBs) are generated by 1–10 keV flare electrons ejected from the exhaust of a magnetic reconnection site in a coronal (loop-top) source region. Surprisingly, it is generally accepted without question that the injection of low-energy electrons occurs significantly earlier than the onset of the type III RBs. Therefore, it is necessary to re-examine the timing of flare electrons. For this, we observed a "normal" event in which the injection of low-energy electrons coincided with the injection of high-energy electrons, and "abnormal" events in which the low-energy electrons seemed to arrive earlier. A high background of low-energy particles lacking any evidence of velocity dispersion characterizes an abnormal event. Due to the existence of a reconnection acceleration that results in similar enhancements at magnetic islands confined by the heliospheric current sheet (HCS), HCS observations are used to establish the empirical criteria for the reconnection acceleration in impulsive electron events. Observations show that 2–8 keV electrons accelerated by magnetic reconnection can change the pitch-angle distribution of background electrons for a time interval of approximately 0.5 hr before or after the time of current-sheet crossing. Therefore, this reconnection acceleration in the solar wind can influence the onset time analysis of electrons by emulating the effect of the earlier arrival of flare electrons. In addition, a technique is developed for estimating the phase velocity of whistler waves in the ion dissipation range, which may significantly affect the pitch-angle scattering analysis of low-energy electrons.

Characteristics of Plasma Cavities That Appeared in the Intensity Dropout Event of Solar Energetic Particles

Lun C. **Tan**

2019 ApJ 871 104

In order to explore the origin of the particle "dropout" phenomenon in the "gradual" solar energetic particle (SEP) event, we have selected 13 dropout intervals from 10 gradual SEP events during solar cycle 23. Our selection criterion is that within the dropout interval the average slab turbulence fraction is >0.8 in the ion dissipation range. In the plasma "cavity" that appeared in the dropout interval we have observed the angles of the wavenumber vector and the solar wind velocity vector relative to the mean magnetic field direction to be ~0° and ~90°, respectively. The distinctive feature of the cavity geometry could inhibit the occurrence of kinetic Alfvén waves (KAWs), leaving the dominance of magnetosonic-whistler waves in its plasma environment. Therefore, by examining the difference of turbulence characteristics between the dropout interval and the ambient solar wind, we are able to differentiate between the effects of KAWs and quasi-parallel whistler waves. Observations of the plasma β dependence of magnetic power density spectra in the ion dissipation range indicate that in the cavity of low plasma β (≤1) and low magnetic variance anisotropy (~3) the turbulence cascade of the magnetosonic-whistler wave branch has reached a sufficiently developed stage.

Electron Spectral Breaking Caused by Magnetic Reconnection in Impulsive Flare Events

Lun C. **Tan**

2018 ApJ 858 25
http://sci-hub.tw/http://iopscience.iop.org/0004-637X/858/1/25/

Using data from the Wind/3D Plasma and Energetic Particle (3DP) instrument, we have analyzed the energy spectral difference of low-energy electrons between the "impulsive" and "gradual" solar energetic particle (SEP) events during solar cycle 23. Since simulations reveal that in the exhaust of magnetic reconnection sites, electrons could form a beam structure in which the parallel speed is limited by the electron Alfvén speed (V_{Ae}), their spectral steepening should be observable at the electron energy E_e, corresponding to V_{Ae}. In addition, the analysis of transversely oscillating coronal loops shows that in the loop-top region, where the reconnection site is located, V_{Ae} corresponds to $E_e < 15$ keV. We hence search for the spectral steepening of electrons in this E_e range. In our search we have taken the effect of local particle acceleration at reconnecting current sheets into consideration. The effect may occur in the solar wind and impact the observed time-intensity profiles of SEPs. Our analysis shows that in the impulsive flare event, the electron spectral steepening occurs at $E_e = 7 \pm 2$ keV, whereas no steepening is seen in the gradual event. Therefore, the comparison between the impulsive and gradual SEP event lists provided by this work could be important for future investigations of particle acceleration in the corona and the solar wind. **1997 November 4, 2002 February 20, 2002 April 21, 2002 October 21**

Table 1 Impulsive Electron Events Examined in this Work (1997-2006)

Table 2 Gradual SEP Events Examined in this Work

Electron–Ion Intensity Dropouts in Gradual Solar Energetic Particle Events during Solar Cycle 23

Lun C. **Tan**

2017 ApJ 846 18

http://iopscience.iop.org.sci-hub.cc/0004-637X/846/1/18/

Since the field-line mixing model of Giacalone et al. suggests that ion dropouts cannot happen in the "gradual" solar energetic particle (SEP) event because of the large size of the particle source region in the event, the observational evidence of ion dropouts in the gradual SEP event should challenge the model. We have searched for the presence of ion dropouts in the gradual SEP event during solar cycle 23. From 10 SEP events the synchronized occurrence of ion and electron dropouts is identified in 12 periods. Our main observational facts, including the mean width of electron–ion dropout periods being consistent with the solar wind correlation scale, during the dropout period the dominance of the slab turbulence component and the enhanced turbulence power parallel to the mean magnetic field, and the ion gyroradius dependence of the edge steepness in dropout periods, are all in support of the solar wind turbulence origin of dropout events. Also, our observation indicates that a wide longitude distribution of SEP events could be due to the increase of slab turbulence fraction with the increased longitude distance from the flare-associated active region. **6 Nov 1997, 12 Aug 2000, 21 Apr 2002, 24 Aug 2002**

Table 1 Electron–ion Dropout Periods Identified from Large SEP Events during Solar Cycle 23

Joint Ne/O and Fe/O Analysis to Diagnose Large Solar Energetic Particle Events during Solar Cycle 23

Lun C. **Tan**[1,2], Olga E. Malandraki[2], and Xi Shao[1]

2017 ApJ 835 192

http://sci-hub.cc/doi/10.3847/1538-4357/835/2/192

We have examined 29 large solar energetic particle (SEP) events with the peak proton intensity $J_{pp}(>60 \text{ MeV}) > 1$ pfu during solar cycle 23. The emphasis of our examination is put on a joint analysis of Ne/O and Fe/O data in the energy range (3–40 MeV nucleon^{-1}) covered by Wind/Low-Energy Matrix Telescope and ACE/Solar Isotope Spectrometer sensors in order to differentiate between the Fe-poor and Fe-rich events that emerged from the coronal mass ejection driven shock acceleration process. An improved ion ratio calculation is carried out by rebinning ion intensity data into the form of equal bin widths in the logarithmic energy scale. Through the analysis we find that the variability of Ne/O and Fe/O ratios can be used to investigate the accelerating shock properties. In particular, the high-energy Ne/O ratio is well correlated with the source plasma temperature of SEPs.

Table 1

Ne/O/0.157 Values for the SEP Events with Jpp(>60 MeV) > 1 pfu during Solar Cycle 23

DROPOUT OF DIRECTIONAL ELECTRON INTENSITIES IN LARGE SOLAR ENERGETIC PARTICLE EVENTS

Lun C. **Tan**[1,2] and Donald V. Reames

2016 ApJ 816 93

In the "gradual" solar energetic particle (SEP) event during solar cycle 23 we have observed the dispersionless modulation ("dropout") in directional intensities of nonrelativistic electrons. The average duration of dropout periods is ~0.8 hr, which is consistent with the correlation scale of solar wind turbulence. During the dropout period electrons could display scatter-free transport in an intermittent way. Also, we have observed a decrease in the anisotropic index of incident electrons with increasing electron energy (Ee), while the index of scattered/reflected electrons is nearly independent of Ee. We hence perform an observational examination of the correlation between the anisotropic index of low-energy scattered/reflected electrons and the signature of the locally measured solar wind turbulence in the dissipation range, which is responsible for resonant scattering of nonrelativistic electrons. Since during the dropout period the slab turbulence fraction is dominant (0.8 ± 0.1), we pay close attention to the effect of slab fraction on the correlation examined. Our observation is consistent with the simulation result that in the dominance of the slab turbulence component there should exist a dispatched structure of magnetic flux tubes, along which electrons could be transported in a scatter-free manner. Since a similar phenomenon is exhibited in the "impulsive" SEP event, electron dropout should be a transport effect. Therefore, being different from most ion dropout events, which are due to a compact flare source, the dropout of directional electron intensities should be caused by the change of turbulence status in the solar wind.

COMPARISON BETWEEN PATH LENGTHS TRAVELED BY SOLAR ELECTRONS AND IONS IN GROUND-LEVEL ENHANCEMENT EVENTS

Lun C. **Tan**1,2, Olga E. Malandraki2, Donald V. Reames3, Chee K. Ng4, Linghua Wang5,6, Ioanna Patsou2, and Athanasios Papaioannou

2013 ApJ 768 68; **File**

We have examined the Wind/3DP/SST electron and Wind/EPACT/LEMT ion data to investigate the path length difference between solar electrons and ions in the ground-level enhancement (GLE) events in solar cycle 23. Assuming that the onset time of metric type II or decameter-hectometric (DH) type III radio bursts is the solar release time of non-relativistic electrons, we have found that within an error range of ±10% the deduced path length of low-energy (~27 keV) electrons from their release site near the Sun to the 1 AU observer is consistent with the ion path length deduced by Reames from the onset time analysis. In addition, the solar longitude distribution and IMF topology of the GLE events examined are in favor of the coronal mass ejection-driven shock acceleration origin of observed non-relativistic electrons. We have also found an increase of electron path lengths with increasing electron energies. The increasing rate of path lengths is correlated with the pitch angle distribution (PAD) of peak electron intensities locally measured, with a higher rate corresponding to a broader PAD. The correlation indicates that the path length enhancement is due to the interplanetary scattering experienced by first arriving electrons. The observed path length consistency implies that the maximum stable time of magnetic flux tubes, along which particles transport, could reach 4.8 hr.

USE OF INCIDENT AND REFLECTED SOLAR PARTICLE BEAMS TO TRACE THE TOPOLOGY OF MAGNETIC CLOUDS

Lun C. **Tan**1,2, Olga E. Malandraki2, Donald V. Reames3, Chee K. Ng4, Linghua Wang5, and Gareth Dorrian

2012 ApJ 750 146

Occasionally, large solar energetic particle (SEP) events occur inside magnetic clouds (MCs). In this work, the onset time analysis, the peak intensity analysis, and the decay phase analysis of SEPs are used to investigate two large SEP events inside MCs: the **1998 May 2 and 2002 April 21** events. The onset time analysis of non-relativistic electrons and ~MeV nucleon–1 heavy ions shows the stability of the magnetic loop structure during a period of a few hours in the events examined. The joint analysis of pitch-angle distributions and peak intensities of electrons exhibits that, depending on the particle pitch angle observed at 1 AU, in the April event the reflection point of particles may be distributed along a wide spatial range, implying that the magnetic loop is a magnetic bottle connected to the Sun with both legs. In contrast, in the May event particle reflection occurs abruptly at the magnetic mirror formed by a compressed field enhancement behind the interplanetary shock, consistent with its open field line topology.

WHAT CAUSES SCATTER-FREE TRANSPORT OF NON-RELATIVISTIC SOLAR ELECTRONS?

Lun C. **Tan**1,6, Donald V. Reames2, Chee K. Ng3,7, Xi Shao4 and Linghua Wang

2011 ApJ 728 133

We have examined the cause of the scatter-free transport of non-relativistic solar electrons. Electron scatter-free transport events are compared with the diffusive transport event. The emphasis of our examination is on the energy dependence of electron angular distributions and the steepening of interplanetary magnetic field (IMF) power spectral densities (PSDs). Near and above the proton gyrofrequency, the effects of both R-mode (whistler) and L-mode (electromagnetic ion cyclotron, EMIC) waves need to be taken into account separately. The PSD spectral steepening due to the EMIC wave damping by solar-wind thermal ions becomes essential. In a fast-rise-fast-decay impulsive electron event we have observed such steepening, which significantly reduces PSD levels at frequencies above the proton gyrofrequency. The spectral steepening thus produced favors the occurrence of scatter-free transport of low-energy electrons. Consequently, within the Wind/3D Plasma and Energetic Particle Instrument/Silicon Semiconductor Telescope measured energy range (~25-500 keV), there appears to be an electron energy window, across which the scatter-free transport of lower energy electrons would change to the diffusive transport of higher energy electrons. We have observed such a change and found it is correlated with the occurrence of broken power-law spectra of electrons. Thus the connection between the transition from diffusive to scatter-free electron transport and the concurrent transition from high to low IMF PSD levels with corresponding breaks in the electron power-law energy spectrum and PSD spectrum has been recognized.

OBSERVATIONAL EVIDENCE ON THE PRESENCE OF AN OUTER REFLECTING BOUNDARY IN SOLAR ENERGETIC PARTICLE EVENTS

Lun C. Tan1,4, Donald V. Reames1,5, Chee K. Ng1,4, Oskari Saloniemi2 and Linghua Wang3,6

ApJ 701 1753-1764, **2009** doi: 10.1088/0004-637X/701/2/1753

We have focused primarily on the **2001 September 24** solar energetic particle (SEP) event to verify previous indications of the presence of an outer reflecting boundary of SEPs. By using energetic electron and ion data obtained from multi-spacecraft observations, we have identified a collimated particle beam consisting of reflected particles returning from an outer boundary. The peak of reflected particles appears before the arrival of particles at 90° pitch angle. In addition, an onset time analysis is carried out in order to determine parameters characterizing the boundary. Our analysis suggests that the presence of a counter-streaming particle beam with a deep depression at ~90° pitch angle during the onset phase is evidence for a nearby reflecting boundary. We have compared this property in the SEP events of **2002 April 21 and August 24**. A reflecting boundary that blocks a flux tube is important in space weather forecasting since it can cause the "reservoir" effect that may enhance the intensity and duration of high-energy particles.

Source investigation of impulsive ^{3}He-rich particle events

Chengming **Tan** and Yihua Yan

Advances in Space Research**,** Volume 41, Issue 6, **2008**, *Pages 992-997*

We have investigated the source characteristic and coronal magnetic field structure of six impulsive solar energetic particle (SEP) events selected from Wang et al. **[Wang, Y.-M., Pick, M., Mason, G.M. Coronal holes, jets, and the origin of ^{3}He-rich particle events. ApJ 639, 495, 2006**] and Pick et al. [**Pick, M., Mason, G.M., Wang, Y.-M., Tan, C., Wang, L. Solar source regions for ^{3}He-rich solar energetic particle events identified using imaging radio, optical, and energetic particle observations. ApJ 648, 1247, 2006**]. Some results are obtained: first, 2 events are associated with wide (≈100°) CMEs (hereafter wide CME events), another 4 events are associated with narrow (⩽40°) CMEs (hereafter narrow CME events); second, the coronal magnetic field configuration of narrow CME events appear more simple than that of the wide CME events; third, the photospheric magnetic field evolutions of all these events show new emergence of fluxes, while one case also shows magnetic flux cancellation; fourth, the EUV jets usually occurred very close to the footpoint of the magnetic field loop, while meter type III bursts occurred near or at the top of the loop and higher than EUV jets. Furthermore, the heights of type III bursts are estimated from the result of the coronal magnetic field extrapolations.

Modeling energetic proton transport in a corotating interaction region - An energetic particle event observed by STEREO-A from 21 to 24 August 2016

Xinyi **Tao**, Fang Shen, Wenwen Wei, Yuji Zhu, Xi Luo and XueShang Feng

A&A 682, A82 (**2024**)

https://www.aanda.org/articles/aa/pdf/2024/02/aa47248-23.pdf

Aims. An energetic particle event related to a corotating interaction region (CIR) structure was observed by the Solar-Terrestrial Relations Observatory-A (STEREO-A) from **21 to 24 August 2016**. Based on an analysis of measurement data, we suggest that instead of being accelerated by distant shocks, a local mechanism similar to diffusive shock acceleration (DSA) acting in the compression region could explain the flux enhancements of 1.8–10.0 MeV nucleon−1 protons. We created simulations to verify our hypothesis.

Methods. We developed a coupled model composed of a data-driven analytical background model providing solar wind configuration and a particle transport model represented by the focused transport equation (FTE). We simulated particle transport in the CIR region of interest in order to obtain the evolution of proton fluxes and derive the spectra.

Results. We find that the simulation is well correlated with the observation. The mechanism of particle scattering back and forth between the trap-like structure of interplanetary magnetic field (IMF) in the compression region is the major factor responsible for the flux enhancements in this energetic particle event, and perpendicular diffusion identified by a ratio of $\kappa_\perp/\kappa_\| \sim 10^{-2}$ plays an important role in the temporal evolution of proton fluxes.

Space weather: the solar perspective -- an update to Schwenn (2006) **Review**

Manuela **Temmer**

Living Reviews in Solar Physics **2021**
https://arxiv.org/pdf/2104.04261.pdf
The Sun, as an active star, is the driver of energetic phenomena that structure interplanetary space and affect planetary atmospheres. The effects of Space Weather on Earth and the solar system is of increasing importance as human spaceflight is preparing for lunar and Mars missions. This review is focusing on the solar perspective of the Space Weather relevant phenomena, coronal mass ejections (CMEs), flares, solar energetic particles (SEPs), and solar wind stream interaction regions (SIR). With the advent of the STEREO mission (launched in 2006), literally, new perspectives were provided that enabled for the first time to study coronal structures and the evolution of activity phenomena in three dimensions. New imaging capabilities, covering the entire Sun-Earth distance range, allowed to seamlessly connect CMEs and their interplanetary counterparts measured in-situ (so called ICMEs). This vastly increased our knowledge and understanding of the dynamics of interplanetary space due to solar activity and fostered the development of Space Weather forecasting models. Moreover, we are facing challenging times gathering new data from two extraordinary missions, NASA's Parker Solar Probe (launched in 2018) and ESA's Solar Orbiter (launched in 2020), that will in the near future provide more detailed insight into the solar wind evolution and image CMEs from view points never approached before. The current review builds upon the Living Reviews paper by Schwenn from 2006, updating on the Space Weather relevant CME-flare-SEP phenomena from the solar perspective, as observed from multiple viewpoints and their concomitant solar surface signatures**. 5-8 Dec 1981, 13-16 Aug 1982, 12 July 2007, December 12, 2008, December 22, 2009, 10 Jun 2010, June 12-13, 2010, 28 Oct 2003, November 18, 2003, 6-8 Aug 2007, March 7, 2011, August 9, 2011, March 7–11, 2012: May 17, 2012, June 30, 2012, 2-4 Dec 2012, June 14, 2012, February 25, 2014, August 24, 2014, January 1, 2016, September 6, 2017, 6-12 Sep 2017,**

Two Exceptions in the Large SEP Events of Solar Cycles 23 and 24

N. **Thakur** , N. Gopalswamy, P. Mäkelä, S. Akiyama, S. Yashiro, H. Xie
Solar Phys. Volume 291, Issue 2, pp 513-530 **2016**
http://link.springer.com/article/10.1007/s11207-015-0830-9
We discuss our findings from a survey of all large solar energetic particle (SEP) events of Solar Cycles 23 and 24, i.e. the SEP events where the intensity of > 10 MeV protons observed by GOES was > 10 pfu. In our previous work (Gopalswamy et al. in Geophys. Res. Lett. 41, 2673, 2014) we suggested that ground level enhancements (GLEs) in Cycles 23 and 24 also produce an intensity increase in the GOES > 700 MeV proton channel. Our survey, now extended to include all large SEP events of Cycle 23, confirms this to be true for all but two events: i) the GLE of **6 May 1998** (GLE57) for which GOES did not observe enhancement in > 700 MeV protons intensities and ii) a high-energy SEP event of **8 November 2000**, for which GOES observed > 700 MeV protons but no GLE was recorded. Here we discuss these two exceptions. We compare GLE57 with other small GLEs, and the 8 November 2000 SEP event with those that showed similar intensity increases in the GOES > 700 MeV protons but produced GLEs. We find that, because GOES > 700 MeV proton intensity enhancements are typically small for small GLEs, they are difficult to discern near solar minima due to higher background. Our results also support that GLEs are generally observed when shocks of the associated coronal mass ejections (CMEs) form at heights 1.2 – 1.93 solar radii [R⊙R⊙] and when the solar particle release occurs between 2 – 6 R⊙R⊙. Our secondary findings support the view that the nose region of the CME-shock may be accelerating the first-arriving GLE particles and the observation of a GLE is also dependent on the latitudinal connectivity of the observer to the CME-shock nose. We conclude that the GOES > 700 MeV proton channel can be used as an indicator of GLEs excluding some rare exceptions, such as those discussed here.

Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event

N. **Thakur**, N. Gopalswamy, H. Xie, P. Makela, S. Yashiro, S. Akiyama, J.M. Davila
E-print, July **2014; File**; ApJL **2014** 790 L13
http://arxiv.org/pdf/1406.7172v2.pdf
We present a study of the **2014 January 6** solar energetic particle (SEP) event, which produced a small ground level enhancement (GLE), making it the second GLE of this unusual solar cycle 24. This event was primarily observed by the South Pole neutron monitors (increase of ~2.5%) whereas a few other neutron monitors recorded smaller increases. The associated coronal mass ejection (CME) originated behind the western limb and had the speed of 1960 km/s. The height of the CME at the start of the associated metric type II radio burst, which indicates the formation of a strong shock, was measured to be 1.61 Rs using a direct image from STEREO-A/EUVI. The CME height at the time of GLE particle release (determined using the South Pole neutron monitor data) was directly measured as 2.96 Rs, from the STEREO-A/COR1 white-light observations. These CME heights are consistent with those obtained for the GLE71, the only other GLE of the current cycle as well as cycle-23 GLEs derived using back-extrapolation. GLE72 is of special interest because it is one of the only two GLEs of cycle 24, one of the two behind-the-limb GLEs and one of the two smallest GLEs of cycles 23 and 24.

Acceleration of Energetic Ions in Corotating Interaction Region near 1.5 au: Evidence from MAVEN.

Thampi, S. V., Krishnaprasad, C., Shreedevi, P. R., Pant, T. K., & Bhardwaj, A.
(**2019**). The Astrophysical Journal, 880(1), L3.

sci-hub.se/10.3847/2041-8213/ab2b43

sci-hub.se/10.3847/2041-8213/ab2b43

The dearth of observations between 1 and 3 au limits our understanding of energetic particle acceleration processes in interplanetary space. We present first-of-their-kind observations of the energetic particle acceleration in a corotating interaction region (CIR) using data from two vantage points, 1 au (near Earth) and 1.5 au (near Mars). The CIR event of 2015 June was observed by the particle detectors aboard the Advanced Composition Explorer satellite as well as the Solar Energetic Particle (SEP) instrument aboard the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft situated near 1.5 au. We find that a CIR shock can accelerate a significant number of particles even at 1.5 au. During this event the acceleration by the shocks associated with the CIR could cause an enhancement of around two orders of magnitude in the SEP energetic ion fluxes in the ~500 keV to 2 MeV range when the observations near 1 and 1.5 au are compared. To demonstrate the differences between SEP acceleration in CIR and other impulsive events, we show the energetic ion flux observations during an intense coronal mass ejection period in March 2015, in which case the enhanced SEP fluxes are seen even at 1 au. These observations provide evidence that CIR shock can accelerate particles in the region between Earth and Mars—that is, only within the short heliocentric distance of 0.5 au—in interplanetary space.

2015 March 3-17, 2015 June 5–17

Cosmic-Ray Propagation Around the Sun - Investigating the Influence of the Solar Magnetic Field on the Cosmic-Ray Sun Shadow

Julia Becker **Tjus**, Paolo Desiati, Niklas Döpper, Horst Fichtner, Jens Kleimann, Mike Kroll, Frederik Tenholt

A&A 633, A83 (2020)

https://doi.org/10.1051/0004-6361/201936306

https://arxiv.org/pdf/1903.12638.pdf

The cosmic-ray Sun shadow, which is caused by high-energy charged cosmic rays being blocked and deflected by the Sun and its magnetic field, has been observed by various experiments such as Argo-YBJ, HAWC, Tibet, and IceCube. Most notably, the shadow's size and depth was recently shown to correlate with the 11-year solar cycle. The interpretation of such measurements, which help to bridge the gap between solar physics and high-energy particle astrophysics, requires a solid theoretical understanding of cosmic-ray propagation in the coronal magnetic field. It is the aim of this paper to establish theoretical predictions for the cosmic-ray Sun shadow in order to identify observables that can be used to study this link in more detail. To determine the cosmic-ray Sun shadow, we numerically compute trajectories of charged cosmic rays in the energy range of 5 to 316 TeV for five different mass numbers. We present and analyse the resulting shadow images for protons and iron, as well as for typically measured cosmic-ray compositions. We confirm the observationally established correlation between the magnitude of the shadowing effect and both the mean sunspot number and the polarity of the magnetic field during the solar cycle. We also show that during low solar activity, the Sun's shadow behaves similarly to that of a dipole, for which we find a non-monotonous dependence on energy. In particular, the shadow can become significantly more pronounced than the geometrical disk expected for a totally unmagnetized Sun. For times of high solar activity, we instead predict the shadow to depend monotonously on energy, and to be generally weaker than the geometrical shadow for all tested energies. These effects should become visible in energy-resolved measurements of the Sun shadow, and may in the future become an independent measure for the level of disorder in the solar magnetic field.

SIMULATIONS OF LATERAL TRANSPORT AND DROPOUT STRUCTURE OF ENERGETIC PARTICLES FROM IMPULSIVE SOLAR FLARES

P. **Tooprakai**[1,2], A. Seripienlert[2,3,4,7], D. Ruffolo[2,3], P. Chuychai[2,5], and W. H. Matthaeus

2016 *ApJ* **831** 195

We simulate trajectories of energetic particles from impulsive solar flares for 2D+slab models of magnetic turbulence in spherical geometry to study dropout features, i.e., sharp, repeated changes in the particle density. Among random-phase realizations of two-dimensional (2D) turbulence, a spherical harmonic expansion can generate homogeneous turbulence over a sphere, but a 2D fast Fourier transform (FFT) locally mapped onto the lateral coordinates in the region of interest is much faster computationally, and we show that the results are qualitatively similar. We then use the 2D FFT field as input to a 2D MHD simulation, which dynamically generates realistic features of turbulence such as coherent structures. The magnetic field lines and particles spread non-diffusively (ballistically) to a patchy distribution reaching up to 25° from the injection longitude and latitude at $r \sim 1$ au. This dropout pattern in field line trajectories has sharper features in the case of the more realistic 2D MHD model, in better qualitative agreement with observations. The initial dropout pattern in particle trajectories is relatively insensitive to particle energy, though the energy affects the pattern's evolution with time. We make predictions for future observations of solar particles near the Sun (e.g., at 0.25 au), for which we expect a sharp pulse of outgoing particles along the dropout pattern, followed by backscattering that first remains close to the dropout pattern and later exhibits cross-field transport to a distribution that is more diffusive, yet mostly contained within the dropout pattern found at greater distances.

Results on Solar Physics from AMS-02

S. Della **Torre**, AMS-02 Collaboration
XXV ECRS 2016 Proceedings - eConf C16-09-04.3 **2016**
https://arxiv.org/pdf/1612.08441v1.pdf
AMS-02 is a wide acceptance high-energy physics experiment installed on the International Space Station in May 2011 and operating continuously since then. Using the largest number of detected particles in space of any space-borne experiment, it performs precision measurements of galactic cosmic rays fluxes. Detailed time variation studies of Protons, Heliums, Electron and Positron fluxes were presented. The low-rigidity range exhibits a decreasing general trend strongly related to the increase of solar activity, as well local decreases associated with strong solar events.
March 7th, 2012.

A Machine Learning Approach to Predicting SEP Events Using Properties of Coronal Mass Ejections

Jesse **Torres**,Lulu Zhao,Philip K. Chan,Ming Zhang
Space Weather e2021SW002797 **Volume20, Issue7** **2022**
https://doi.org/10.1029/2021SW002797
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021SW002797
Solar energetic particles (SEPs) can cause severe damage to astronauts and their equipment, and can disrupt communications on Earth. A lack of thorough understanding the eruption processes of solar activities and the subsequent acceleration and transport processes of energetic particles makes it difficult to forecast the occurrence of an SEP event and its intensity using conventional modeling with physics-based parameters. Therefore, in order to provide an advance warning for astronauts to seek shelter in a timely manner, we apply neural networks to forecast the occurrence of SEP events. We use the properties of coronal mass ejections (CMEs) archived in the Coordinated Data Analysis Workshops (CDAW) catalog based on SOHO Large Angle and Spectrometric Coronagraph Experiment (LASCO) observations. We also derive some features based on these properties associated with the CME, and analyze the contribution of each feature to the overall prediction. Our algorithm achieves an average True Skill Statistic (TSS) of 0.906, an average F1 score of 0.246, an average probability of detection (POD) of 0.920, and an average false alarm rate (FAR) of 0.882. An analysis of the features shows that sunspot number and a feature based on Type II radio bursts contribute the most, but when grouped together, CME speed-related features are the most important features. **22 Jun 2013, 18 Apr 2014, 22 Jun 2015, 25 Jun 2015**

Observations of IMF coherent structures and their relationship to SEP dropout events,

Trenchi, L., Bruno, R., D'Amicis, R., Marcucci, M. F., and Telloni, D.:
Ann. Geophys., 31, 1333-1341, **2013**.
The solar energetic particle (SEP) events from impulsive solar flares are often characterized by short-timescale modulations affecting, at the same time, particles with different energies. Several models and simulations suggest that these modulations are observed when SEPs propagate through magnetic structures with a different connection with the flare site. However, in situ observations rarely showed clear magnetic signatures associated with these modulations.
In this paper we used the Grad–Shafranov reconstruction to perform a detailed analysis of the local magnetic field topology during the SEP event of **9–10 January 1999**, characterized by several SEP dropouts. An optimization procedure is used to identify, during this SEP event, the magnetic structures which better satisfy the Grad–Shafranov assumptions and to evaluate the direction of their invariant axis.
We found that these two-dimensional structures, which are flux ropes or current sheets with a more complex field topology, are generally associated with the maxima in the SEP counts. This association suggests that the SEPs propagate within these structures and, since their gyration radii is much smaller than the transverse dimension of these structure, cannot escape from them.

SOLAR ENERGETIC PARTICLE MODULATIONS ASSOCIATED WITH COHERENT MAGNETIC STRUCTURES

L. **Trenchi**1, R. Bruno1, D. Telloni2, R. D'amicis1, M. F. Marcucci1, T. H. Zurbuchen3, and M. Weberg
2013 ApJ 770 11

In situ observations of solar energetic particles (SEPs) often show rapid variations of their intensity profile, affecting all energies simultaneously, without time dispersion. A previously proposed interpretation suggests that these modulations are directly related to the presence of magnetic structures with a different magnetic topology. However, no compelling evidence of local changes in magnetic field or in plasma parameters during SEP modulations has been reported. In this paper, we performed a detailed analysis of SEP events and we found several signatures in the local magnetic field and/or plasma parameters associated with SEP modulations. The study of magnetic helicity allowed us to identify magnetic boundaries, associated with variations of plasma parameters, which are thought to represent the borders between adjacent magnetic flux tubes. It is found that SEP dispersionless modulations are generally associated with such magnetic boundaries. Consequently, we support the idea that SEP modulations are observed when the spacecraft passes through magnetic flux tubes, filled or devoid of SEPs, which are alternatively connected and not connected with the flare site. In other cases, we found SEP dropouts associated with large-scale magnetic holes. A possible generation mechanism suggests that these holes are formed in the high solar corona as a consequence of magnetic reconnection. This reconnection process modifies the magnetic field topology, and therefore, these holes can be magnetically isolated from the surrounding plasma and could also explain their association with SEP dropouts.

Fundamentals of collisionless shocks for astrophysical application, 1. Non-relativistic shocks

R. A. **Treumann**

Astronomy and Astrophysics Review, Volume 17, Number 4, p. 409-535, **2009**

A comprehensive review is given of the theory and properties of nonrelativistic shocks in hot collisionless plasmas—in view of their possible application in astrophysics. Understanding non-relativistic collisionless shocks is an indispensable step towards a general account of collisionless astrophysical shocks of high Mach number and of their effects in dissipating flow-energy, in heating matter, in accelerating particles to high—presumably cosmic-ray—energies, and in generating detectable radiation from radio to X-rays. Non-relativistic shocks have Alfvénic Mach numbers $_A \ll \sqrt{m_i/m_e}(\omega_{pe}/\omega_{ce})$, where m_i/m_e is the ion-to-electron mass ratio, and ω_{pe}, ω_{ce} are the electron plasma and cyclotron frequencies, respectively. Though high, the temperatures of such shocks are limited (in energy units) to $T < m_e c^2$. This means that particle creation is inhibited, classical theory is applicable, and reaction of radiation on the dynamics of the shock can be neglected. The majority of such shocks are supercritical, meaning that non-relativistic shocks are unable to self-consistently produce sufficient dissipation and, thus, to sustain a stationary shock transition. As a consequence, supercritical shocks act as efficient particle reflectors. All these shocks are microscopically thin, with shock-transition width of the order of the ion inertial length $\lambda_i = c/\omega_{pi}$ (with ω_{pi} the ion plasma frequency). The full theory of such shocks is developed, and the different possible types of shocks are defined. Since all collisionless shocks are magnetised, the most important distinction is between quasi-perpendicular and quasi-parallel shocks. The former propagate about perpendicularly, the latter roughly parallel to the upstream magnetic field. Their manifestly different behaviours are described in detail. In particular, although both types of shocks are non-stationary, they have completely different reformation cycles. From numerical full-particle simulations it becomes evident that, on ion-inertial scales close to the shock transition, all quasi-parallel collisionless supercritical shocks are locally quasi-perpendicular. This property is of vital importance for the particle dynamics near the quasi-parallel shock front. Considerable interest focusses on particle acceleration and the generation of radiation. Radiation from non-relativistic shocks results mainly in wave–wave interactions among various plasma waves. Non-thermal charged particles can be further accelerated to high energies by a Fermi-like mechanism. The important question is whether the shock can pre-accelerate shock-reflected particles to sufficiently high energies in order to create the seed-population of the non-thermal particles required by the Fermi mechanism. Based on preliminary full-particle numerical simulations, this question is answered affirmatively. Such simulations provide ample evidence that collisionless shocks with high-Mach numbers—even when non-relativistic—could probably by themselves produce the energetic seed-particle population for the Fermi-process.

Quasi-ballistic and superdiffusive transport for impulsive solar particle events

E. M. **Trotta** and G. Zimbardo

A&A 530, A130 (**2011**)

Context. The propagation of solar energetic particles encompasses a number of transport regimes, which goes from diffusive transport to scatter-free propagation. On the other hand, numerical simulations in the presence of magnetic turbulence, as well as the analysis of propagating particles accelerated at interplanetary shocks, show that superdiffusive regimes, which are intermediate between scatter free and diffusive propagation, can be found.
Aims. In this work we study both proton and electron transport in order to understand whether both superdiffusive and ballistic propagation are indeed possible, at variance with the standard paradigm.
Methods. We carry out an analysis of impulsive solar energetic particles (SEPs) events, for which the observed time profile of energetic particle fluxes represents the propagator of the corresponding transport equation. Time profiles

are fitted by power laws. Assuming well-known forms of the particle propagator, with power-law asymptotic behaviour, we determine the transport regime of particle propagation from the time profiles.
Results. Using data obtained from ACE and SoHO spacecraft, several proton and electron events that exhibit both superdiffusive and ballistic transport will be shown. When these anomalous regimes are found, no finite mean free path can be defined.

Statistical Evidence for Contributions of Flares and Coronal Mass Ejections to Major Solar Energetic Particle Events
G. **Trottet**, S. Samwel, K.-L. Klein, T. Dudok de Wit, R. Miteva
Solar Phys. Volume 290, Issue 3, pp 819-839 **2015**
http://arxiv.org/abs/1411.4133 ;
https://link.springer.com/content/pdf/10.1007/s11207-014-0628-1.pdf **File**
Solar energetic particle (SEP) events are related to flares and coronal mass ejections (CMEs). This work is a new investigation of statistical relationships between SEP peak intensities - deka-MeV protons and near-relativistic electrons - and characteristic quantities of the associated solar activity. We consider the speed of the CME and quantities describing the flare-related energy release: peak flux and fluence of soft X-ray (SXR) emission, fluence of microwave emission. The sample comprises 38 SEP events associated with strong SXR bursts (classes M and X) in the western solar hemisphere between **1997 and 2006**, and where the flare-related particle acceleration is accompanied by radio bursts indicating electron escape to the interplanetary space. The main distinction of the present statistical analysis from earlier work is that besides the classical Pearson correlation coefficient the partial correlation coefficients are calculated in order to disentangle the effects of correlations between the solar parameters themselves. The classical correlation analysis shows the usual picture of correlations with broad scatter between SEP peak intensities and the different parameters of solar activity, and strong correlations between the solar activity parameters themselves. The partial correlation analysis shows that the only parameters that affect significantly the SEP intensity are the CME speed and the SXR fluence. The SXR peak flux and the microwave fluence have no additional contribution. **We conclude that these findings bring statistical evidence that both flare acceleration and CME shock acceleration contribute to the deka-MeV proton and near-relativistic electron populations in large SEP events.** 3 March 2000, 24 Aug 2002, 29 October 2003, 6 May 2005 **Tables**
Table 1 Parameters of SoWi events: columns (1) event date, (2) SXR start time, (3) quality flag for the microwave fluence calculation and particle escape, (4) and (5) frequency where the microwave fluence is maximum in GHz and peak fluence in 105 sfu s (6) peak soft X-ray flux in the 0.1 – 0.8 nm channel in 10−4 Wm−2**, (7) start-to-peak fluence [10−4 Jm−2] in this wavelength range,** (8) projected CME speed in kms−1, (9) – (11) peak intensities in (cm2 s srMeV)−1 of electrons (38 – 53 and 175 – 315 keV) and of protons (15 – 40 MeV).

Solar Energetic Particles and Intensity of Metric Type II Radio Bursts.
Tsap, Y.T., Isaeva, E.A. & Kopylova, Y.G.
Sol Phys 299, 4 (**2024**).
https://doi.org/10.1007/s11207-023-02247-x
We perform a statistical analysis of 112 proton events from 24 November 2000 to 20 December 2014, accompanied by an increase in the intensity of solar energetic particles (SEPs) with energy ��>1–850 MeV using GOES data. All events were accompanied by metric type II radio bursts in the frequency range of 25–180 MHz observed with the Radio Solar Telescope Network. A correlation in the peak proton integral intensity �� with the intensity of type II radio bursts �� and the frequency drift rate � is shown. Taking into account the helio-longitudinal weakening, i.e. the dependence of SEP intensity on the heliographic longitude of the flare, we find that the correlation coefficients between �� and ��, as well as between �� and � for protons with ��>30 MeV are 0.79 and 0.71, respectively. This suggests that non-thermal electrons, which drive type II radio bursts, and energetic protons are generated at the front of the same shock wave. The correlation coefficients mentioned above decrease for ��≳100 MeV. Therefore, the contribution of high energetic protons to the integral intensity �� is rather determined by accelerated processes in the flare energy release region. The weak dependence of SEP intensity on the helio-longitudinal weakening is discussed.

On the Relationship of Solar Energetic Particles with Metric Type II Radio Bursts.
Tsap, Y.T., Isaeva, E.A. & Kopylova, Y.G.
Geomagn. Aeron. 63, No. 7, 1086–1092 (**2023**).
https://doi.org/10.1134/S0016793223070241

According to the data from the GOES satellites and the SRS solar radio spectrograph, 112 proton events were analyzed for the time interval from November 24, 2000 to December 20, 2014, accompanied by an increase in the intensity of solar energetic particles (protons) Ip with energies Ep > 1–850 MeV and type II radio bursts in the range of 25–180 MHz. A correlation was found for the proton intensity Ip with the intensity of type II radio bursts Ii and the frequency drift rate V. The correlation coefficients between Ip and Ii, as well as between Ip and V, reach approximately 0.82 and 0.67, respectively. The correlation decreases quite sharply at Ep > 100 MeV. *Nonthermal electrons responsible for type II radio bursts and energetic protons are generated at the fronts of the same shock waves, while the acceleration of relativistic particles with Ep > 100 MeV is determined by nonthermal processes in the region of flare energy release.*

Acceleration of solar cosmic rays and the fine spectral structure of type II radio bursts

Yu. T. **Tsap**, E. A. Isaeva

Cosmic Research, March **2013**, Volume 51, Issue 2, pp 108-113, **File**

Kosmicheskie Issledovaniya, **2013**, Vol. 51, No. 2, pp. 119–124.

On the basis of data, obtained by means of the ground-based solar service RSTN (Radio Solar Telescope Network) and the geostationary satellite system GOES, the relationship between the solar cosmic rays (SCR) intensity I p with the proton energy **E p > 1 MeV** and parameters of meter-decameter type II radio bursts in the frequency range of 25–180 MHz is studied. The process of proton acceleration by shock waves was characterized by the frequency drift velocity of radio bursts V mII and the relative difference between radio emission frequencies at the first two harmonics b. It is shown that the coefficient of correlation between I p and b increases with E p growing from 0.40 to 0.70, while a similar coefficient between I p and V mII does not exceed 0.30. Indications in favor of the two-stage SCR acceleration model are obtained. Table: 2000-2006

Upper limits on the solar-neutron flux at the Yangbajing neutron monitor from BATSE-detected solar flares:

H. **Tsuchiya**, H. Miyasaka, E. Takahashi, S. Shimoda, Y. Yamada, I. Kondo, K. Makishima, F. Zhu, Y. Tan, H. Hu, Y. Tang, J. Zhang, H. Lu and X. Meng

A&A 468 (**2007**) 1089-1097

Review of the August 1972 and March 1989 Space Weather Events: Can We Learn Anything New From Them?

Bruce T. **Tsurutani**, Abhijit Sen, Rajkumar Hajra, Gurbax S. Lakhina, Richard B. Horne, Tohru Hada

JGR volume : 129, number: e2024JA032622,

2024

https://doi.org/10.1029/2024JA032622

https://arxiv.org/pdf/2409.00452

Updated summaries of the August 1972 and March 1989 space weather events have been constructed. The features of these two events are compared to the Carrington 1859 event and a few other major space weather events. It is concluded that solar active regions release energy in a variety of forms (X-rays, EUV photons, visible light, coronal mass ejection (CME) plasmas and fields) and they in turn can produce other energetic effects (solar energetic particles (SEPs), magnetic storms) in a variety of ways. It is clear that there is no strong one-to-one relationship between these various energy sinks. The energy is often distributed differently from one space weather event to the next. Concerning SEPs accelerated at interplanetary CME (ICME) shocks, it is concluded that the Fermi mechanism associated with quasi-parallel shocks is relatively weak and that the gradient drift mechanism (electric fields) at quasi-perpendicular shocks will produce harder spectra and higher fluxes. If the 4 Augusut 1972 intrinsic magnetic cloud condition (southward interplanetary magnetic field instead of northward) and the interplanetary Sun to 1 au conditions were different, a 4 August 1972 magnetic storm and magnetospheric dawn-to-dusk electric fields substantially larger than the Carrington event would have occurred. Under these special interplanetary conditions, a Miyake et al. (2012)-like extreme SEP event may have been formed. The long duration complex 1989 storm was probably greater than the Carrington storm in the sense that the total ring current particle energy was larger. **2-7 Aug 1972, 6–19 Mar 1989**

Filaments related to solar energetic particles

Ts. **Tsvetkov**, R. Miteva, N. Petrov

AIP Conference Proceedings 2075, 090013 (**2019**); https://doi.org/10.1063/1.5091227

http://sci-hub.se/https://aip.scitation.org/doi/abs/10.1063/1.5091227 **File**

We investigate the kinematics of 13 solar energetic particle (SEP) related eruptive prominences (EPs) and SEP spectral indices (using SOHO/ERNE proton data) for well observed set of events in the SDO era. From the height-time profiles of the EPs, we measured their average velocities and eruptive phase velocities. Relationships between

proton spectral index γ and properties of the other associated solar phenomena (flare peak flux, CME speed, EPs speeds) are investigated.
TABLE 1. Table of selected EP-related SOHO/ERNE proton events and related solar events (2011-2015)

On the relationship between filament eruptions and solar energetic particles

Ts. **Tsvetkov**, R. Miteva, N. Petrov
Journal of Atmospheric and Solar-Terrestrial Physics, Volume 179, p. 1-10 **2018**
https://reader.elsevier.com/reader/sd/pii/S1364682618301329?token=1CBD60A7469EB2F75927AA56974DED22493B3EC137A454727D84E8977F753F0FF751963B22453513B236A229DA3EBA5D
In the current study the association rate between solar energetic particles (protons) and filaments and/or filament eruptions (FEs) is investigated using a larger event sample than previously. Proton events observed in the period 2010□2016 are accompanied by filaments in 53% (82/156) of the cases. Due to the lack of comprehensive catalog of all filaments, a catalog of FE is used for the reversed association. Only about 5% of FEs have in situ proton signatures of larger median intensity, compared to the median of the entire proton sample. Other eruptive phenomena (ares and coronal mass ejections) related to the proton events show difierences in their distributions compared to the respective FE-samples. The indication for a shock wave formation using the type II radio signatures is also considered and discussed.
Table 3 Table of~20 MeV SOHO/ERNE proton events (2010–2016) and associated solar events (**Большая таблица**)

Motion and transport of solar cosmic rays in heliospheric traps: The event on January 28–31, 2001

V. I. **Tulupov**, E. E. Grigorenko, N. A. Vlasova, G. P. Lyubimov
Cosmic Research, November **2012**, Volume 50, Issue 6, pp 397-404
Kosmicheskie Issledovaniya, **2012**, Vol. 50, No. 6, pp. 427–434.
The results of studying the enhancement of solar cosmic ray fluxes on **January 28–31, 2001** in a wide energy range are presented using the ACE spacecraft data. A comparative analysis of temporal variations of the fluxes of charged particles and of the interplanetary medium parameters (interplanetary magnetic field and solar wind) has been performed on the basis of the “reflection” model of motion, accumulation, and modulation of cosmic rays. It is shown that a magnetic trap for solar cosmic rays was created by a plasma stream and flare ejection from an active region in the western part of the solar disk. Particles of low energies (<10 MeV) were captured inside the trap; the dispersion of distribution of particles with different energies inside the trap being determined by its complicated magnetic structure. The power-low dependence of the time of maximum for the flux of particles on their energy is found, and softer energy spectrum inside the trap is explained.

Upgrade of GLE database: Assessment of effective dose rate at flight altitude

S.**Tuohino**aA.IbragimovbI.UsoskincdA.Mishev
Advances in Space Research Volume 62, Issue 2, 15 July **2018**, Pages 398-407
http://sci-hub.tw/http://linkinghub.elsevier.com/retrieve/pii/S0273117718303363
A new database for assessment of radiation doses at cruise flight altitude in the Earth atmosphere, related to ground level enhancement (GLE) events is created under VarSiTi/SCOSTEP support and incorporated to the International ground level enhancement (GLE) database (gle.oulu.fi). The upgraded database provides, for each GLE event, where possible, information on the estimated energy/rigidity spectra of solar energetic particles and the corresponding computed effective doses at cruise flight altitude of 35 kft (10,668 m above sea level). The computations are performed for various reconstructions of solar energetic particles spectra, available in literature, thus for some events there are several results. Computations were performed using a recent model for assessment of effective dose due to cosmic ray particles, applied specifically in the polar region, where the exposure is maximal. This upgrade allows one to estimate the radiation effects at cruise flight altitude caused by major GLE events over several decades.

An improved forecast system for relativistic electrons at geosynchronous orbit

Turner, D. L.; Li, X.; Burin des Roziers, E.; Monk, S.
Space Weather, Vol. 9, No. 6, S06003, **2011**
http://dx.doi.org/10.1029/2010SW000647
Here we provide a review of existing forecast models for Earth's outer radiation belt electrons, discuss some recent improvements to two of these models, and present a new and improved forecast system for relativistic electrons at GEO. For the first time, we can forecast at a local hour resolution around GEO using a statistical tool included in the system. This forecast system also includes several real-time forecast models, two previously existing and one that is a new development. This new model incorporates an internal electron source, simulating local acceleration by wave-

particle interactions, and it proves to be the most accurate of the models in the system. For 2007–2008, it achieves +1 and +2 day prediction efficiencies of 0.90 and 0.63. We conclude this work with a discussion of how these models are currently operational and providing results to the community online in real time, and we also speculate on future possibilities to allow for forecasts with extended lead times and ranges throughout the rest of the outer radiation belt.

Initial Fe/O Enhancements in Large, Gradual, Solar Energetic Particle Events: Observations from Wind and Ulysses

Allan J. **Tylka**, Olga E. Malandraki, Gareth Dorrian, Yuan-Kuen Ko, Richard G. Marsden, Chee K. Ng and Cecil Tranquille

Solar Phys. July **2013**, Volume 285, Issue 1-2, pp 251-267

Shocks driven by fast coronal mass ejections (CMEs) are the dominant particle accelerators in large, "gradual" solar energetic particle (SEP) events. In these events, the event-integrated value of the iron-to-oxygen ratio (Fe/O) is typically ∼ 0.1, at least at energies of a few MeV/nucleon. However, at the start of some gradual events, when intensities are low and growing, initially Fe/O is ∼ 1. This value is also characteristic of small, "impulsive" SEP events, in which particle acceleration is due to magnetic reconnection. These observations suggested that SEPs in gradual events also include a direct contribution from the flare that accompanied the CME launch. If correct, this interpretation is of critical importance: it indicates a clear path to interplanetary space for particles from the reconnection region beneath the CME. A key issue for the flare origin is "magnetic connectedness", i.e., proximity of the flare site to the solar footpoint of the observer's magnetic field line.

We present two large gradual events observed in 2001 by Wind at L1 and by Ulysses, when it was located at > 60∘ heliolatitude and beyond 1.6 AU. In these events, transient Fe/O enhancements at 5 – 10 MeV/nucleon were seen at both spacecraft, even though one or both is not "well-connected" to the flare. These observations demonstrate that an initial Fe/O enhancement cannot be cited as evidence for a direct flare component. Instead, initial Fe/O enhancements are better understood as a transport effect, driven by the different mass-to-charge ratios of Fe and O. We further demonstrate that the time-constant of the roughly exponential decay of the Fe/O ratio scales as R 2, where R is the observer's radial distance from the Sun. This behavior is consistent with radial diffusion. These observations thus also provide a potential constraint on models in which SEPs reach high heliolatitudes by cross-field diffusion.

A New and Comprehensive Analysis of Proton Spectra in Ground-Level Enhanced (GLE) Solar Particle Events

Allan J. **Tylka**∗ and William F. Dietrich†∗

PROCEEDINGS OF THE 31st ICRC, ŁOD´ Z **2009**

http://icrc2009.uni.lodz.pl/proc/pdf/icrc0273.pdf

Proton acceleration to energies above ∼500 MeV is a controversial and poorly understood aspect of solar energetic particle (SEP) physics. We have developed a new technique for analyzing data from the world-wide neutron monitor (NM) network. We have used the method to derive absolutelynormalized event-integrated proton spectra for 53 of the 66 GLEs recorded since 1956. As a check on our results, we have compared the fluences from our NM spectra to satellite measurements at ∼300-700 MeV available from IMP8, SAMPEX, and GOES. We further show that the combined satellite and neutron-monitor measurements, ranging from ∼10 MeV to ∼10 GeV, can often be well-represented as a double power-law fit to the integral spectrum in rigidity, using the formulation given by Band et al. 1993. These comprehensive results are a useful starting point for investigations of the acceleration mechanism(s) in GLEs and for practical applications. **1989-Sep-29, 1989-Oct-24, 2001- Apr-15**,

A Model for Spectral and Compositional Variability at High Energies in Large, Gradual Solar Particle Events

Allan J. **Tylka**1 and Martin A. Lee2

Astrophysical Journal, 646:1319Y1334, **2006**

https://iopscience.iop.org/article/10.1086/505106/pdf

Shocks driven by fast coronal mass ejections (CMEs) are generally believed to be the dominant accelerators in large, gradual solar energetic particle (SEP) events. A key challenge for this notion has been the highly variable spectral and compositional characteristics of these events above a few tens of MeV per nucleon. We have recently proposed that this variability results from the interplay of two factors: evolution in the shock-normal angle as the shock moves outward from the Sun; and a compound seed population, typically comprising at least suprathermals from the corona (or solar wind) and suprathermals from flares. We present here a simple analytical implementation of these ideas. Our calculations semiquantitatively reproduce key features of the observed variability, including spectral morphologies and energy dependence in Fe/O, 3He/4He, and mean ionic charges, in ways that are consistent with correlations in the data. The model makes a prediction for the average high-energy Fe/O enhancement that is borne out by 30 years of observations; the model also provides a quantitative explanation for the Breneman & Stone fractionation effect, a fundamental but previously unexplained aspect of SEP phenomenology. Our calculations must be bolstered by future efforts incorporating realistic CME-shock simulations and a rigorous treatment of particle transport. Suprathermal densities in the corona, as well as details of the injection process at shocks of arbitrary obliquity, require further investigation. Nevertheless, these first results suggest a comprehensive framework for understanding the complexity of high-energy variability in terms of shock physics for most, if not all, large SEP events.

Shock Geometry, Seed Populations, and the Origin of Variable Elemental Composition at High Energies in Large Gradual Solar Particle Events

A. J. **Tylka**1, C. M. S. Cohen2, W. F. Dietrich3, M. A. Lee4, C. G. Maclennan5, R. A. Mewaldt2, C. K. Ng6,7, and D. V. Reames6

Astrophysical Journal, 625:474–495, **2005**

https://iopscience.iop.org/article/10.1086/429384/pdf

Above a few tens of MeV per nucleon, large, gradual solar energetic particle (SEP) events are highly variable in their spectral characteristics and elemental composition. The origin of this variability has been a matter of intense and ongoing debate. In this paper, we propose that this variability arises from the interplay of two factors—shock geometry and a compound seed population, typically comprising both solar-wind and flare suprathermals. Whereas quasi-parallel shocks generally draw their seeds from solar-wind suprathermals, quasi-perpendicular shocks—by requiring a higher initial speed for effective injection—preferentially accelerate seed particles from flares. Solar-wind and flare seed particles have distinctive compositional characteristics, which are then reflected in the accelerated particles. We first examine our hypothesis in the context of particles locally accelerated near 1 AU by traveling interplanetary shocks. We illustrate the implications of our hypothesis for SEPs with two very large events, 2002 April 21 and 2002 August 24. These two events arise from very similar solar progenitors but nevertheless epitomize extremes in high-energy SEP variability. We then test our hypothesis with correlation studies based on observations of 43 large SEP events in 1997-2003 by the Advanced Composition Explorer, Wind, the Interplanetary Monitoring Platform 8, and GOES. We consider correlations among high-energy Fe/O, event size, spectral characteristics, the presence of GeV protons, and event duration at high energies. The observed correlations are all qualitatively consistent with our hypothesis. Although these correlation studies cannot be construed as proof of our hypothesis, they certainly confirm its viability. We also examine the alternative hypothesis in which a direct flare component—rather than flare particles subsequently processed through a shock—dominates at high energies. This alternative would produce compositional characteristics similar to those of our hypothesis. However, the observed longitude distribution of the enhanced Fe/O events, their spectral characteristics, and recent timing studies all pose serious challenges for a direct flare component. We also comment on measurements of the mean ionic charge state of Fe at high energies. **We conclude that shock geometry and seed population potentially provide a framework for understanding the overall high-energy variability in large SEP events.** We suggest additional studies for testing this hypothesis.

Analysis of Cosmic Ray Fluxes at Different Stations during Geomagnetic Storms using Wavelet Based Approaches: Continuous Wavelet Transform and Multi-Resolution Analysis

Uga, CI ; Adhikari, B ; Teferi, D

GEOMAGNETISM AND AERONOMY Volume 63, Issue 6, Page 818-838, **2024**

DOI 10.1134/S0016793223600418

This study investigated the impact of different types of geomagnetic storms on cosmic ray fluxes at different stations using various wavelet-based approaches such as continuous wavelet transformation (CWT) and multi-resolution analysis (MRA). We used the cosmic ray intensity data from the NAIN, INVK, OULU, and NEWK neutron monitor stations and solar-interplanetary activity data from the OMNI web data center for this study. We considered four different geomagnetic storm events: **23 June 2015, 13 October 2016, 8 September 2017, and 26 August 2018**. The study revealed that the selected geomagnetic storms had a significant impact on cosmic ray fluxes and that the variations of cosmic ray fluxes differed throughout stations and events. The October 13, 2016, event showed a greater modulation of cosmic ray fluxes than the other three selected storms. Furthermore, the analysis shows the varying periodicity corresponding to cosmic ray fluctuations over different stations during the selected geomagnetic storms. This may be due to various factors, such as interplanetary magnetic field strength and orientation, observer location, and local magnetic fields. These findings provide insights into the effect on cosmic ray intensity at ground-based monitor stations due to geomagnetic storms and may serve as a reference for future studies.

Analysis of ground level enhancement events of 29 September 1989; 15 April 2001 and 20 January 2005

Romanius Ejike **Ugwoke**, Augustine Ubachukwu, Johnson Ozoemena Urama, Ogbonnaya Okike, Jibrin Adejoh Alhassan, Augustine Ejikeme Chukwude
Research in Astronomy and Astrophysics **2022**
https://arxiv.org/pdf/2208.12572.pdf
We present the results of analyses of the ground level enhancements (GLEs) of cosmic ray (CR) events of **29 September 1989; 15 April 2001 and 20 January 2005**. This involve examination of hourly raw CR counts of an array of neutron monitors (NMs) spread across different geographical latitudes and longitudes. Using awk script and computer codes implemented in R-software, the pressure corrected raw data plots of the NMs were grouped into low-, mid-, and, high-latitudes. The results show both similarities and differences in the structural patterns of the GLE signals. In an attempt to explain why the CR count during the decay phase of GLEs is always higher than the count before peak, we interpreted all counts prior to the peak as coming from direct solar neutrons and those in the decay phase including the peak as coming from secondary CR neutrons generated by the interactions of primary CRs with the atoms and molecules in the atmosphere. We identified NMs that detected these primary neutrons and found that they are close in longitudes. Previous authors seemingly identified these two species as impulsive and gradual events. Although there are a number of unexplained manifestations of GLE signals, some of the results suggest that geomagnetic rigidity effectively determines the intensity of CRs at low- and mid-latitudes. Its impact is apparently insignificant in high-latitude regions. Nevertheless, the results presented should be validated before making any firm statements. Principally, the contributions of the ever-present and intractable CR diurnal anisotropies to GLE signals should be accounted for in future work.

Trends and Characteristics of High-Frequency Type II Bursts Detected by CALLISTO Spectrometers

A.C.**Umuhire** (1), J.Uwamahoro (2), K. Sasikumar Raja (3), A.Kumar (4), C.Monstein (5)
Advances In Space Research **2021**
https://arxiv.org/pdf/2106.09310.pdf
Solar radio type II bursts serve as early indicators of incoming geo-effective space weather events such as coronal mass ejections (CMEs). In order to investigate the origin of high-frequency type II bursts (HF type II bursts), we have identified 51 of them (among 180 type II bursts from SWPC reports) that are observed by ground-based Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) spectrometers and whose upper-frequency cutoff (of either fundamental or harmonic emission) lies in between 150 MHz-450 MHz during 2010-2019. We found that 60% of HF type II bursts, whose upper-frequency cutoff $\geq$ 300 MHz originate from the western longitudes. Further, our study finds a good correlation $\sim$ 0.73 between the average shock speed derived from the radio dynamic spectra and the corresponding speed from CME data. Also, we found that analyzed HF type II bursts are associated with wide and fast CMEs located near the solar disk. In addition, we have analyzed the spatio-temporal characteristics of two of these high-frequency type II bursts and compared the derived from radio observations with those derived from multi-spacecraft CME observations from SOHO/LASCO and STEREO coronagraphs.
4.2. SEPs and the analyzed high starting frequency type II bursts
13 June 2010, August 22, 2015, November 04, 2015
Table 1: Details of the events: Type II bursts, CMEs and Flares (2010-2019)
Table 2: Type II bursts associated with SEP events (2011-2014)

Extreme Solar Events: Setting up a Paradigm **Review**

Usoskin, I., Miyake, F., Baroni, M. et al.
Space Sci Rev 219, 73 (**2023**).
https://doi.org/10.1007/s11214-023-01018-1
https://link.springer.com/content/pdf/10.1007/s11214-023-01018-1.pdf **File**
The Sun is magnetically active and often produces eruptive events on different energetic and temporal scales. Until recently, the upper limit of such events was unknown and believed to be roughly represented by direct instrumental observations. However, two types of extreme events were discovered recently: extreme solar energetic particle events on the multi-millennial time scale and super-flares on sun-like stars. Both discoveries imply that the Sun might rarely produce events, called extreme solar events (ESE), whose energy could be orders of magnitude greater than anything we have observed during recent decades. During the years following these discoveries, great progress has been achieved in collecting observational evidence, uncovering new events, making statistical analyses, and developing theoretical modelling. The ESE paradigm lives and is being developed. On the other hand, many outstanding questions still remain open and new ones emerge. Here we present an overview of the current state of the art and the forming paradigm of ESE from different points of view: solar physics, stellar–solar projections, cosmogenic-isotope data, modelling, historical data, as well as terrestrial, technological and societal effects of ESEs. Special focus is paid to open questions and further developments. This review is based on the joint work of the International Space Science Institute (ISSI) team #510 (2020–2022). 7176 BCE and 5259 BCE, **5410 BCE, 1279 CE, 1052 CE, 1859, 4-6 Dec 2006, 13 Dec 2006**

Consistency of the average flux of solar energetic particles over timescales of years to megayears

I. G. **Usoskin**1, S. A. Koldobskiy1, S. V. Poluianov1, O. Raukunen2,3, R. Vainio2 and G. A. Kovaltsov1
A&A 670, L22 (**2023**)
https://www.aanda.org/articles/aa/pdf/2023/02/aa45810-22.pdf

Aims. Solar energetic particles (SEPs) have been measured directly in space over the past decades. Rare extreme SEP events are studied based on terrestrial cosmogenic proxy data for the past ten millennia. Lunar rocks record the average SEP fluxes on the megayear timescale. The question of whether the SEP fluxes averaged over different timescales are mutually consistent is still open. Here we analyze these different datasets for mutual consistency.
Methods. Using the data from directly measured SEPs over the past decades and reconstructions of extreme SEP events in the past, we built a distribution function of the occurrence of annual SEP fluences for SEPs with energies above 30, 60, 100, and 200 MeV. The distribution function was fit with the Weibull and other types of distributions, and the long-term average SEP flux was computed and compared with the megayear SEP flux estimated from lunar data.
Results. In contrast to the current paradigm, the direct space-era data are not representative of the long-term averaged SEP flux because they are only 20–55% of it, while the major fraction was formed by rare extreme SEP events in the past. The combined statistics of direct and proxy data are fully consistent with megayear lunar data, implying that our knowledge of the whole range of the SEP fluxes, from frequent weak to rare extreme events, is now consistent.

Extreme solar events: A new paradigm

Ilya **Usoskin**
2nd SCOSTEP/PRESTO Online Seminar July 20, **2020**, 12-13 UT
Zoom Registration URL (pre-registration is necessary): https://us02web.zoom.us/webinar/register/WN_1aFIAJm-RUCqmVg81Ouk9w

The Sun provides the energy for life on Earth and always shine in seemingly the same way, as was believed until recently. But we also know that it can produce sporadic eruptive events, such as solar bright flares and huge coronal mass ejections. Such events are often accompanied by the so-called solar particle storms, which are short-term events with very intense fluxes of solar energetic particles (SEPs) observed in space near Earth. These events remained beyond our detection abilities even several decades ago, but now we know that they may pose a serious threat to our modern technological society and even human lives outside the protective Earth's atmosphere and magnetosphere. Our knowledge of such events was limited to nearly 70 years, with the strongest directly observed solar particle storm occurred on 23-Feb-1956 with a ~5000 % enhancement over the galactic cosmic-ray background. The following questions may arise: Can even stronger storms appear? How much stronger and how often? What could be the "worst-case scenario"? What consequences of such events would be for modern society? The era of direct measurements is too short to answer these questions, but nature gives us a unique chance to get answers. Thanks to the recent discoveries, we know that there are extreme events on the Sun on the large-time scale and on distant sun-like stars. Here we present an overview of the current state of the art in the study of extreme SEP events based on different indirect methods, including cosmogenic isotope (14C, 10Be, 36Cl) in terrestrial archives and lunar rocks, as well as an extensive statistic of the superflares on sun-like stars.

Revisited reference solar proton event of 23-Feb-1956: Assessment of the cosmogenic-isotope method sensitivity to extreme solar events

Ilya G. **Usoskin**, Sergey A. Koldobskiy, Gennady A. Kovaltsov, Eugene V. Rozanov, Timophei V. Sukhodolov, Alexander L. Mishev, Irina A. Mironova
JGR **Volume125, Issue6**, e2020JA027921 (**2020**)
https://arxiv.org/pdf/2005.10597.pdf
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020JA027921
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020JA027921?casa_token=JL5jrXVkjWYAAAAA:XTazdqoNcbN8oPkR_r8rakoA8o3enkq5lkcMfWt4tBrx_Zeb5GrVJLXPx2cGH7NNmoURjpVeduoiBjHS

Our direct knowledge of solar eruptive events is limited to several decades and does not include extreme events, which can only be studied by the indirect proxy method over millennia, or by a large number of sun-like stars. There is a gap, spanning 1--2 orders of magnitude, in the strength of events between directly observed and reconstructed ones. Here, we study the proxy-method sensitivity to identify extreme solar particle events (SPEs). First, the strongest directly observed SPE (23-Feb-1956), used as a reference for proxy-based reconstructions, was revisited using the newly developed method. Next, the sensitivity of the cosmogenic-isotope method to detect a reference SPE was assessed against the precision and number of individual isotopic records, showing that it is too weak by a factor ≈30 to be reliably identified in a single record. Uncertainties of 10Be and 14C data are shown to be dominated by local/regional patterns and measurement errors, respectively. By combining several proxy records, an SPE 4--5 times stronger than the reference one can be potentially detected, increasing the present-day sensitivity by an order of magnitude. This will allow filling the observational gap in SPE strength distribution, thus enriching statistics of extreme events from 3--4 presently known ones to several tens. This will provide a solid basis for research in the field of extreme events, both for fundamental science, viz. solar and stellar physics, and practical applications, such as the risk assessments of severe space-based hazards for the modern technological society.

Analysis of Ground-Level Enhancements: Strong events are hard

I. **Usoskin**, E. Asvestari, T. Willamo, A. Gil, G. Kovaltsov, V. Mikhailov and A. Mayorov
Proc. of 35th International Cosmic Ray Conference — ICRC2017 10–20 July, **2017** Bexco, Busan, Korea
https://pos.sissa.it/301/126/pdf

Ground Level Enhancements (GLEs) recorded by neutron monitor detectors are characterized by a variety of energy spectra of solar energetic particles (SEP), which vary between soft (as in August 1972) and hard (February 1956) ones. The aim of this work is to investigate the statistical relation between the hardness of the energy spectra and the event-integrated intensity. We calculated the event-integrated omnidirectional fluence of protons above 30 MeV (F30) and above 200 MeV (F200) using energy spectra reconstructed from both ground-based and space-borne data. The ratio of the F30-to-F200 fluences is considered as an index of the hardness of the events spectra. The main results of this study is that all strong events (with the event-integrated intensity greater than 100 %*hr) are characterized by a hard or very hard spectrum, while weak and moderate events do not show any clear pattern between the hardness and the intensity of the event.

Database of Ground Level Enhancements (GLE) of High Energy Solar Proton Events.

Usoskin, I., Ibragimov, A., Shea, M., Smart, D.
In: Procs. of 34th Interna. Cosmic Ray Conf. den Haag, the Netherlands, p. ID 054, **2015**
http://pos.sissa.it/archive/conferences/236/054/ICRC2015_054.pdf

Solar proton events (SPE) occur as a result of massive acceleration of charged particles in the solar corona and/or interplanetary space. Usually such events provide quite a soft spectrum of energetic particles, but sometimes the spectrum is sufficiently hard that the initial solar protons can generate secondary nucleons that can be detected as an increase in the cosmic ray flux at ground level. Such exceptional events are called GLE (ground-level enhancements) of cosmic rays and are numbered consecutively from the first event that was detected in 1942. Here we present an international GLE database hosted by the University of Oulu, that is an inheritance of pervious similar databases developed in the USA and Australia. We acknowledge the work of Louise Gentile, Mark Duldig and Harm Moraal.
The database is located at http://gle.oulu.fi
The interface and data organization are discussed as well as a possibility for accessing and mir-roring the database.

OCCURRENCE OF EXTREME SOLAR PARTICLE EVENTS: ASSESSMENT FROM HISTORICAL PROXY DATA

Ilya G. **Usoskin**1 and Gennady A. Kovaltsov
2012 ApJ 757 92
doi: 10.1088/0004-637X/757/1/92

The probability of occurrence of extreme solar particle events (SPEs) with proton fluence (>30 MeV) F 30 ≥ 1010 cm–2 is evaluated based on data on the cosmogenic isotopes 14C and 10Be in terrestrial archives covering centennial-millennial timescales. Four potential candidates with F 30 = (1-1.5) × 1010 cm–2 and no events with F 30 > 2 × 1010 cm–2 are identified since 1400 AD in the annually resolved 10Be data. A strong SPE related to the Carrington flare of 1859 AD is not supported by the data. For the last 11,400 years, 19 SPE candidates with F 30 = (1-3) × 1010 cm–2 are found and clearly no event with F 30 > 5 × 1010 cm–2 (50 times the SPE of 1956 February 23) has occurred. These values serve as observational upper limits on the strength of SPEs on the timescale of tens of millennia. Two events, ca. 780 and 1460 AD, appear in different data series making them strong candidates for extreme SPEs. We build a distribution of the occurrence probability of extreme SPEs, providing a new strict observational constraint. Practical limits can be set as F 30 1, 2-3, and 5×1010 cm–2 for occurrence probabilities 10–2, 10–3, and 10–4 yr–1, respectively. Because of the uncertainties, our results should be interpreted as a conservative upper limit on the SPE occurrence near Earth. The mean solar energetic particle (SEP) flux is evaluated as 40 (cm2 s)–1, in agreement with estimates from lunar rocks. On average, extreme SPEs contribute about 10% to the total SEP fluence .

Particle Acceleration Mechanisms Tutorial Review

Rami **Vainio** and Alexandr Afanasiev
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis Chapter 3, **2018**

https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
This chapter provides a short tutorial review on particle acceleration in dynamic electromagnetic fields under scenarios relevant to the problem of particle acceleration in the solar corona and solar wind during solar eruptions. It concentrates on fundamental aspects of the acceleration process and refrains from presenting detailed modeling of the specific conditions in solar eruptive plasmas. All particle acceleration mechanisms (in the solar corona) are related to electric fields that can persist in the highly conductive plasma: either electrostatic (or potential) or inductive related to temporally variable magnetic fields through Faraday's law. Mechanisms involving both kinds of fields are included in the tutorial.

Why is solar cycle 24 an inefficient producer of high-energy particle events?

Rami **Vainio**, Osku Raukunen, Allan J. Tylka, William F. Dietrich, Alexandr Afanasiev
A&A 604, A47 **2017**
https://arxiv.org/pdf/1707.00485.pdf
sci-hub.tw/10.1051/0004-6361/201730547
The aim of the study is to investigate the reason for the low productivity of high-energy SEPs in the present solar cycle. We employ scaling laws derived from diffusive shock acceleration theory and simulation studies including proton-generated upstream Alfv\'en waves to find out how the changes observed in the long-term average properties of the erupting and ambient coronal and/or solar wind plasma would affect the ability of shocks to accelerate particles to the highest energies. Provided that self-generated turbulence dominates particle transport around coronal shocks, it is found that the most crucial factors controlling the diffusive shock acceleration process are the number density of seed particles and the plasma density of the ambient medium. Assuming that suprathermal populations provide a fraction of the particles injected to shock acceleration in the corona, we show that the lack of most energetic particle events as well as the lack of low charge-to-mass ratio ion species in the present cycle can be understood as a result of the reduction of average coronal plasma and suprathermal densities in the present cycle over the previous one.

A semi-analytical foreshock model for energetic storm particle events inside 1 AU

Rami **Vainio**1,2*, Arttu Pönni1, Markus Battarbee2, Hannu E. J. Koskinen1,3, Alexandr Afanasiev1 and Timo Laitinen
J. Space Weather Space Clim. 4 (**2014**) A08
http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130035.pdf
We have constructed a semi-analytical model of the energetic-ion foreshock of a CME-driven coronal/interplanetary shock wave responsible for the acceleration of large solar energetic particle (SEP) events. The model is based on the analytical model of diffusive shock acceleration of Bell (1978), appended with a temporal dependence of the cut-off momentum of the energetic particles accelerated at the shock, derived from the theory. Parameters of the model are re-calibrated using a fully time-dependent self-consistent simulation model of the coupled particle acceleration and Alfvén-wave generation upstream of the shock. Our results show that analytical estimates of the cut-off energy resulting from the simplified theory and frequently used in SEP modelling are overestimating the cut-off momentum at the shock by one order magnitude. We show also that the cut-off momentum observed remotely far upstream of the shock (e.g., at 1 AU) can be used to infer the properties of the foreshock and the resulting energetic storm particle (ESP) event, when the shock is still at small distances from the Sun, unaccessible to the in-situ observations. Our results can be used in ESP event modelling for future missions to the inner heliosphere, like the Solar Orbiter and Solar Probe Plus as well as in developing acceleration models for SEP events in the solar corona.

The first SEPServer event catalogue ~68-MeV solar proton events observed at 1 AU in 1996–2010

Rami **Vainio** 1,*, Eino Valtonen2, Bernd Heber3, Olga E. Malandraki4, Athanasios Papaioannou4, Karl-Ludwig Klein5, Alexander Afanasiev1, Neus Agueda6, Henry Aurass7, Markus Battarbee2, Stephan Braune7, Wolfgang Dro¨ge8, Urs Ganse8, Clarisse Hamadache9, Daniel Heynderickx10, Kalle Huttunen-Heikinmaa2, Ju¨ rgen Kiener9, Patrick Kilian8, Andreas Kopp3, Athanasios Kouloumvakos11, Sami Maisala1, Alexander Mishev12, Rositsa Miteva5, Alexander Nindos11, Tero Oittinen1, Osku Raukunen2, Esa Riihonen2, Rosa Rodrı´guez-Gase´n5,9, Oskari Saloniemi2, Blai Sanahuja6, Renate Scherer3, Felix Spanier8, Vincent Tatischeff9, Kostas Tziotziou4, Ilya G. Usoskin12, and Nicole Vilmer5
J. Space Weather Space Clim. 3 (**2013**) A12; **File**
SEPServer is a three-year collaborative project funded by the seventh framework programme (FP7-SPACE) of the European Union. The objective of the project is to provide access to state-of-the-art observations and analysis tools for the scientific community on solar energetic particle (SEP) events and related electromagnetic (EM) emissions. The project will eventually lead to better understanding of the particle acceleration and transport processes at the

Sun and in the inner heliosphere. These processes lead to SEP events that form one of the key elements of space weather. In this paper we present the first results from the systematic analysis work performed on the following datasets: SOHO/ERNE, SOHO/EPHIN, ACE/EPAM, Wind/WAVES and GOES X-rays.
A catalogue of SEP events at 1 AU, with complete coverage over solar cycle 23, based on high-energy (~68-MeV) protons from SOHO/ERNE and electron recordings of the events by SOHO/EPHIN and ACE/EPAM are presented. A total of 115 energetic particle events have been identified and analysed using velocity dispersion analysis (VDA) for protons and time-shifting analysis (TSA) for electrons and protons in order to infer the SEP release times at the Sun. EM observations during the times of the SEP event onset have been gathered and compared to the release time estimates of particles. Data from those events that occurred during the European day-time, i.e., those that also have observations from ground-based observatories included in SEPServer, are listed and a preliminary analysis of their associations is presented. We find that VDA results for protons can be a useful tool for the analysis of proton release times, but if the derived proton path length is out of a range of 1 AU < s < 3 AU, the result of the analysis may be compromised, as indicated by the anti-correlation of the derived path length and release time delay from the associated X-ray flare. The average path length derived from VDA is about 1.9 times the nominal length of the spiral magnetic field line. This implies that the path length of first-arriving MeV to deka-MeV protons is affected by interplanetary scattering. TSA of near-relativistic electrons results in a release time that shows significant scatter with respect to the EM emissions but with a trend of being delayed more with increasing distance between the flare and the nominal footpoint of the Earth-connected field line.

SOLAR ENERGETIC PARTICLE ACCELERATION IN REFRACTING CORONAL SHOCK WAVES

Rami **Vainio** and Josef I. Khan1,2

Astrophysical Journal, 600:451–457, **2004**

Gradual solar energetic particle (SEP) events are known to be correlated with coronal mass ejections (CMEs) and soft X-ray flares. The current paradigm of particle acceleration in these events attributes it to CME-driven shock waves in the solar corona and in interplanetary space. Even in small gradual SEP events related to CMEs with speeds in the (possibly submagnetosonic) range of 300–800 km s_1, shock waves at global coronal scales, as evidenced by associated metric type II radio bursts, are important. Recent observational evidence from soft X-ray imaging data supports models of coronal shock wave propagation in the solar atmosphere as freely propagating blast waves that refract toward the solar surface as they propagate away from the flare site. Based on these observations, we study a model of test-particle acceleration in such a global refracting coronal shock wave. Such shocks may also be generated by solar eruptions other than flares, e.g., slow CMEs. The geometry of the shock wave results in the observer in the interplanetary medium being magnetically connected with the downstream region of the shock wave. Thus, steady-state diffusive shock acceleration predicts that the energy spectrum of the escaping ions is a power law, as typically observed—a result that is not obtained naturally if the observer is connected to the upstream region of the shock wave. Using parameters of upstream turbulence obtained from models of a cyclotron-heated solar corona, we calculate typical timescales of diffusive proton acceleration and show them to be consistent with the maximum proton energies typically observed in small, gradual SEP events. Acceleration in refracting coronal shock waves may also provide a preacceleration mechanism for further acceleration in CME-driven shocks in large gradual SEP events.

Seven Decades of Neutron Monitors (1951–2019): Overview and Evaluation of Data Sources

Pauli **Väisänen**, Ilya Usoskin, Kalevi Mursula

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020JA028941

https://doi.org/10.1029/2020JA028941

The worldwide network of neutron monitors (NMs) is the primary instrument to study cosmic-ray variability on time scales of up to 70 yr. Since the 1950s, 147 NMs with publicly available data have been in operation, and their records are archived in and distributed through different repositories and data sources. A comprehensive analysis of all available NM data sets (300 data sets from 147 NMs) is performed here to check the quality and consistency of the data. The data sources include World Data Center for Cosmic Rays, the Neutron Monitor Database, the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation (IZMIRAN) and individual station/institution databases. It was found that The data from the same NM can be nonidentical and of different quality in different sources. We give and tabulate here a recommendation for the optimal data source of each NM. We also present here a list of 29 “prime” stations with the longest and most reliable data. Verified data sets for these prime stations are provided as supplementary information.

Features of relativistic solar proton spectra derived from ground level enhancement events (GLE) modeling

E. V. **Vashenyuk**, Yu. V. Balabin, and B. B. Gvozdevsky
Astrophys. Space Sci. Trans., 7, 459–463, **2011**
https://sci-hub.ru/10.5194/astra-7-459-2011
http://www.astrophys-space-sci-trans.net/7/459/2011/astra-7-459-2011.pdf
With the developed by the authors of a ground level enhancements events (GLE) modeling technique, the modeling study of 35 large GLEs for the period 1956–2006 has been carried out. The basic characteristics of relativistic solar protons (RSP) are obtained: a rigidity (energetic) spectrum, anisotropy axis direction, and pitch angle distributions for each event. It is shown that in nearly all events there existed two components (population) of relativistic solar particles: prompt and delayed. The prompt component (PC) prevails in the beginning of the event. It is characterized by an impulsive profile, strong anisotropy and exponential energetic spectrum. The delayed component (DC) dominates during maximum and decline phases of the events. It has a gradual intensity profile, moderate anisotropy and a power law energetic spectrum. The analysis of the large number GLE shows the value of a characteristic energy in the exponential spectrum of PC has rather stable meaning ~0.5 GeV and well agrees with the spectrum of protons accelerated in an electric field arising during the magnetic reconnection in the solar corona. The value of a spectral exponent of the power law spectrum of DC is distributed from 4 up to 6 with most at 5. This is close to the simulated spectrum arising in the process of stochastic acceleration in turbulent solar plasma. **20 Jan 2005**
Table 1. Parameters of energetic spectra of relativistic solar protons in the GLEs 1956 – 2006.

Some features of the sources of relativistic particles at the Sun in the solar cycles 21-23.

Vashenyuk, E. V., Balabin, Y. V., Perez-Peraza, J., Gallegos-Cruz, A., and Miroshnichenko, L. I. (**2006**). Adv. Space Res. 38, 411–417.
https://doi.org/10.1016/j.asr.2005.05.012
https://sci-hub.ru/10.1016/j.asr.2005.05.012
Regularities of relativistic solar protons (RSP) generation and release from the Sun in the events of 21 23 solar cycles on data of neutron monitors, balloons and spacecraft have been studied. In all, 11 Ground Level Enhancements (GLE) of solar cosmic rays (SCR) were analyzed. The two-peak structure of solar proton intensity profiles gives certain evidence of that two distinct particle populations (components) exist: the early impulse-like intensity increase with a hard energy spectrum (prompt component, PC) and late gradual increase with a soft energy spectrum (delayed component, DC). The existence of two RSP populations is also confirmed by different forms of spectral fitting for PC and DC and by their dynamics as derived from neutron monitor data with optimization methods. It is shown that the PC energy spectrum has exponential form that may be an evidence of the acceleration by electric fields arising in the reconnecting current sheets in the corona. The DC energy spectrum may be fitted by a power-law function. Considering the timing of generation and release of two RSP components from the solar corona, the following scenario may be suggested. The prompt component of RSP is produced during initial energy release in a low-coronal magnetic null point. This process is linked with the H-alpha eruption, onset of CME and type II radio emission. The accelerated particles of PC leave the corona along open field lines with diverging geometry that results in strong focusing of a bunch. Particles of DC originally are trapped in magnetic arches in the low corona and accelerated by a stochastic mechanism at the MHD turbulence in expanding flare plasma. Accelerated particles of DC can be then carried out to the outer corona by an expanding CME. They are released into interplanetary space after the magnetic trap is destroyed giving rise to the source of accelerated particles that is extended in time and azimuth. **20 Jan 2005**
Table 1. Parameters of energetic spectra of relativistic solar protons in the GLEs 1956 – 2006.

Major X-class solar flare from earth-facing active region AR 12887 on October 28, 2021 and first cosmic ray GLE 73 in solar cycle 25.

Velinov, P.I.Y.:
2022, C. R. Acad. Bulgare Sci. 75(2), 248. **File**
http://www.proceedings.bas.bg/index.php/cr/article/download/29/29/39
A phenomenological study of the new Ground Level Enhancement GLE 73 of cosmic rays (CRs) on October 28, 2021 is presented in this work. The investigated GLE 73 appears as one of the first major events of the Sun in the new solar cycle 25 (2019–2030). The recent GLE 73 occurred as a result of an X-class solar flare and was measured on the surface of both the Earth (by Neutron Monitors) and PAMELA satellite-borne instruments.This GLE occurs as a result of massive acceleration of charged particles in the solar corona and interplanetary space. Usually such event provides quite a soft spectrum of energetic particles, but sometimes the spectrum is sufficiently hard so that the initial solar protons can generate secondary nucleons that can be detected as an increase in the cosmic ray flux at ground level. Such exceptional event represents the studied GLE 73. These GLEs of cosmic rays are numbered consecutively from the first events that were detected on February 28, 1942 (GLE 1) and March 7, 1942 (GLE 2) J exactly 80 years ago. During the past 80 years of GLE studies some fundamental results of space physics have been achieved. Analyzing the list of all GLEs registered until now in the period (1942–2021) some characteristics that are

important parameters can be determined. The quantification of GLEs in different solar cycles is presented by calculating the frequency of GLE occurrence in solar cycles 17–25.

Dynamics of the energy spectra of solar proton events observed in solar cycle 23

I. S. **Veselovsky**, I. N. Myagkova & O. S. Yakovchouk

Solar System Research, Volume 46 Number 3, S. 235-258, **2012**

Vyyavlena i proanalizirovana zavisimost' ot vremeni energeticheskikh spektrov I(E, t) protonov v oblasti desyatkov megaelektronvol't po nablyudeniyam na ISZ GOES v period protonnykh vozrastanii v 23-m tsikle solnechnoi aktivnosti. Postroena approksimatsiya energeticheskikh spektrov stepennymi funktsiyami i naideno bol'shoe raznoobrazie funktsii I(E, t) dlya issledovannykh sobytii. Kakaya-libo universal'naya zavisimost' spektrov ot vremeni otsutstvuet, odnako nekotorye obshchie cherty obnaruzhivayutsya dlya trekh grupp protonnykh sobytii, chto pozvolyaet priblizit'sya k ikh empiricheskoi klassifikatsii v budushchem s ispol'zovaniem ryada bezrazmernykh masshtabnykh parametrov. Svoi vklad v formirovanie etikh zakonomernostei vnosyat dinamicheskie protsessy na Solntse, v geliosfere i magnitosfere.

O prognoze solnechnykh protonnykh sobytii po dannym nazemnykh neitronnykh monitorov

Veselovskii I.S., Yakovchuk O.S.

Astron. vestn. **2011**. T. 45. № 4. C. 365–375.

Energetic particles in the solar atmosphere Review

Vilmer, N., Musset, S.

SF2A-2019: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics **2019**

http://sf2a.eu/proceedings/2019/2019sf2a.conf..0283V.pdf

The Sun is an efficient particle accelerator. These particles play a major role in the active Sun because they contain a large amount of the magnetic energy released during flares. Energetic electrons and ions interact with the solar atmosphere and produce high-energy X-rays and γ-rays. Energetic particles can also escape to the corona and interplanetary medium and may eventually reach the Earth's orbit. It is currently admitted that solar flares are powered by magnetic energy previously stored in the coronal magnetic field and that magnetic energy release is likely to occur on coronal current sheets along regions of strong gradient of magnetic connectivity. Particle transport from the acceleration region to the emission sites must also be considered to infer properties of the accelerated particles (and thus of the acceleration processes) from the observations of their radiation. In this paper, we will present the results of some recent studies using RHESSI observations: relationship found in some flares between ribbons of electric currents observed at the photospheric level and the flare energetic electrons traced by their X-ray emissions. We will also present some results on electron transport in solar flares and comment on the role of scattering in this process. We will finally describe some recent results from FERMI/LAT observations on the production of GeV protons in connection with solar flares and/or coronal mass ejections. **2002.07.23, 21 May 2004, 15 Feb 2011, 24 Feb 2014**

3 FERMI/LAT observations of long duration γ-ray events

Sources of Solar Energetic Particles Review

Loukas **Vlahos** , Anastasios Anastasiadis2 , Athanasios Papaioannou2 , Athanasios Kouloumvakos3 and Heinz Isliker1

Philosophical Transactions of the Royal Society A v. 377 Issue 2148 Article ID: **20180095** **2019** **File**

https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2018.0095

https://arxiv.org/pdf/1903.08200.pdf

Solar Energetic Particles (SEP) are an integral part of the physical processes related with Space Weather. We present a review for the acceleration mechanisms related to the explosive phenomena (flares and/or CMEs) inside the solar corona. For more than 40 years, the main 2D cartoon representing our understanding of the explosive phenomena inside the solar corona remained almost unchanged. The acceleration mechanisms related to solar flares and CMEs also remained unchanged and were part of the same cartoon. In this review, we revise the standard cartoon and present evidence from recent global MHD simulations that supports the argument that explosive phenomena will lead to the spontaneous formation of current sheets in different parts of the erupting magnetic structure. The evolution of the large scale current sheets and their fragmentation will lead to strong turbulence and turbulent reconnection during solar flares and turbulent shocks. In other words, the acceleration mechanism in flares and CME-driven shocks may be the same, and their difference will be the overall magnetic topology, the ambient plasma parameters, and the duration of the unstable driver. 28 October 2003, 29 October 2003, 4 August 2011, 27 January 2012 **Хороший справочник литературы.**

2. Key observational constraints for particle acceleration theories in the solar corona
(a) Location of solar energetic particles acceleration and release sites
(b) Critical properties of coronal mass ejections and the associated shock waves
(c) Impulsive, gradual and mixed events
(d) Elemental abundance and spectral variability
(e) What about solar energetic particles without flares or coronal mass ejections?
(f) A summary of the key observational points
3. The evolution of magnetic topologies and eruptive phenomena
4. Energization of particles in weak and strong turbulence during explosive events
(a) Weak turbulence (b) Strong turbulence
5. Energization of particles during magnetic flux emergence
6. Acceleration of particles by coronal mass ejection-driven shocks

PARTICLE ACCELERATION AND HEATING BY TURBULENT RECONNECTION

Loukas **Vlahos**1, Theophilos Pisokas1, Heinz Isliker1, Vassilis Tsiolis1, and Anastasios Anastasiadis

2016 ApJ 827 L3

Turbulent flows in the solar wind, large-scale current sheets, multiple current sheets, and shock waves lead to the formation of environments in which a dense network of current sheets is established and sustains "turbulent reconnection." We constructed a 2D grid on which a number of randomly chosen grid points are acting as scatterers (i.e., magnetic clouds or current sheets). Our goal is to examine how test particles respond inside this large-scale collection of scatterers. We study the energy gain of individual particles, the evolution of their energy distribution, and their escape time distribution. We have developed a new method to estimate the transport coefficients from the dynamics of the interaction of the particles with the scatterers. Replacing the "magnetic clouds" with current sheets, we have proven that the energization processes can be more efficient depending on the strength of the effective electric fields inside the current sheets and their statistical properties. Using the estimated transport coefficients and solving the Fokker–Planck (FP) equation, we can recover the energy distribution of the particles only for the stochastic Fermi process. We have shown that the evolution of the particles inside a turbulent reconnecting volume is not a solution of the FP equation, since the interaction of the particles with the current sheets is "anomalous," in contrast to the case of the second-order Fermi process.

See CESRA highlight https://www.astro.gla.ac.uk/users/eduard/cesra/?p=687

Scattering of solar energetic electrons in interplanetary space

C. **Vocks** and G. Mann

A&A 502, 325-332 (**2009**)
DOI: 10.1051/0004-6361/200911738

Context. Solar energetic electrons are observed to arrive between 10 and 30 min later at 1 AU compared to the expectation based on their production in a solar flare and the travel time along the Parker spiral. Both a delayed release of electrons from the Sun and scattering of the electrons along their path are discussed as possible underlying mechanisms.
Aims. We investigate to what extent scattering of energetic electrons in interplanetary space influences the arrival times of electrons at a solar distance of 1 AU, as a function of electron energy and for different scattering models.
Methods. A kinetic model for electrons in interplanetary space is used to study the propagation of solar-flare electrons injected into the corona. The electrons are scattered by resonant interaction with a whistler-wave spectrum that is based on observed magnetic field fluctuation spectra in the solar wind. The arrival times of the electrons at 1 AU is determined by the electron flux exceeding a given threshold value.
Results. The simulation results show a significant influence of the scattering on electron arrival times. Electrons with energies in the range of several tens of keV are delayed by up to about one minute for a pure pitch-angle scattering model. It is demonstrated that this simplification is not applicable, and the full quasi-linear diffusion equation needs to be considered. This reduces the delays to values below 30 s.
Conclusions. It follows from these numerical studies that scattering of electrons in interplanetary space due to resonant interaction with whistler waves cannot explain the observed delays of 600 s, unless an unrealistic wave spectrum is assumed in interplanetary space.

Jovian electrons in the inner heliosphere

Proposing a new source spectrum based on 30 years of measurements

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A&A 613, A28 (**2018**)

https://www.aanda.org/articles/aa/pdf/2018/05/aa31736-17.pdf

Context. Since the Pioneer 10 flyby of Jupiter it has become well known that electrons of Jovian origin dominate the lower MeV range of charged energetic particles in the inner heliosphere.

Aims. Because the Jovian source can be treated as point-like in numerical models, many attempts to investigate charged particle transport in the inner heliosphere have utilized Jovian electrons as test particles. The reliability of the derived parameters for convective and diffusive transport processes are therefore highly dependent on an accurate estimation of the Jovian source spectrum. In this study we aim to provide such an estimation.

Methods. In this study we have proposed a new electron source spectrum, specified at the boundary of the Jovian magnetosphere, fitted to flyby measurements by Pioneer 10 and Ulysses, with a spectral shape also in agreement with measurements at Earth's orbit by Ulysses, Voyager 1, ISEE and SOHO.

Results. The proposed spectrum is consistent with all previous theoretical suggestions, but deviates considerably in the lower MeV range which was inaccessible to those studies.

The Solar Energetic Particle Event of 14 December 2006

T.T. **von Rosenvinge** · I.G. Richardson · D.V. Reames · C.M.S. Cohen · A.C. Cummings · R.A. Leske · R.A. Mewaldt · E.C. Stone · M.E. Wiedenbeck

Solar Phys (**2009**) 256: 443–462, DOI 10.1007/s11207-009-9353-6

STEREO SCIENCE RESULTS AT SOLAR MINIMUM

The solar energetic particle event on 14 December 2006 was observed by several near-Earth spacecraft including the Advanced Composition Explorer (ACE), STEREO A and B, SOHO and *Wind*. An interesting feature of this event is a series of unusual fluctu ations in the particle intensity that occurred during the first few hours. These fluctuations were observed inside a magnetic cloud that originated in a solar event on **13 December** and show both similarities and variations at the different spacecraft. Interestingly, the most striking difference is between observations at the two *closely-separated* STEREO spacecraft. In particular, large fluctuations in the proton intensity were seen by the High Energy Telescope (HET) on STEREO A, and to a lesser extent at *Wind* and ACE, but not by the STEREO B HET.We conclude that the differences in intensity-time profiles were caused by anisotropies in the particle distribution and the different viewing directions of the individual particle telescopes. The intensity/anisotropy variations suggest that flux tubes with different particle propagation conditions existed within this magnetic cloud despite the absence of local magnetic field signatures associated with these regions. The intensity fluctuations are similar to those occasionally seen in impulsive particle events. There were also spacecraft to spacecraft differences during the onset of the particle event. An initial rapid onset of energetic (>40 MeV) protons was observed by the STEREO A and B spacecraft outside the magnetic cloud, but not by spacecraft such as SOHO that were already inside the magnetic cloud at this time. The latter spacecraft observed a slower, lower intensity increase. Evidently, energetic proton propagation from the solar event to the vicinity of Earth was inhibited within the magnetic cloud compared to outside.

Radial Evolution of ICME-Associated Particle Acceleration Observed by Solar Orbiter and ACE

Malik H. **Walker**, Robert C. Allen, Gang Li, George C. Ho, Glenn M. Mason, Javier Rodriguez-Pacheco, Robert F. Wimmer-Schweingruber, Athanasios Kouloumvakos

A&A **2024**

https://arxiv.org/pdf/2410.01885

On 2022 March 10, a coronal mass ejection (CME) erupted from the Sun, resulting in Solar Orbiter observations at 0.45 au of both dispersive solar energetic particles arriving prior to the interplanetary CME (ICME) and locally accelerated particles near the ICME-associated shock structure as it passed the spacecraft on 2022 March 11. This shock was later detected on 2022 March 14 by the Advanced Composition Explorer (ACE), which was radially aligned with Solar Orbiter, at 1 au. Ion composition data from both spacecraft -- via the Solar Orbiter Energetic Particle Detector/ Suprathermal Ion Spectrograph (EPD/SIS) and the Ultra Low Energy Isotope Spectrometer (ULEIS) on ACE -- allows for in-depth analysis of the radial evolution of species-dependent ICME shock-associated acceleration processes for this event. We present a study of the ion spectra observed at 0.45 and 1 au during both the gradual solar energetic particle (SEP) and energetic storm particle (ESP) phases of the event. We find that the shapes of the spectra seen at each spacecraft have significant differences that were likely caused by varying shock geometry: Solar Orbiter spectra tend to lack spectral breaks, and the higher energy portions of the ACE spectra have comparable average flux to the Solar Orbiter spectra. Through an analysis of rigidity effects on the spectral breaks observed by ACE, we conclude that the 1 au observations were largely influenced by a suprathermal pool of He+ ions that were enhanced due to propagation along a stream interaction region (SIR) that was interacting with the ICME at times of observation. **10-11 Mar 2022**

A statistical study on the peak and fluence spectra of Solar Energetic Particles observed over 4 solar cycles

Yubao **Wang**, Jingnan Guo

ApJ 691, A54 **2024**

https://arxiv.org/pdf/2410.13186

https://www.aanda.org/articles/aa/pdf/2024/11/aa50046-24.pdf

Solar energetic particles (SEPs) are an important space radiation source, especially for the space weather environment in the inner heliosphere. The energy spectrum of SEP events is crucial both for evaluating their radiation effects and for understanding their acceleration process at the source region and their propagation mechanism. In this work, we investigate the properties of the SEP peak flux spectra and the fluence spectra and their potential formation mechanisms using statistical methods. We aim to advance our understanding of both SEPs' acceleration and propagation mechanisms. Employing the dataset of European Space Agency's Solar Energetic Particle Environment Modelling (SEPEM) program, we have obtained and fitted the peak-flux and fluence proton spectra of more than a hundred SEP events from 1974 to 2018. We analyzed the relationship among the solar activity, X-ray peak intensity of solar flares and the SEP spectral parameters. Based on the assumption that the initial spectrum of accelerated SEPs generally has a power-law distribution and also the diffusion coefficient has a power-law dependence on particle energy, we can assess both the source and propagation properties using the observed SEP event peak flux and fluence energy spectra. We confirm that SEPs' spectral properties are influenced by the solar source and the interplanetary conditions and their transportation process can be influenced by different phases of solar cycle. This study provides an observational perspective on the double power-law spectral characteristics of the SEP energy spectra, showing their correlation with the adiabatic cooling and diffusion processes during the particle propagation from the Sun to the observer. This contributes to a deeper understanding of the acceleration and propagation of SEP events, in particular the possible origins of the double-power law.

1997.11.06

ESA's Solar Energetic Particle Environment Modelling (SEPEM) http://sepem.eu

SEPEM reference event list http://sepem.eu/help/event_ref.html 1973-2013

Solar Eruptive Phenomena Associated with Solar Energetic Electron Spectral Types

Wen **Wang**1,2, Linghua Wang2, Wenyan Li 2, Säm Krucker3,4, Robert F. Wimmer-Schweingruber5, and Zheng Sheng1

2024 ApJ 969 164

https://iopscience.iop.org/article/10.3847/1538-4357/ad47be/pdf

The energy spectral shape of solar energetic electron events carries important information on the energetic electron source/acceleration at the Sun. We investigate the association of six newly identified solar energetic electron spectral types with solar eruptive phenomena, including the downward double-power-law (DDPL) spectrum with break energy EB above 20 keV (DDPLEB⩾20keV), DDPL with EB below 20 keV (DDPLEB<20keV), upward double-power law (UDPL), single-power-law (SPL), Ellision–Ramaty–like (ER), and logarithmic-parabola (LP). We find that the SPL type shows (the other five types show) an association with hard X-ray flares of ∼38% (∼55%–82%) and an association with west-limb coronal mass ejections (CMEs) of ∼76% (∼85%–93%). Among the other five types, the DDPLEB<20keV and ER (LP and DDPLEB⩾20keV) types only have an association with type II radio bursts of ∼7%–8% (∼16%–20%) and an association with halo CMEs of ∼5%–9% (∼11%–21%); however, the UDPL type exhibits a significant (∼47% and ∼50%) association with type II bursts and halo CMEs, with a significantly faster median CME speed of 1000−120+550 km s−1. For DDPLEB⩾20keV (DDPLEB<20keV) with a positive (no) correlation between spectral indexes and no (a positive) correlation between the spectral index and break energy, the spectrum appears to be flatter as the associated CME (flare) becomes faster (stronger). These results suggest that the SPL type can result from the initial acceleration process that likely occurs high in the corona, and then provide seed populations for further acceleration processes to form the other five types: the DDPLEB<20keV and ER types via flare-related processes, the LP and DDPLEB⩾20keV types via CME-related processes, and the UDPL type via CME-driven shocks. **2002-12-19**

The effect of solar wind on the charged particles' diffusion coefficients

J. F. **Wang**, G. Qin

ApJ **2023**

https://arxiv.org/pdf/2310.09211.pdf

The transport of energetic charged particles through magnetized plasmas is ubiquitous in interplanetary space and astrophysics, and the important physical quantities are the along-field and cross-field spatial diffusion coefficients of energetic charged particles. In this paper, the influence of solar wind on particle transport is investigated. Using the focusing equation, we obtain along- and cross-field diffusion coefficient accounting for the solar wind effect. For different conditions, the relative importance of solar wind effect to diffusion are investigated. It is shown that when energetic charged particles are close to the sun, for along-field diffusion the solar wind effect needs to be taken into account. These results are important for studying energetic charged particle transport processes in the vicinity of the sun.

The Crucial Role of Perpendicular Diffusion in the Longitude Distribution of >10 MeV Solar Energetic Protons

Yang **Wang**1,2 and Gang Qin1,2

2023 ApJ 954 81

https://iopscience.iop.org/article/10.3847/1538-4357/ace35b/pdf **File**

Gradual solar proton events are thought to consist of solar components originating near the Sun and interplanetary components associated with interplanetary shocks, and the role of interplanetary shocks is considered to be crucial in supplying particles to regions that are not magnetically connected to the solar source region. We calculate the ratios of the peak intensities for the four energy channels (13–16, 20–25, 32–40, and 40–64 MeV) and compare the ratios observed by multiple spacecraft at different locations. We often find that the ratio of peak intensities observed at different locations in the same event remains almost constant as the energy varies. In other words, the ratio of peak intensities from the different energy channels remains almost constant as the position of the spacecraft changes. The phenomenon implies that in many gradual events, energetic particles observed at different locations are mainly composed of solar components that undergo perpendicular diffusion in both the vicinity of the Sun and the interplanetary space, and that perpendicular diffusion is the main factor enabling energetic particles to be observed in regions without magnetic connection to the solar source region. **2011 November 3, 05 March 2013, 2013 October 11.**

Table 1 Energetic Proton Events That Satisfy the Equal Ratio Relations Observed by STEREO-A, STEREO B, and SOHO 2010-2014

The 2013 November 12 Solar Energetic Electron Event Associated with Solar Jets

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2023 ApJ 950 118

https://iopscience.iop.org/article/10.3847/1538-4357/accc86/pdf

We investigate the hard X-ray (HXR) flare-associated "prompt" solar energetic electron (SEE) **2013 November 12** event with joint EUV jet observations from Solar Dynamics Observatory/Atmospheric Imaging Assembly and STEREO-A/EUVI. The SEE energy spectrum observed by Wind/3D Plasma and Energetic Particle shows a triple-power-law shape with a low-energy break of 10.0 ± 1.7 keV and a high-energy break of 56.6 ± 8.9 keV, which has never been reported before for jet-related SEE events. Associated HXR emissions observed by RHESSI and FGST/Gamma-ray Burst Monitor show three distinctive peaks with different spectral indices βHPE of HXR-producing electrons (HPEs) derived by means of thick-target bremsstrahlung model. The high-energy spectral index β3 = 4.63 ± 0.65 of SEE is consistent with the HPE spectral index βHPE derived in HXR peak 1 but different from βHPE of HXR peak 2 and peak 3. The main stream of EUV jets reaches a speed of 370 ± 25 km s−1 after an acceleration of up to 2.9 ± 0.4 km s−2 in a timescale of ∼2 minutes, and the acceleration time coincides with the decay phase of HXR peak 1. EUV observations from two different viewing directions help to reconstruct the jet magnetic configurations. After the investigation on HXR emissions and jet configurations, the interchange-reconnection model triggered by the emerging flux could be a satisfactory explanation for this jet event.

Energy Spectrum of Solar Energetic Electron Events over 25 Years

Wen **Wang** (王雯)1,2, Linghua Wang (王玲华)2, Säm Krucker3,4, and Robert F. Wimmer-Schweingruber5

2023 ApJ 948 51

https://iopscience.iop.org/article/10.3847/1538-4357/acbea2/pdf

We investigate the peak flux energy spectrum of 458 solar energetic electron (SEE) events with a clear velocity dispersion detected at energies from ≤4.2 to ≥108 keV by Wind/3DP from 1994 December through 2019 December, utilizing a pan-spectrum fitting method. According to the fitted spectral parameters, these 458 events are self-consistently classified into five spectral types: 304 downward double-power-law (DDPL) events, 32 upward double-power-law (UDPL) events, 23 single-power-law (SPL) events, 44 Ellison–Ramaty (ER) events, and 55 logarithmic–parabola (LP) events. The DDPL events can be further divided into two types: 231 $\mathrm{DDPL}_{E_B \geqslant 20\mathrm{keV}}$ events and 73 $\mathrm{DDPL}_{E_B < 20\mathrm{keV}}$ events, since their break energy EB exhibits a double-peak distribution separated by a dip at ∼20 keV. The $\mathrm{DDPL}_{E_B < 20\mathrm{keV}}$ ($\mathrm{DDPL}_{E_B \geqslant 20\mathrm{keV}}$) events show a power-law spectral index of $2.0^{+0.2}_{-0.2}$ ($2.1^{+0.3}_{-0.3}$) at energies below $E_B = 5.6^{+2.3}_{-2.4}$ (61^{+23}_{-12}) keV and an index of $3.3^{+0.5}_{-0.3}$ ($3.9^{+0.6}_{-0.7}$) at energies above. The UDPL events have a spectral index of $3.0^{+0.3}_{-0.3}$ at energies below $E_B = 5.1^{+4.2}_{-1.8}$ keV and an index of $2.2^{+0.2}_{-0.3}$ at energies above. The SPL events exhibit a spectral index of $2.8^{+0.5}_{-0.2}$. The ER events show a spectral index of $1.9^{+0.3}_{-0.3}$ at energies below $E_c = 31^{+19}_{-11}$ keV. The LP events are characterized by a spectral slope of $1.8^{+0.4}_{-0.3}$ ($3.6^{+0.7}_{-0.5}$) at 2.8 keV (108 keV). The six spectral types also behave differently in the relationship between spectral parameters and in solar cycle variations. The spectral shape of most SEE events appears to be unrelated to the estimated electron path lengths. These results suggest that the formation of SEE events can involve complex processes/sources. **2000-06-28, 2000-12-28, 2002-10-07, 2001-11-22, 2002-04-16, 2005-03-16**

The Quantitative Relation of the Time Profiles of Intensities in the Well-connected Solar Energetic Particle Events

Yang **Wang**1, Dan Lyu1, Xinghui Wu1, and Gang Qin1
2022 ApJ 940 67
https://iopscience.iop.org/article/10.3847/1538-4357/ac99da/pdf
In this work, the quantitative relation of the intensity time profiles in the well-connected energetic particle events has been identified. Focusing on the propagation processes of energetic protons in the energy channels of about 13–64 MeV, solar energetic particle (SEP) events observed by STEREO A, STEREO B, and SOHO have been studied. The intensities observed by the spacecraft with the best magnetic connection to the source region tend to rise the fastest and have the highest peak intensities. In the cases without multiple injections or significant acceleration of particles by interplanetary shocks, particle intensities with the highest peaks are fitted by using a solution of the diffusion equation, and the time profiles of particle intensities could be described by two parameters. By fitting 59 energetic proton events, we find that the two parameters satisfy a power-law model in different events, and the distribution of peak time is also obtained. The power-law model helps one to obtain a quantitative relation of SEP intensities with the fitting function, and the distribution of peak time could provide a basis for determining the magnetic connection between the spacecraft and the source region. **2013 October 11, 2011 November 3**
Table 1 Fitting Results for the Intensities of SEP Events Observed by STEREO A, STEREO B, and SOHO 2010-2014

Solar Energetic Electron Events Associated with Hard X-Ray Flares

Wen **Wang**1, Linghua Wang1, Säm Krucker2,3, Glenn M. Mason4, Yang Su5,6, and Radoslav Bučík7
2021 ApJ 913 89
https://iopscience.iop.org/article/10.3847/1538-4357/abefce/pdf
https://doi.org/10.3847/1538-4357/abefce
We investigate 16 solar energetic electron (SEE) events measured by WIND/3DP with a double-power-law spectrum and the associated western hard X-ray (HXR) flares measured by RHESSI with good count statistics, from 2002 February to 2016 December. In all the 16 cases, the presence of an SEE power-law spectrum extending down to ≤5 keV at 1 au implies that the SEE source would be high in the corona, at a heliocentric distance of ≥1.3 solar radii, while the footpoint or footpoint-like emissions shown in HXR images suggest that the observed HXRs are likely produced mainly by HXR-producing electrons via thick-target bremsstrahlung processes very low in the corona. We find that for all the 16 cases, the estimated power-law spectral index of HXR-producing electrons is no less than the observed high-energy spectral index of SEEs, and it shows a positive correlation with the high-energy spectral index of SEEs. In addition, the estimated number of SEEs is only ~10^{-4}–10^{-2} of the estimated number of HXR-producing electrons at energies above 30 keV, but with a positive correlation between the two numbers. These results suggest that in these cases, SEEs are likely formed by upward-traveling electrons from an acceleration source high in the corona, while their downward-traveling counterparts may undergo a secondary acceleration before producing HXRs via thick-target bremsstrahlung processes. In addition, the associated ^{3}He/^{4}He ratio is positively correlated with the observed high-energy spectral index of SEEs, indicating a possible relation of the ^{3}He ion acceleration with high-energy SEEs. **4 Aug 2002, 1 Nov 2004**
Table 1 Spectral Parameters of SEEs and Associated HXR Flares (2002-2016)
Table 4 SEEs Associated with Other Solar Phenomena

The Effects of Magnetic Boundary on the Uniform Distribution of Energetic Particle Intensities Observed by Multiple Spacecraft

Yang **Wang**1, Dan Lyu1, Gang Qin1, and Boxi Xiao1
2021 ApJ 913 66
https://iopscience.iop.org/article/10.3847/1538-4357/abf9a4/pdf
https://doi.org/10.3847/1538-4357/abf9a4
In the decay phase of solar energetic particle (SEP) events, particle intensities observed by widely separated spacecraft usually present comparable intensities (within a factor of 2–3) that evolve similarly in time. The phenomenon of SEP events is called a reservoir, which could be observed frequently in intensive gradual SEP events. In this work, we find the effects of the magnetic boundary could help to form the reservoir phenomenon in energetic proton and electron events. In the **1978 January 1** and the **2000 November 8** SEP events, we find the effects of the magnetic boundary associated with the reservoir phenomenon were observed simultaneously in the sheath of magnetic cloud/interplanetary coronal mass ejection. Based on the observations, we suggest that the effects of the magnetic boundary could be due to the magnetic mirrors and/or the small diffusion coefficients in the

sheath region and they could help to form the reservoir phenomenon in both the energetic proton and electron events in some large SEP events.

Solar Energetic Electrons Entering the Earth's Cusp/Lobe

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2021 ApJ 910 12

https://doi.org/10.3847/1538-4357/abdb2b

https://iopscience.iop.org/article/10.3847/1538-4357/abdb2b/pdf

We present a comprehensive study of three solar energetic electron events observed in the Earth's cusp/lobe regions by the BeiDa Image Electron Spectrometer (BD-IES) on board a BeiDou satellite in an inclined (55°) geosynchronous orbit in 2015 October, 2015 November, and 2016 January, respectively. In all three events at energies above 50 keV, the electron omnidirectional differential fluxes from BD-IES show a strong (~0.7–0.9) correlation with the simultaneous electron fluxes from the Wind 3DP instrument in the interplanetary medium, but generally with a smaller intensity. Compared to the Wind 3DP spectra of electron flux versus energy, the BD-IES electron spectra also fit well to a power-law function, $J_{\rm IES} \propto E^{-\gamma_{\rm IES}}$, but the power-law spectral index appears to be mostly smaller than the 3DP spectral index, for all three events. These measurements provide the first observational evidence that solar/interplanetary energetic electrons can directly and continuously enter the planet's cusp/lobe regions and get trapped there, probably leading to a contribution to the energetic electrons and/or seed particles for acceleration in the planetary magnetosphere. **28-30 Oct 2015, 4-5 Nov 2015, 1-4 Jan 2016**

Statistical Survey of Reservoir Phenomenon in Energetic Proton Events Observed by Multiple Spacecraft

Yang **Wang**1, Dan Lyu1, Boxi Xiao1, Gang Qin1, Yushui Zhong1, and Lele Lian1

2021 ApJ 909 110

https://iopscience.iop.org/article/10.3847/1538-4357/abda39/pdf

https://doi.org/10.3847/1538-4357/abda39

In this work, reservoir phenomenon in the decay phase of gradual solar energetic particle (SEP) events are investigated with two Helios and the IMP 8 spacecraft from 1976 January to 1980 March and two STEREO and the SOHO spacecraft from 2010 January to 2014 September. Using these data, 62 reservoir events of solar energetic protons were identified, and the effects of perpendicular diffusion and magnetic mirroring on the formation of the reservoir phenomenon have been studied. We find that the reservoir events could be observed in almost all longitudes in the ecliptic at 1 au; thus, the perpendicular diffusion in interplanetary space is an important mechanism to explain the uniform distribution of SEPs. Furthermore, in the **1976 April 30** event, the effects of magnetic mirroring associated with an interplanetary coronal mass ejection were observed during the reservoir phenomenon. Therefore, the effects of magnetic mirroring could also help to form the reservoir phenomenon. This study could improve the understanding of the propagation of SEPs in interplanetary space.

The Energy Spectrum of Solar Energetic Electron Events

Linghua **Wang**, Zixuan Liu, Haobo Fu, and Sam Krucker

EGU2020-1944 May **2020**

https://meetingorganizer.copernicus.org/EGU2020/displays/36057

Solar energetic electron events (SEEs) are one of the most common particle acceleration phenomena occurring at the Sun, and their energy spectrum likely reflects the crucial information on the acceleration. Here we present a statistical survey of the energy spectrum of 160 SEEs measured by Wind/3DP with a clear velocity dispersion at energies of ~1-200 keV from January 1995 through December 2016, utilizing a general spectrum formula proposed by Liu et al. (2000). We find that among these 160 SEEs, 144 (90%) have a power-law (or power-law-like) spectrum bending down at high energies, including 108 (67.5%) double-power-law events, 24 (15%) Ellison-Ramaty-like events and 12 (7.5%) log-parabola events, while 16 (10%) have a power-law spectrum extending to high energies. The average power-law spectral index β1 is 2.1±0.4 for double-power-law events, 1.7±0.8 for Ellison-Ramaty-like events, and 2.8±0.11 for single-power-law events. For the 108 double-power-law events, the spectral break energy E0 ranges from 2 keV to 165 keV, with an average of 71±79 keV, while the average spectral index β2 at energies above E0is 4.4±2.3. E0 shows a positive correlation with the electron peak flux at energies above ~40 keV, while β1 has a negative correlation with the electron peak flux at energies above ~15 keV.

Particle Acceleration at the Pileup Collision of the Twin Shock

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2019 ApJ 885 66

https://doi.org/10.3847/1538-4357/ab4655

Ground-level enhancement (GLE) events are often associated with large gradual solar events such as fast coronal mass ejections (CMEs), but not all fast CMEs lead to GLE events. Is there a type of coordinated CME that could produce GLEs with larger intensity and higher energies than those in the normal fast isolated CMEs? Here we propose a twin-shock scenario driven by the twin CME coordinately, in which the posterior shock catches up with the preceding shock and has a pileup collision. In the present study, we chose the first GLE event of the solar cycle 24 occurring on **2012 May 17** as an example to investigate the probable association with the twin-shock scenario. We use a dynamic Monte Carlo method to examine the energy spectrum with relevance to the GLE event. In the twin-shock scenario, the seed energetic particles produced by the normal preceding shock can be injected into the posterior shock for reacceleration efficiently. As a result, we obtain the detailed energy spectrum of the solar energetic particles (SEPs) with different behaviors at the related episodes of the twin-shock evolution. Therefore, we predict that the pileup collision of the twin shock would dominate a concave energy spectral slope in the 2012 May 17 SEP event.

A solar electron event model in near-Earth space

Jian-zhao **Wang**, Ying Wang, Shu-wu Dai, Chen Wang, ... Jia-wen Qiu

Advances in Space Research Volume 64, Issue 9, 1 November **2019**, Pages 1825-1837

sci-hub.se/10.1016/j.asr.2019.07.039

A new solar electron event model is developed based on Virtual Timeline Method (VTM). We study events individually by analyzing the 17-year data of 3DP instrument on WIND spacecraft. This model is established in different solar cycle phases and is based on statistics of duration, fluence, and waiting time of solar electron events. The fluences follow a log-normal distribution and logarithmic durations fit well with logarithmic fluences linearly. We prove that waiting times of events significantly deviates from the Poisson process by investigating the stationary and event independence property of Poisson distribution. After a comparison study on waiting times, we choose the Lévy distribution in solar minimum and maximum years. During solar minimum, the event frequency is much lower than that of solar maximum, but the event magnitude is independent of solar cycle period. Large events also happen in solar minimum years. In different solar cycle phases, this model can output a spectrum with confidence level and mission duration by generating many series of virtual timelines composed of many pseudo-events based on Monte Carlo method. On the other hand, spectra in solar minimum years are softer than that in solar maximum years. The fluences in solar maximum years are about one order of magnitude higher than that in solar minimum years in a given mission period. We also compare this model with Interplanetary Electron Model (IEM) quantitatively and prove that this model is advanced. **1995 April 22, 27 May 1999**

Did the 2000 November 8 solar flare accelerate protons to >=40 GeV?

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2017

https://arxiv.org/pdf/1708.02474.pdf

It has been reported that a 5.7sigma directional muon excess coincident with the **2000 July 14** solar flare was registered by the L3 precision muon spectrometer [Ruiguang Wang, Astroparticle Phys., 31(2009) 149]. Using a same analysis method and similar criteria of event selection, we have analyzed the L3 precision muon spectrometer data during November 2000. The result shows that a 4.7sigma muon excess appeared at a time coincident with the solar flare of **8 of November 2000**. This muon excess corresponds to above 40 GeV primary protons which came from a sky cell of solid angle 0.048 sr. The probability of being a background fluctuation is estimated to be about 0.1%. It has been convinced that solar protons could be accelerated to tens of GeV in those Class X solar flares which usually arose solar cosmic ray ground level enhancement (GLE) events. However, whether a Class M solar flare like the non-GLE event of 8 November 2000 may also accelerate solar protons to such high energies? It is interesting and noteworthy.

Particles Acceleration in Converged Two Shocks

Xin **Wang**, Joe Giacalone, Yihua Yan, Mingde Ding, Na Wang, Hao Shan

2017   ApJ 842 74

http://arxiv.org/pdf/1509.07934v1.pdf

Observations show that there is a proton spectral "break" with Ebreak at 1-10MeV in some large CME-driven shocks. Theoretical model usually attribute this phenomenon to a diffusive shock acceleration. However, the underlying physics of the shock acceleration still remains uncertain. Although previous numerical models can hardly predict this "break" due to either high computational expense or shortcomings of current models, the present paper focuses on simulating this energy spectrum in converged two shocks by Monte Carlo numerical method. Considering the **Dec 13 2006** CME-driven shock interaction with an Earth bow shock, we examine whether the energy spectral "break" could occur on an interaction between two shocks. As result, we indeed obtain the maximum proton energy up to 10MeV, which is the premise to investigate the existence of the energy spectral "break". Unexpectedly, we further find a proton spectral "break" appears distinctly at the energy ∼5MeV.

The injection of ten electron/3He-rich SEP events

Linghua **Wang**1, Säm Krucker2,3, Glenn M. Mason4, Robert P. Lin2 and Gang Li

A&A 585, A119 (**2016**)

http://arxiv.org/pdf/1605.07882v1.pdf

https://www.aanda.org/articles/aa/pdf/2016/01/aa27270-15.pdf

We have derived the particle injections at the Sun for ten good electron/^{3}He-rich solar energetic particle (SEP) events, using a 1.2 AU particle path length (suggested by analysis of the velocity dispersion). The inferred solar injections of high-energy (~10 to 300 keV) electrons and of ~MeV/nucleon ions (carbon and heavier) start with a delay of 17 ± 3 min and 75 ± 14 min, respectively, after the injection of low-energy (~0.4 to 9 keV) electrons. The injection duration (averaged over energy) ranges from ~200 to 550 min for ions, from ~90 to 160 min for low-energy electrons, and from ~10 to 30 min for high-energy electrons. Most of the selected events have no reported H*α* flares or GOES SXR bursts, but all have type III radio bursts that typically start after the onset of a low-energy electron injection. All nine events with SOHO/LASCO coverage have a relatively fast (>570 km s^{-1}), mostly narrow (≲30°), west-limb coronal mass ejection (CME) that launches near the start of the low-energy electron injection, and reaches an average altitude of ~1.0 and 4.7 R_S, respectively, at the start of the high-energy electron injection and of the ion injection. The electron energy spectra show a continuous power law extending across the transition from low to high energies, suggesting that the low-energy electron injection may provide seed electrons for the delayed high-energy electron acceleration. The delayed ion injections and high ionization states may suggest an ion acceleration along the lower altitude flanks, rather than at the nose of the CMEs. **1998 Aug 18, 1999 Aug 7, 2000 Apr 1, 2000 June 4, 2002 Jun 30, 2002 Sep 22, 2002 Sep 24, 2002 Oct 20, 2002 December 12**

Table 1. the Ten Electron/3He-rich SEP Events

Energy Spectral Property in an Isolated CME-driven Shock

Xin **Wang**, Yihua Yan, Mingde Ding, Na Wang, Hao Shan

Research in Astron. Astrophys (RAA) **2015**

http://arxiv.org/pdf/1509.04182.pdf

Observations from multiple spacecraft show that there are energy spectral "breaks" at 1-10MeV in some large CME-driven shocks. However, numerical models can hardly simulate this property due to high computational expense. The present paper focuses on analyzing these energy spectral "breaks" by Monte Carlo particle simulations of an isolated CME-driven shock. Taking the **Dec 14 2006** CME-driven shock as an example, we investigate the formation of this energy spectral property. For this purpose, we apply different values for the scattering time in our isolated shock model to obtain the highest energy "tails", which can potentially exceed the "break" energy range. However, we have not found the highest energy "tails" beyond the "break" energy range, but instead find that the highest energy "tails" reach saturation near the range of energy at 5MeV. So, we believe that there exists an energy spectral "cut off" in an isolated shock. If there is no interaction with another shock, there would not be formation of the energy spectral "break" property.

Estimation of the Release Time of Solar Energetic Particles near the Sun

Yang **Wang** and Gang Qin

2015 ApJ 799 111

This paper investigates the onset time of solar energetic particle (SEP) events with numerical simulations and analyzes the accuracy of the velocity dispersion analysis (VDA) method. Using a three-dimensional focused transport model, we calculate the fluxes of protons observed in the ecliptic at 1 AU in the energy range between 10 MeV and 80 MeV. In particular, three models are used to describe different SEP sources produced by flare or coronal shock, and the effects of particle perpendicular diffusion in the interplanetary space are also studied. We have the following findings. When the observer is disconnected from the source, the effects of perpendicular diffusion in the interplanetary space and particles propagating in the solar atmosphere have a significant influence on the VDA results. As a result, although the VDA method is valid with impulsive source duration, low background, and weak scattering in the interplanetary space or fast diffusion in the solar atmosphere, the method is not valid with gradual source duration, high background, or strong scattering.

Simulations of the spatial and temporal invariance in the spectra of gradual solar energetic particle events

Yang **Wang**, Gang Qin

2015 ApJ 806 252

http://arxiv.org/pdf/1501.02956v1.pdf

The spatial and temporal invariance in the spectra of energetic particles in the gradual solar events is reproduced in the simulations. Based on a numerical solution of the focused transport equation, we obtain the intensity time profiles of solar energetic particles (SEPs) accelerated by an interplanetary shock in the three-dimensional interplanetary space. The shock is treated as a moving source of energetic particles with a distribution function. The time profiles of particle flux with different energies are calculated in the ecliptic at 1 AU. We find that the spatial and temporal invariance in SEP spectra are the results of the effects of perpendicular diffusion and adiabatic cooling in the interplanetary space in our model. Furthermore, a spectra invariant region, which agrees with observations but is different than the one suggested by Reames and co-workers, is proposed based on our simulations.

Simulation of Energetic Neutral Atoms from Solar Energetic Particles

Linghua **Wang**1, Gang Li2, Albert Y. Shih3, Robert P. Lin4, and Robert F. Wimmer-Schweingruber

2014 ApJ 793 L37

Energetic neutral atoms (ENAs) provide the only way to observe the acceleration site of coronal-mass-ejection-driven (CME-driven) shock-accelerated solar energetic particles (SEPs). In gradual SEP events, energetic protons can charge exchange with the ambient solar wind or interstellar neutrals to become ENAs. Assuming a CME-driven shock with a constant speed of 1800 km s–1 and compression ratio of 3.5, propagating from 1.5 to 40 RS , we calculate the accelerated SEPs at 5-5000 keV and the resulting ENAs via various charge-exchange interactions. Taking into account the ENA losses in the interplanetary medium, we obtain the flux-time profiles of these solar ENAs reaching 1 AU. We find that the arriving ENAs at energies above ~100 keV show a sharply peaked flux-time profile, mainly originating from the shock source below 5 RS , whereas the ENAs below ~20 keV have a flat-top time profile, mostly originating from the source beyond 10 RS . Assuming the accelerated protons are effectively trapped downstream of the shock, we can reproduce the STEREO ENA fluence observations at ~2-5 MeV/nucleon. We also estimate the flux of ENAs coming from the charge exchange of energetic storm protons, accelerated by the fast CME-driven shock near 1 AU, with interstellar hydrogen and helium. Our results suggest that appropriate instrumentation would be able to detect ENAs from SEPs and to even make ENA images of SEPs at energies above ~10-20 keV.

A numerical simulation of solar energetic particle dropouts during impulsive events

Y. **Wang**, G. Qin, M. Zhang, S. Dalla

2014, ApJ 789 157

http://arxiv.org/pdf/1403.6544.pdf

This paper investigates the conditions for producing rapid variations of solar ener- getic particle (SEP) intensity commonly known as dropouts. In particular, we use numerical model simulations based on solving the focused transport equation in the 3-dimensional Parker interplanetary magnetic field to put constraints on the properties of particle transport coefficients both in the direction perpendicular and parallel to the magnetic field. To simulate the effect of field lines that may alternatively connect and disconnect an observer from a compact SEP source on the solar surface, we place several smaller SEP sources that release particles impulsively and simultaneously at separate longitudes on the solar surface. We let magnetic flux tubes filled or devoid of energetic particles pass the observer. The perpendicular particle diffusion tends to smooth out the intensity variation. Our calculations of the temporal intensity profile of 0.5 and 5 MeV protons at the Earth show that the perpendicular diffusion must be small enough while the parallel mean free path should be long in order to reproduce the phenomenon of SEP dropouts. When the parallel mean free path is a fraction of 1 AU and the observer is located at 1 AU, the perpendicular to parallel diffusion ratio must be below 10−5 if we want to see the particle flux dropping by at least several times within three hours. When the observer is located at a larger solar radial distance, the perpendicular to parallel diffusion ratio for reproducing the dropouts should be even lower than that in the case of 1 AU distance. A shorter parallel mean free path or a larger radial distance from the source to observer will cause the particles to arrive later, making the effect of perpendicular diffusion more prominent and SEP dropouts disappear.

A STATISTICAL STUDY OF SOLAR ELECTRON EVENTS OVER ONE SOLAR CYCLE

Linghua **Wang**1,2, R. P. Lin2,3,4, Säm Krucker2,5, and Glenn M. Mason

2012 ApJ 759 69

We survey the statistical properties of 1191 solar electron events observed by the WIND 3DP instrument from <1 keV to 300 keV for a solar cycle (1995 through 2005). After taking into account times of high background, the corrected occurrence frequency of solar electron events versus peak flux exhibits a power-law distribution over three orders of magnitude with exponents between –1.0 and –1.6 for different years, comparable to the frequency distribution of solar proton events, microflares, and coronal mass ejections (CMEs), but significantly flatter than that of soft X-ray (SXR) flares. At 40 keV (2.8 keV), the integrated occurrence rate above ~0.29 (~330) cm–2 s–1 sr–1 keV–1 near 1 AU is ~1000 year–1 (~600 year–1) at solar maximum and ~35 year–1 (~25 year–1) at solar minimum, about an order of magnitude larger than the observed occurrence rate. We find these events typically extend over ~45° in longitude, implying the occurrence rate over the whole Sun is ~104 year–1 near solar maximum. The observed solar electron events have a 98.75% association with type III radio bursts, suggesting all type III bursts may be associated with a solar electron event.

They have a close (~76%) association with the presence of low-energy (~0.02-2 MeV nucleon–1), 3He-rich (3He/4He ≥ 0.01) ion emissions measured by the ACE ULEIS instrument. For these electron events, only ~35% are associated with a reported GOES SXR flare, but ~60% appear to be associated with a CME, with ~50% of these CMEs being narrow. These electrons are often detected down to below 1 keV, indicating a source high in the corona.

EFFECTS OF PERPENDICULAR DIFFUSION ON ENERGETIC PARTICLES ACCELERATED BY THE INTERPLANETARY CORONAL MASS EJECTION SHOCK

Y. **Wang**1,2, G. Qin1, and M. Zhang

2012 ApJ 752 37

In this work, based on a numerical solution of the focused transport equation, we obtained the intensity and anisotropy time profiles of solar energetic particles (SEPs) accelerated by an interplanetary shock in the three-dimensional Parker magnetic field. The shock is treated as a moving source of energetic particles with an assumed particle distribution function. We computed the time profiles of particle flux and anisotropy as measured by an observer at 1 AU, equatorial plane, and various longitudes with respect to the shock propagation direction. With perpendicular diffusion, energetic particles can cross magnetic field lines. Particles may be detected before the observer's field line is connected to the shock. After the observer's field line breaks from the shock front, the observer still can see more particles are injected into its field line. Our simulations show that the particle onset time, peak time, peak intensity, decay rate, and duration of SEP event could be significantly influenced by the effect of perpendicular diffusion. The anisotropy with perpendicular diffusion is almost the same as that without perpendicular diffusion, but there is an obvious difference at the moment when the observer's field line begins to be connected to the shock.

Solar energetic electron events over one solar cycle,

Linghua **Wang**

RHESSI Scince Nuggets, May **2012**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Solar_energetic_electron_events_over_one_solar_cycle

The occurrence distributions of solar electron events.

PITCH-ANGLE DISTRIBUTIONS AND TEMPORAL VARIATIONS OF 0.3-300 keV SOLAR IMPULSIVE ELECTRON EVENTS

L. **Wang**1, R. P. Lin1,2,3 and Säm Krucker1

2011 ApJ 727 121

We investigate the propagation of ~0.3-300 keV electrons in five solar impulsive electron events, observed by the WIND three-dimensional Plasma and Energetic Particle instrument, that have rapid-rise and rapid-decay temporal profiles. In two events, the temporal profiles above 25 keV show a second peak of inward-traveling electrons tens of minutes after the first peak, followed by a third peak due to outward-traveling electrons minutes later—likely due to reflection/scattering first at ~0.7-1.7 AU past the Earth, and then in the inner heliosphere inside 1 AU. In the five events, below a transition energy E 0 (~10-40 keV), the pitch-angle distributions are highly anisotropic with a pitch-angle width at half-maximum (PAHM) of <15° (unresolved) through the time of the peak; the ratio Λ of the peak flux of scattered (225-90° relative to the outward direction) to field-aligned scatter-free (0°-225) electrons is 0.1. Above E 0, the PAHM at the flux peak increases with energy up to 85° at 300 keV, and Λ also increases with energy up to ~0.8 at 300 keV. Thus, low-energy electrons propagated essentially scatter-free through the interplanetary medium, while high-energy electrons experienced pitch-angle scattering, with scattering strength increasing with energy. The transition energy E 0 between the two populations is always such that the electron gyroradius (ρ e) is approximately equal to the local thermal proton gyroradius (ρ Tp), suggesting that the higher energy electrons were scattered by resonance with turbulent fluctuations at scale ρ Tp in the solar wind.

Statistical characteristics of solar energetic proton events from January 1997 to June 2005,

Wang, R.

(**2006**), Astroparticles Phys., 26, 202**–**208.

We have made a statistical study of 163 solar proton events (SPEs) associated with X-ray flares, coronal mass ejections (CMEs) and radio type II bursts during January 1997–June 2005. These SPEs were categorized by the peak fluxes of >10 MeV solar protons into three groups. There are 37 large SPEs with fluxes of more than 100 protons cm−2 s−1 sr−1, 34 moderate SPEs with flux ranges of 10–100 protons cm−2 s−1 sr−1 and 92 minor SPEs with flux ranges of 1–10 protons cm−2 s−1 sr−1. To understand the determinant of solar proton events, we have examined the association of these SPEs with X-ray flares, CMEs and radio type II emissions from metric to decametric-hectometric (DH) wave ranges. The primary results from this study are: (1) most SPEs (112/163) corresponded to the solar flares favorably located at solar western hemisphere and the center of the activity source region tended to shifted to the west with increasing of the solar proton fluxes; (2) there seems a longitudinal cutoff for each group of

SPEs, which also moves toward west with increasing of the solar proton flux; (3) each SPE observed at Earth was associated with a fast (average speed 1228 km s−1) and wide (average angle width of 266°) CME; (4) the percentage of these SPEs associated with metric (DH) type II burst increased from 54% (42%) to 81% (100%). Overall, The most intensive SPEs are more likely to be produced by major flares located near central meridian of the Sun and shock waves driven by very fast halo CMEs (v 1600 km s−1). This suggested that CME-driven shock acceleration is a necessary condition for large SPEs production.

Coronal holes, jets, and the origin of ^{3}He-rich particle events.

Wang, Y.-M., Pick, M., Mason, G.M.

ApJ 639, 495, **2006**

http://www.journals.uchicago.edu/doi/pdf/10.1086/499355

Using magnetograph measurements, coronal field extrapolations, and imaging observations, we investigate the solar origins of 25 ^{3}He-rich particle events from the period 1997–2003. In essentially every case we find that the source of the impulsive solar energetic particles (SEPs) lies next to a coronal hole containing Earth-directed open field lines. Averaged over all events, the source-hole separation is only _4_ at the photosphere. The source itself is typically a small, flaring active region located between longitudes _W25 and _W72. Around the estimated particle injection time, EUV images often show a jetlike ejection aligned with the open field lines. In some cases, a corresponding white-light jet is seen at heliocentric distances k2 R_, similar to those studied earlier byWang & Sheeley. The jets show a tendency to recur, a behavior that is reflected in the time variation of the measured ^{3}He and Fe particle intensities. We interpret the jets as signatures of magnetic reconnection (‘‘footpoint exchange’’) between closed and open field lines. On the basis of these findings, we expect ^{3}He enrichments to be observed whenever Earth-connected open field lines undergo footpoint exchanges with nearby active or ephemeral region fields. Because small bipoles emerge continually inside coronal holes, moderate enhancements in the ^{3}He level can occur even when no significant flaring activity is recorded.

Physics of ion acceleration in the solar flare on 2005 September 7 determines γ-ray and neutron production

K. **Watanabe**[a], R.P. Lin[b], S. Krucker[b], R.J. Murphy[c], G.H. Share[d], M.J. Harris[e], M. Gros[f], Y. Muraki[g], T. Sako[h], Y. Matsubara[h], T. Sakai[i], S. Shibata[j], J.F. Valdés-Galicia[k], L.X. González[k], A. Hurtado[k], O. Musalem[k], P. Miranda[l], N. Martinic[l], R. Ticona[l], A. Velarde[l], F. Kakimoto[m], Y. Tsunesada[m], H. Tokuno[n] and S. Ogio[o]

Advances in Space Research, Volume 44, Issue 7, 1 October **2009**, Pages 789-793

Relativistic neutrons were observed by the neutron monitors at Mt. Chacaltaya and Mexico City and by the solar neutron telescopes at Chacaltaya and Mt. Sierra Negra in association with an X17.0 flare on 2005 September 7. The neutron signal continued for more than 20 min with high statistical significance. Intense emissions of γ-rays were also registered by INTEGRAL, and during the decay phase by RHESSI. We analyzed these data using the solar-flare magnetic-loop transport and interaction model of Hua et al. [Hua, X.-M., Kozlovsky, B., Lingenfelter, R.E. et al. Angular and energy-dependent neutron emission from solar flare magnetic loops, Astrophys. J. Suppl. Ser. 140, 563–579, 2002], and found that the model could successfully fit the data with intermediate values of loop magnetic convergence and pitch-angle scattering parameters. **These results indicate that solar neutrons were produced at the same time as the γ-ray line emission and that ions were continuously accelerated at the emission site.**

Forecasting >300 MeV SEP events: Extending SPARX to high energies

Charlotte O. G. **Waterfall**, Silvia Dalla, Mike S. Marsh, Timo Laitinen, Adam Hutchinson

Space Weather **Volume21, Issue6** e2023SW003445 **2023**

https://arxiv.org/pdf/2306.01530.pdf

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003445 **File**

The forecasting of solar energetic particles (SEPs) is a prominent area of space weather research. Numerous forecasting models exist that predict SEP event properties at proton energies <100MeV. One of these models is the SPARX system, a physics-based forecasting tool that calculates >10MeV and >60MeV flux profiles within minutes of a flare being detected. This work describes SPARX-H, the extension of SPARX to forecast SEP events above 300MeV . SPARX-H predicts fluxes in three high energy channels up to several hundred MeV. Correlations between SEP peak flux and peak intensity of the associated solar flare are seen to be weak at high energies, but improved when events are grouped based on the field polarity during the event. Initial results from this new high energy forecasting tool are presented here and the applications of high energy forecasts are discussed. Additionally, the new high energy version of SPARX is tested on a set of historic SEP events. We see that SPARX-H performs best when predicting peak fluxes from events with source locations in well-connected regions, where many large SEP events tend to originate. **2 November 2003**

High Energy Solar Particle Events and Their Relationship to Associated Flare, CME and GLE Parameters

C. O. G. **Waterfall**, S. Dalla, O. Raukunen, D. Heynderickx, P. Jiggens, R. Vainio
Space Weather Volume21, Issue3 e2022SW003334 **2023**
https://arxiv.org/pdf/2303.03935
https://doi.org/10.1029/2022SW003334
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003334 **File**
Large solar eruptive events, including solar flares and coronal mass ejections (CMEs), can lead to solar energetic particle (SEP) events. During these events, protons are accelerated up to several GeV and pose numerous space weather risks. These risks include, but are not limited to, radiation hazards to astronauts and disruption to satellites and electronics. The highest energy SEPs are capable of reaching Earth on timescales of minutes and can be detected in ground level enhancements (GLEs). Understanding and analyzing these events is critical to future forecasting models. However, the availability of high energy SEP data sets is limited, especially that which covers multiple solar cycles. The majority of analysis of SEP events considers data at energies <100 MeV. In this work, we use a newly calibrated data set using data from Geostationary Operational Environmental Satellite-high energy proton and alpha detector between 1984 and 2017. Analysis of the SEP events in this time period over three high energy channels is performed, and SEP properties are compared to flare and CME parameters. In addition, neutron monitor (NM) observations are examined for the relevant GLE events. We find that correlations between SEP peak intensity and the CME speed are much weaker than for lower SEP energies. Correlations with flare intensity are broadly similar or weaker. Strong correlations are seen between >300 MeV data and GLE properties from NM data. The results of our work can be utilized in future forecasting models for both high energy SEP and GLE events. **29 Sep 1989, 19-25 Oct 1989, 22 Oct 1989, 24 Oct 1989, 24 May 1990, 15 Jun 1991, 14 Jul 2000, 15 Apr 2001, 20 Jan 2005, 13 Dec 2006,**
Table 2 List of Solar Events That Produced High Energy Solar Energetic Particle Enhancements Meeting the Criteria
Table 3 Solar Energetic Particle Events That Are Present in the High Energy Channels but occurred behind the limb

Modelling the transport of relativistic solar protons along a heliospheric current sheet during historic GLE events

Charlotte O. G. **Waterfall**, Silvia Dalla, Timo Laitinen, Adam Hutchinson, Mike Marsh
ApJ **934** 82 **2022**
https://arxiv.org/pdf/2206.11650.pdf **File**
https://iopscience.iop.org/article/10.3847/1538-4357/ac795d/pdf
There are many difficulties associated with forecasting high-energy solar particle events at Earth. One issue is understanding why some large solar eruptive events trigger ground level enhancement (GLE) events and others do not. In this work we perform 3D test particle simulations of a set of historic GLEs to understand more about what causes these powerful events. Particular focus is given to studying how the heliospheric current sheet (HCS) affects high-energy proton transport through the heliosphere following an event. Analysis of ≥M7.0 flares between 1976−2020 shows that active regions located closer to the HCS (<10∘) are more likely to be associated with a GLE event. We found that modelled GLE events where the source region was close to the HCS also led to increased heliospheric transport in longitude and higher count rates (when the Earth was located in the drift direction). In a model that does not include perpendicular diffusion associated with turbulence, the HCS is the dominant mechanism affecting heliospheric particle transport for **GLE 42 and 69**, and varying other parameters (e.g. a narrow, 10∘, or wider, 60∘, injection width) causes little change. Overall in our model, the HCS is relevant in 71% of our analysed GLEs and including it more accurately reproduces observed intensities near Earth. Our simulations enable us to produce model profiles at Earth that can be compared to existing observations by the GOES satellites and neutron monitors, as well as for use in developing future forecasting models. **1984 Feb 02 (39), 1989 Aug 16 (41), 1989 Sep 29 (42), 1989 Oct 19 (43), 1989 Oct 22 (44), 1989 Oct 24 (45), 1991 Jun 15 (52), 1997 Nov 06 (55), 2001 Apr 15 (60), 2001 Apr 18 (61), 2003 Oct 28 (65), 2003 Oct 29 (66), 2003 Nov 02 (67), 20 January 2005 (GLE69), 2006 Dec 13 (70), 2012 May 17 (71), 2017 Sep 10 (72)**
Table 1. List of GLE events, ordered by date, modelled with the 3D test particle code. GLEs are selected according to criteria in Section 2. 1984-2017

Modeling and data analysis of a Forbush decrease

Anna **Wawrzynczaka**, , , and Michael V. Alania
Advances in Space Research, Volume 45, Issue 5, 1 March **2010**, Pages 622-631
We study the Forbush decrease of the galactic cosmic ray intensity observed in **9–25 September 2005** using the experimental data and a newly developed time-dependent three dimensional modeling. We analyze neutron monitors and muon telescopes, and the interplanetary magnetic field data. We demonstrate a clear relationship between the rigidity (R) spectrum exponent (γ) of the Forbush decrease and the exponent (ν) of the power spectral density of the components of the interplanetary magnetic field in the frequency range of ∼ 10−6–10 −5 Hz. We confirm that an

inclusion of the time-dependent changes of the exponent ν makes the newly developed nonstationary three dimensional model of the Forbush decrease compatible with the experimental data. Also, we show that the changes of the rigidity spectrum exponent γ does not depend on the level of convection of the galactic cosmic rays stream by solar wind; depending on the changes of the exponent ν, i.e. on the state of the turbulence of the interplanetary magnetic field.

Energy Spectra Variations of Energetic Ions Associated With a Stream Interaction Region
Wenwen **Wei**,Bin Zhuang,Jia Huang,Fang Shen,Lulu Zhao,Mingzhe Liu,Xiaoxin Zhang,Xueshang Feng
JGR   Volume127, Issue10 e2022JA030652   **2022**
https://doi.org/10.1029/2022JA030652
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022JA030652
Understanding the evolution of energetic particles in the heliosphere is one of the most outstanding topics in heliophysics studies. The spectra of energetic particles are pivotal to investigate their origin, acceleration and transport processes. Using STEREO A data, we investigate an intensity enhancement of energetic ions associated with a stream interaction region (SIR) during the decay phase of a gradual solar energetic particle (SEP) event. We find the SIR has fine structures include the stream interface (SI) and a forward-reverse shock pair, and the energy spectra of energetic ion intensities show complex variations around them. Furthermore, we compare the ions' energy spectra in different regions of the SIR. The results show that this SIR is capable of accelerating protons to about 35 MeV nuc−1, which is about two times of the upper limit of the energy as identified by previous observations, but they are still of the same order. We suggest this may be explained by the fact that the SIR could further accelerate the remnant lower energy ions from the gradual SEP event to higher energies. Moreover, the energetic ions in the SIR event have two populations that are accelerated by shock-associated and non-shock-associated mechanisms, respectively. In addition, the ion intensity exhibits significant directional anisotropies during this SIR event, which may be a result of the combined influence of the transport effect, shock, and the intervening small flux rope.

Modeling solar energetic particle transport in 3D background solar wind: Influences of the compression regions
Wenwen **Wei**   FangShenabcZicaiYangabLuluZhaodYangWangcPingbingZuocJieZhange
JASTP Volume 182, January **2019**, Pages 155-164
https://www.sciencedirect.com/science/article/pii/S1364682618304243?dgcid=raven_sd_via_email
In modeling the transport process of solar energetic particles(SEPs) in the heliosphere, previous simulation works often simplify the solar wind velocity as radial and constant, and treat the magnetic field as Parker spiral. In order to fully understand the effect of solar wind velocity and interplanetary magnetic fieldon the particles' transport process, a realistic background solar wind and magnetic field is required. In this work, we use the focused transport model to investigate the transport of SEPs in the solar wind velocity and magnetic field generated by the 3D high-resolution MHD model with a six-component grid. We find that in the uncompressed solar wind, the time intensity profiles of energetic particles show similar trend in both the MHD background and the Parker magnetic field assumption. However, the simulated SEP flux displays an enhancement in the decay phase when a compression region sweeps past the local observer. Through investigating various effects, we find that the magnetic focusing effect is primarily responsible for the intensity enhancement, suggesting that the magnetic focusing effect has an important influence on the transport of SEPs. Further, we show that the magnetic focusing could also be effective in large heliocentric distances.

Timing Issues for 2005 Jan 20
Stephen **White**
Presentation at "Ground Level Enhancement (GLE)"
Comparative Data Analysis Workshop (CDAW), LMSAL, Jan 6-9, **2009**
Address the relative contributions of "flare" and "CME" accelerated particles to SEPs

SEPVAL 2023 Post Analysis Results
Whitman, K., Quinn, P., Egeland, R., et al.
Incoming email 04.04.**2024**
SEPVAL2023_PostAnalysisResults_20240403.pdf   **File**
You are receiving this message if you registered for SEPVAL 2023 last year. Despite our extended silence, we have been working hard on a post analysis of the forecasts submitted to the SEPVAL challenges. We have been making updates to our validation code, SPHINX, to add more features and metrics and to fix bugs or add in new capabilities to handle the different types of forecasts that were submitted.
I am attaching a presentation with an overview of the SEPVAL effort along with anonymized summary plots showing the range of model performance for All Clear, probability, and peak flux forecasts for >10 MeV, 10 pfu events.

Review of solar energetic particle models. **Review**
Whitman, K., Egeland, R., Richardson, I. G., Allison, C., Quinn, P., Barzilla, J., et al.
Adv. Space Res. Volume 72, Issue 12, 15 December **2023**, Pages 5161-5242, 82 p. **File**
doi:10.1016/j.asr.2022.08.006
https://reader.elsevier.com/reader/sd/pii/S0273117722007244
Solar Energetic Particle (SEP) events are interesting from a scientific perspective as they are the product of a broad set of physical processes from the corona out through the extent of the heliosphere, and provide insight into processes of particle acceleration and transport that are widely applicable in astrophysics. From the operations perspective, SEP events pose a radiation hazard for aviation, electronics in space, and human space exploration, in particular for missions outside of the Earth's protective magnetosphere including to the Moon and Mars. Thus, it is critical to improve the scientific understanding of SEP events and use this understanding to develop and improve SEP forecasting capabilities to support operations. Many SEP models exist or are in development using a wide variety of approaches and with differing goals. These include computationally intensive physics-based models, fast and light empirical models, machine learning-based models, and mixed-model approaches. The aim of this paper is to summarize all of the SEP models currently developed in the scientific community, including a description of model approach, inputs and outputs, free parameters, and any pulished validations or comparisons with data

Implications of improved measurements of the highest energy SEPs by AMS and PAMELA **Review**
K. **Whitman**, , V. Bindi, C. Consolandi, C. Corti, B. Yamashiro
Advances in Space Research Volume 60, Issue 4, 15 August **2017**, Pages 768–780 **File**
http://sci-hub.ru/10.1016/j.asr.2017.02.042
Solar energetic particles (SEP) are a key target of heliophysics research, not only as exemplars of particle acceleration and transport processes that are ubiquitous in astrophysical plasmas, but also as the most intense transient radiation hazard for human and robotic space explorers. SEPs are very well-observed by spacecraft covering particle energies below several hundred MeV/nucleon. Multiple missions, stretching back over decades, have yielded a fairly complete description of SEP intensity, energy spectra, and composition up to a few hundred MeV/nucleon. SEP characteristics at higher energies are, by comparison, only poorly understood due to the relative dearth of high-energy measurements. This lack of high energy measurements has contributed to a disagreement within the heliophysics community regarding the source regions and mechanisms that accelerate particles up to GeV energies. In solar cycle 24, the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) and the Alpha Magnetic Spectrometer (AMS) have been taking measurements of the highest energy SEPs from ∼100 MeV to the GeV. Since the literature has discussed SEP acceleration to GeV energies in terms of Ground Level Enhancements (GLE), we will review the findings for GLEs in solar cycle 23. We will discuss the models and theories that address acceleration up to the GeV and how AMS and PAMELA measurements have the potential to advance the current understanding of SEP acceleration physics. Lastly, only 1–2 GLEs have occurred during solar cycle 24, so we will explore a set of SEP events that were observed in the ⩾100 MeV GOES channels, most of which were also observed by PAMELA and AMS. **December 13, 2006**, **January 28, 2012, March 7, 2012, May 17, 2012**
Table 1: A subset of events taken from Gopalswamy et al. (2014) that show a signal in the GOES-13 80 to 165 MeV channel or higher

Multi-spacecraft observations of solar flare particles in the inner heliosphere.
Wibberenz G, Cane HV
(**2006**) Astrophys J 650:1199–1207. doi:10.1086/506598
https://iopscience.iop.org/article/10.1086/506598/pdf
For a number of impulsive solar particle events we examine variations of maximum intensities and times to maximum intensity as a function of longitude, using observations from the two Helios spacecraft and near the Earth. We find that electrons in the MeV range can be detected more than 80 from the flare longitude, corresponding to a considerably wider ''well connected'' region than that (20 half-width) reported for 3 He-rich impulsive solar events. This wide range and the decrease of peak intensities with increasing connection angle revive the concept of some diffusive propagation process in the low corona. Delays to intensity maxima are not systematically correlated with connection angles. We argue that interplanetary scattering parallel to the average interplanetary magnetic field, which varies with position in space, plays an important role in flare particle events. In a specific case variations of the time profiles with radial distance and with particle rigidity are used to quantitatively confirm spatial diffusion. For a few cases near the edges of the well-connected region, the very long times to maximum intensity might result from interplanetary lateral transport.
TABLE 1 Three-Spacecraft Events 1977-1980

3He-rich Solar Energetic Particle Observations at the Parker Solar Probe and near Earth

M. E. **Wiedenbeck**1, R. Bučík2,3, G. M. Mason4, G. C. Ho4, R. A. Leske5, C. M. S. Cohen5, E. R. Christian6, A. C. Cummings5, A. J. Davis5, M. I. Desai7Show full author list

2020 ApJS 246 42

https://iopscience.iop.org/article/10.3847/1538-4365/ab5963/pdf

The Integrated Science Investigation of the Sun (IS⊙IS) instrument suite on the Parker Solar Probe (PSP) spacecraft is making in situ observations of energetic ions and electrons closer to the Sun than any previous mission. Using data collected during its first two orbits, which reached perihelion distances of 0.17 au, we have searched for ^{3}He-rich solar energetic particle (SEP) events under very quiet solar minimum conditions. On **2019**-110–111 (**April 20–21**), ^{3}He-rich SEPs were observed at energies near 1 MeV nucleon–1 in association with energetic protons, heavy ions, and electrons. This activity was also detected by the Ultra-Low-Energy Isotope Spectrometer and the Electron, Proton, and Alpha Monitor instruments on the Advanced Composition Explorer (ACE) spacecraft located near Earth, 0.99 au from the Sun. At that time, PSP and ACE were both magnetically connected to locations near the west limb of the Sun. Remote sensing measurements showed the presence of type III radio bursts and also helical jets from this region of the Sun. This combination of observations is commonly associated with ^{3}He-rich SEP acceleration on the Sun. AR 12738, which was located at Carrington coordinates from which numerous X-ray flares were observed over a period of more than 6 months, was identified as the source of the ^{3}He-rich events. This region was also the source of several other SEP events detected at PSP or ACE. Aside from the period in 2019 April, IS⊙IS did not observe any other ^{3}He-rich SEPs during orbits 1 and 2.

OBSERVATIONS OF SOLAR ENERGETIC PARTICLES FROM 3He-RICH EVENTS OVER A WIDE RANGE OF HELIOGRAPHIC LONGITUDE

M. E. **Wiedenbeck**1, G. M. Mason2, C. M. S. Cohen3, N. V. Nitta4, R. Gómez-Herrero5,6, and D. K Haggerty

2013 ApJ 762 54

https://iopscience.iop.org/article/10.1088/0004-637X/762/1/54/pdf

A prevailing model for the origin of 3He-rich solar energetic particle (SEP) events attributes particle acceleration to processes associated with the reconnection between closed magnetic field lines in an active region and neighboring open field lines. The open field from the small reconnection volume then provides a path along which accelerated particles escape into a relatively narrow range of angles in the heliosphere. The narrow width (standard deviation <20°) of the distribution of X-ray flare longitudes found to be associated with 3He-rich SEP events detected at a single spacecraft at 1 AU supports this model. We report multispacecraft observations of individual 3He-rich SEP events that occurred during the solar minimum time period from 2007 January through 2011 January using instrumentation carried by the two Solar Terrestrial Relations Observatory spacecraft and the Advanced Composition Explorer. We find that detections of 3He-rich events at pairs of spacecraft are not uncommon, even when their longitudinal separation is >60°. We present the observations of the 3He-rich event of **2010 February 7**, which was detected at all three spacecraft when they spanned 136° in heliographic longitude. Measured fluences of 3He in this event were found to have a strong dependence on longitude which is well fit by a Gaussian with standard deviation ~48° centered at the longitude that is connected to the source region by a nominal Parker spiral magnetic field. We discuss several mechanisms for distributing flare-accelerated particles over a wide range of heliographic longitudes including interplanetary diffusion perpendicular to the magnetic field, spreading of a compact cluster of open field lines between the active region and the source surface where the field becomes radial and opens out into the heliosphere, and distortion of the interplanetary field by a preceding coronal mass ejection. Statistical studies of additional 3He-rich events detected at multiple spacecraft will be needed to establish the relative importance of the various mechanisms. **2010 February 7**

Table 1 3He-rich SEP Events Detected by STEREO-A/LET or STEREO-B/LET from 2007 January Through 2011 January

Heavy-ion Fractionation in the Impulsive Solar Energetic Particle Event of 2002 August 20: Elements, Isotopes, and Inferred Charge States

M. E. **Wiedenbeck**, C. M. S. Cohen, R. A. Leske, R. A. Mewaldt, A. C. Cummings, E. C. Stone, and T. T. von Rosenvinge

2010 ApJ 719 1212-1229

Cosmic Ray Transport in Heliospheric Magnetic Structures: I. Modeling Background Solar Wind Using the CRONOS MHD Code

Tobias **Wiengarten**, Jens Kleimann, Horst Fichtner, Patrick Kühl, Andreas Kopp, Bernd Heber, Ralf Kissmann
Astrophysical Journal, Volume 788, Issue 1, article id. 80, 16 pp. (**2014**)
http://arxiv.org/pdf/1406.0293v1.pdf
The transport of energetic particles such as Cosmic Rays is governed by the properties of the plasma being traversed. While these properties are rather poorly known for galactic and interstellar plasmas due to the lack of in situ measurements, the heliospheric plasma environment has been probed by spacecraft for decades and provides **a** unique opportunity for testing transport theories. Of particular interest for the 3D heliospheric transport of energetic particles are structures such as corotating interaction regions (CIRs), which, due to strongly enhanced magnetic field strengths, turbulence, and associated shocks, can act as diffusion barriers on the one hand, but also as accelerators of low energy CRs on the other hand as well. In a two-fold series of papers we investigate these effects by modeling inner-heliospheric solar wind conditions with a numerical magnetohydrodynamic (MHD) setup (this paper), which will serve as an input to a transport code employing a stochastic differential equation (SDE) approach (second paper). In this first paper we present results from 3D MHD simulations with our code CRONOS: for validation purposes we use analytic boundary conditions and compare with similar work by Pizzo. For a more realistic modeling of solar wind conditions, boundary conditions derived from synoptic magnetograms via the Wang-Sheeley-Arge (WSA) model are utilized, where the potential field modeling is performed with a finite-difference approach (FDIPS) in contrast to the traditional spherical harmonics expansion often utilized in the WSA model. Our results are validated by comparing with multi-spacecraft data for ecliptical (STEREO-A/B) and out-of-ecliptic (Ulysses) regions.

The effect of the ambient solar wind medium on a CME-driven shock and the associated gradual solar energetic particle event

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ApJ **950** 172 **2023**
https://arxiv.org/pdf/2305.09525.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/acd1ed/pdf
We present simulation results of a gradual solar energetic particle (SEP) event detected on **2021 October 9** by multiple spacecraft, including BepiColombo (Bepi) and near-Earth spacecraft such as the Advanced Composition Explorer (ACE). A peculiarity of this event is that the presence of a high speed stream (HSS) affected the low-energy ion component (≲5 MeV) of the gradual SEP event at both Bepi and ACE, despite the HSS having only a modest solar wind speed increase. Using the EUHFORIA (European Heliospheric FORecasting Information Asset) magnetohydrodynamic model, we replicate the solar wind during the event and the coronal mass ejection (CME) that generated it. We then combine these results with the energetic particle transport model PARADISE (PArticle Radiation Asset Directed at Interplanetary Space Exploration). We find that the structure of the CME-driven shock was affected by the non-uniform solar wind, especially near the HSS, resulting in a shock wavefront with strong variations in its properties such as its compression ratio and obliquity. By scaling the emission of energetic particles from the shock to the solar wind compression at the shock, an excellent match between the PARADISE simulation and in-situ measurements of ≲5 MeV ions is obtained. Our modelling shows that the intricate intensity variations observed at both ACE and Bepi were influenced by the non-uniform emission of energetic particles from the deformed shock wave and demonstrates the influence of even modest background solar wind structures on the development of SEP events.

On the seed population of solar energetic particles in the inner heliosphere

Nicolas **Wijsen**, Gang Li, Zheyi Ding, David Lario, Stefaan Poedts, Rachael Filwett, Robert Allen, Maher Dayeh
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Particles measured in large gradual solar energetic particle (SEP) events are believed to be predominantly accelerated at shocks driven by coronal mass ejections (CMEs). Ion charge state and composition analyses suggest that the origin of the seed particle population for the mechanisms of particle acceleration at CME-driven shocks is not the bulk solar wind thermal material, but rather a suprathermal population present in the solar wind. This suprathermal population could result from remnant material accelerated in prior solar flares and/or preceding CME-driven shocks. In this work, we examine the distribution of this suprathermal particle population in the inner heliosphere by combining a magnetohydrodynamic (MHD) simulation of the solar wind and a Monte-Carlo simulation of particle acceleration and transport. Assuming that the seed particles are uniformly distributed near the

Sun by solar flares of various magnitudes, we study the longitudinal distribution of the seed population at multiple heliocentric distances. We consider a non-uniform background solar wind, consisting of fast and slow streams that lead to compression and rarefaction regions within the solar wind. Our simulations show that the seed population at a particular location (e.g., 1 au) is strongly modulated by the underlying solar wind configuration. Corotating interaction regions (CIRs) and merged interactions regions (MIRs) can strongly alter the energy spectra of the seed particle populations. In addition, cross-field diffusion plays an important role in mitigating strong variations of the seed population in both space and energy.

Observation-based modelling of the energetic storm particle event of 14 July 2012

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https://www.aanda.org/articles/aa/pdf/2022/03/aa42698-21.pdf

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We model the energetic storm particle (ESP) event of **14 July 2012** using the energetic particle acceleration and transport model named PARADISE, together with the solar wind and coronal mass ejection (CME) model named EUHFORIA. The simulation results illustrate both the capabilities and limitations of the utilised models. We show that the models capture some essential structural features of the ESP event; however, for some aspects the simulations and observations diverge. We describe and, to some extent, assess the sources of errors in the modelling chain of EUHFORIA and PARADISE and discuss how they may be mitigated in the future. The PARADISE model evolves energetic particle distributions in a background solar wind generated by the ideal MHD module of EUHFORIA. The CME generating the ESP event is simulated by using the spheromak model of EUHFORIA, which approximates the CME's flux rope as a linear force-free spheroidal magnetic field. In addition, a tool was developed to trace CME-driven shock waves in the EUHFORIA simulation domain. This tool is used in PARADISE to (i) inject 50 keV protons continuously at the CME-driven shock and (ii) include a foreshock and a sheath region, in which the energetic particle parallel mean free path, λ‖, decreases towards the shock wave. The value of λ‖ at the shock wave is estimated from in situ observations of the ESP event. For energies below 1 MeV, the simulation results agree well with both the upstream and downstream components of the ESP event observed by the Advanced Composition Explorer (ACE). This suggests that these low-energy protons are mainly the result of interplanetary particle acceleration. In the downstream region, the sharp drop in the energetic particle intensities is reproduced at the entry into the following magnetic cloud, illustrating the importance of a magnetised CME model.

The effect of drifts on the decay phase of SEP events

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A&A 634, A82 (**2020**)

sci-hub.si/10.1051/0004-6361/201937026

Aims. We study the effect of the magnetic gradient and curvature drifts on the pitch-angle dependent transport of solar energetic particles (SEPs) in the heliosphere, focussing on ∼3–36 MeV protons. By considering observers located at different positions in the heliosphere, we investigate how drifts may alter the measured intensity-time profiles and energy spectra. We focus on the decay phase of solar energetic proton events in which a temporal invariant spectrum and disappearing spatial intensity gradients are often observed; a phenomenon known as the “reservoir effect” or the “SEP flood”. We study the effects of drifts by propagating particles both in nominal and non-nominal solar wind conditions.

Methods. We used a three-dimensional (3D) particle transport model, solving the focused transport equation extended with the effect of particle drifts in the spatial term. Nominal Parker solar wind configurations of different speeds and a magnetohydrodynamic (MHD) generated solar wind containing a corotating interaction region (CIR) were considered. The latter configuration gives rise to a magnetic bottle structure, with one bottleneck at the Sun and the other at the CIR. We inject protons from a fixed source at 0.1 AU, the inner boundary of the MHD model.

Results. When the drift induced particle net-flux is zero, the modelled intensity-time profiles obtained at different radial distances along an IMF line show the same intensity fall-off after the prompt phase of the particle event, which is in accordance with the SEP flood phenomenon. However, observers magnetically connected close to the edges of the particle injection site can experience, as a result of drifts, a sudden drop in the intensities occurring at different times for different energies such that no SEP flood phenomenon is established. In the magnetic bottle structure, this effect is enhanced due to the presence of magnetic field gradients strengthening the nominal particle drifts. Moreover, anisotropies can be large for observers that only receive particles through drifts, illustrating the importance of pitch-angle dependent 3D particle modelling. We observe that interplanetary cross-field diffusion can mitigate the effects of particle drifts.

Conclusions. Particle drifts can substantially modify the decay phase of SEP events, especially if the solar wind contains compression regions or shock waves where the drifts are enhanced. This is, for example, the case for our CIR solar wind configuration generated with a 3D MHD model, where the effect of drifts is strong. A similar decay rate in different energy channels and for different observers requires the mitigation of the effect of drifts. One way to accomplish this is through interplanetary cross-field diffusion, suggesting thus a way to determine a minimum value for the cross-field diffusion strength.

Interplanetary spread of solar energetic protons near a high-speed solar wind stream

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sci-hub.se/10.1051/0004-6361/201935139

Aims. We study how a fast solar wind stream embedded in a slow solar wind influences the spread of solar energetic protons in interplanetary space. In particular, we aim at understanding how the particle intensity and anisotropy vary along interplanetary magnetic field (IMF) lines that encounter changing solar wind conditions such as the shock waves bounding a corotating interaction region (CIR). Moreover, we study how the intensities and anisotropies vary as a function of the longitudinal and latitudinal coordinate, and how the width of the particle intensities evolves with the heliographic radial distance. Furthermore, we study how cross-field diffusion may alter these spatial profiles.
Methods. To model the energetic protons, we used a recently developed particle transport code that computes particle distributions in the heliosphere by solving the focused transport equation (FTE) in a stochastic manner. The particles are propagated in a solar wind containing a CIR, which was generated by the heliospheric model, EUHFORIA. We study four cases in which we assume a delta injection of 4 MeV protons spread uniformly over different regions at the inner boundary of the model. These source regions have the same size and shape, yet are shifted in longitude from each other, and are therefore magnetically connected to different solar wind conditions.
Results. The intensity and anisotropy profiles along selected IMF lines vary strongly according to the different solar wind conditions encountered along the field line. The IMF lines crossing the shocks bounding the CIR show the formation of accelerated particle populations, with the reverse shock wave being a more efficient accelerator than the forward shock wave. The longitudinal intensity profiles near the CIR are highly asymmetric in contrast to the profiles obtained in a nominal solar wind. For the injection regions that do not cross the transition zone between the fast and slow solar wind, we observe a steep intensity drop of several orders of magnitude near the stream interface (SI) inside the CIR. Moreover, we demonstrate that the longitudinal width of the particle intensity distribution can increase, decrease, or remain constant with heliographic radial distance, reflecting the underlying IMF structure. Finally, we show how the deflection of the IMF at the shock waves and the compression of the IMF in the CIR deforms the three-dimensional shape of the particle distribution in such a way that the original shape of the injection profile is lost.

Modelling three-dimensional transport of solar energetic protons in a corotating interaction region generated with EUHFORIA⋆

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Aims. We introduce a new solar energetic particle (SEP) transport code that aims at studying the effects of different background solar wind configurations on SEP events. In this work, we focus on the influence of varying solar wind velocities on the adiabatic energy changes of SEPs and study how a non-Parker background solar wind can trap particles temporarily at small heliocentric radial distances ($\lesssim$1.5 AU) thereby influencing the cross-field diffusion of SEPs in the interplanetary space.
Methods. Our particle transport code computes particle distributions in the heliosphere by solving the focused transport equation (FTE) in a stochastic manner. Particles are propagated in a solar wind generated by the newly developed data-driven heliospheric model, EUHFORIA. In this work, we solve the FTE, including all solar wind effects, cross-field diffusion, and magnetic-field gradient and curvature drifts. As initial conditions, we assume a delta injection of 4 MeV protons, spread uniformly over a selected region at the inner boundary of the model. To verify the model, we first propagate particles in nominal undisturbed fast and slow solar winds. Thereafter, we simulate and analyse the propagation of particles in a solar wind containing a corotating interaction region (CIR). We study the particle intensities and anisotropies measured by a fleet of virtual observers located at different positions in the heliosphere, as well as the global distribution of particles in interplanetary space.
Results. The differential intensity-time profiles obtained in the simulations using the nominal Parker solar wind solutions illustrate the considerable adiabatic deceleration undergone by SEPs, especially when propagating in a fast solar wind. In the case of the solar wind containing a CIR, we observe that particles adiabatically accelerate when propagating in the compression waves bounding the CIR at small radial distances. In addition, for r $\gtrsim$ 1.5 AU, there are particles accelerated by the reverse shock as indicated by, for example, the anisotropies and pitch-angle distributions of the particles. Moreover, a decrease in high-energy particles at the stream interface (SI) inside the CIR is observed. The compression/shock waves and the magnetic configuration near the SI may also act as a magnetic mirror, producing long-lasting high intensities at small radial distances. We also illustrate how the efficiency of the cross-field diffusion in spreading particles in the heliosphere is enhanced due to compressed magnetic fields. Finally, the inclusion of cross-field diffusion enables some particles to cross both the forward compression wave at small radial distances and the forward shock at larger radial distances. This results in the formation of an accelerated particle population centred on the forward shock, despite the lack of magnetic

connection between the particle injection region and this shock wave. Particles injected in the fast solar wind stream cannot reach the forward shock since the SI acts as a diffusion barrier.

SEP environment in the inner heliosphere from Solar Orbiter and Parker Solar Probe

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Proceedings IAU Symposium 388 **2024**

The Sun drives a supersonic wind which inflates a giant plasma bubble in our very local interstellar neighborhood, the heliosphere. It is bathed in an extremely variable background of energetic ions and electrons which originate from a number of sources. Solar energetic particles (SEPs) are accelerated in the vicinity of the Sun, whereas shocks driven by solar disturbances are observed to accelerate energetic storm particles (ESPs). Moreover, a dilute population with a distinct composition forms the anomalous cosmic rays (ACRs) which are of a mixed interstellar-heliospheric origin. Particles are also accelerated at planetary bow shocks. We will present recent observations of energetic particles by Solar Orbiter and Parker Solar Probe, as well as other spacecraft that allow us to study the acceleration and transport of energetic particles at multiple locations in the inner heliosphere.

Unusually long path length for a nearly scatter-free solar particle event observed by Solar Orbiter at 0.43 au

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https://www.aanda.org/articles/aa/pdf/2023/10/aa46319-23.pdf

Context. After their acceleration and release at the Sun, solar energetic particles (SEPs) are injected into the interplanetary medium and are bound to the interplanetary magnetic field (IMF) by the Lorentz force. The expansion of the IMF close to the Sun focuses the particle pitch-angle distribution, and scattering counteracts this focusing. Solar Orbiter observed an unusual solar particle event on **9 April 2022** when it was at 0.43 astronomical units (au) from the Sun.
Aims. We show that the inferred IMF along which the SEPs traveled was about three times longer than the nominal length of the Parker spiral and provide an explanation for this apparently long path.
Methods. We used velocity dispersion analysis (VDA) information to infer the spiral length along which the electrons and ions traveled and infer their solar release times and arrival direction.
Results. The path length inferred from VDA is approximately three times longer than the nominal Parker spiral. Nevertheless, the pitch-angle distribution of the particles of this event is highly anisotropic, and the electrons and ions appear to be streaming along the same IMF structures. The angular width of the streaming population is estimated to be approximately 30 degrees. The highly anisotropic ion beam was observed for more than 12 h. This may be due to the low level of fluctuations in the IMF, which in turn is very probably due to this event being inside an interplanetary coronal mass ejection The slow and small rotation in the IMF suggests a flux-rope structure. Small flux dropouts are associated with very small changes in pitch angle, which may be explained by different flux tubes connecting to different locations in the flare region.
Conclusions. The unusually long path length along which the electrons and ions have propagated virtually scatter-free together with the short-term flux dropouts offer excellent opportunities to study the transport of SEPs within interplanetary structures. The 9 April 2022 solar particle event offers an especially rich number of unique observations that can be used to limit SEP transport models.

Solar Orbiter nugget #17 2023 https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-unusually-long-path-length-for-a-nearly-scatter-free-solar-particle-event-observed-by-solar-orbiter-at-0.43-au

First year of energetic particle measurements in the inner heliosphere with Solar Orbiter's Energetic Particle Detector

R. F. **Wimmer-Schweingruber**, N. Janitzek, D. Pacheco, I. Cernuda, …..

A&A **2021**
https://arxiv.org/pdf/2108.02020.pdf

Solar Orbiter strives to unveil how the Sun controls and shapes the heliosphere and fills it with energetic particle radiation. To this end, its Energetic Particle Detector (EPD) has now been in operation, providing excellent data, for just over a year. EPD measures suprathermal and energetic particles in the energy range from a few keV up to (near-) relativistic energies (few MeV for electrons and about 500 MeV/nuc for ions). We present an overview of the initial results from the first year of operations and we provide a first assessment of issues and limitations. During this first year of operations of the Solar Orbiter mission, EPD has recorded several particle events at distances between 0.5 and 1 au from the Sun. We present dynamic and time-averaged energy spectra for ions that were measured with a combination of all four EPD sensors, namely: the SupraThermal Electron and Proton sensor (STEP), the Electron Proton Telescope (EPT), the Suprathermal Ion Spectrograph (SIS), and the High-Energy

Telescope (HET) as well as the associated energy spectra for electrons measured with STEP and EPT. We illustrate the capabilities of the EPD suite using the **10-11 December 2020** solar particle event. This event showed an enrichment of heavy ions as well as 3He, for which we also present dynamic spectra measured with SIS. The high anisotropy of electrons at the onset of the event and its temporal evolution is also shown using data from these sensors. We discuss the ongoing in-flight calibration and a few open instrumental issues using data from the **21 July and the 10-11 December 2020** events and give guidelines and examples for the usage of the EPD data. We explain how spacecraft operations may affect EPD data and we present a list of such time periods in the appendix. A list of the most significant particle enhancements as observed by EPT during this first year is also provided.
Table A.1. List of electron intensity enhancements observed by EPT during the first year of observations.
Table A.2. List of ion intensity enhancements observed by EPT during the first year of observations.

Type II and Type III Radio Bursts and their Correlation with Solar Energetic Proton Events

L.M. **Winter**, K. Ledbetter
ApJ **809** 105 **2015**
http://arxiv.org/pdf/1507.01620v1.pdf
https://iopscience.iop.org/article/10.1088/0004-637X/809/1/105/pdf
Using the Wind/WAVES radio observations from 2010-2013, we present an analysis of the 123 decametric-hectometric (DH) type II solar radio bursts during this period, the associated type III burst properties, and their correlation with solar energetic proton (SEP) properties determined from analysis of the Geostationary Operational Environmental Satellite (GOES) observations. We present a useful catalog of the type II burst, type III burst, Langmuir wave, and proton flux properties for these 123 events, which we employ to develop a statistical relationship between the radio properties and peak proton flux that can be used to forecast SEP events. We find that all SEP events with a peak > 10 MeV flux above 15 pfu are associated with a type II burst and virtually all SEP events, 92%, are also associated with a type III radio burst. Based on a principal component analysis, the radio burst properties that are most highly correlated with the occurrence of gradual SEP events and account for the most variance in the radio properties are the type III burst intensity and duration. Further, a logistic regression analysis with the radio-derived principal component (dominated by the type III and type II radio burst intensity and type III duration) obtains SEP predictions approaching the human forecaster rates, with a false alarm rate of 22%, a probability of detection of 62%, and with 85% of the classifications correct**.** ***Therefore, type III radio bursts that occur along with a DH type II burst are shown to be an important diagnostic that can be used to forecast SEP events.*** **15 Feb 2011, 21 March 2011, 4-5 Aug 2011, 22 Sept 2011, 22 Oct 2011, 24 Jan 2012, 7-8 March 2012, 10 March 2012, 6 June 2012, 9 June 2012, 2 July 2012, 11 Apr 2013, 22-23 May 2013**
The Wind/WAVES type II and Type IV solar radio burst list is found here:
http://www-lep.gsfc.nasa.gov/ waves/data_products.html.

The Solar Electron and Proton Telescope aboard STEREO -- understanding proton spectra

S. **Wraase**, B. Heber, S. Böttcher, N. Dresing, P. Kühl, R. Müller-Mellin
Solar Phys. **2018**
https://arxiv.org/pdf/1801.09513.pdf
The Solar Electron and Proton Telescope (SEPT) aboard the Solar Terrestrial Relations Observatory (STEREO) is designed to provide the three-dimensional distribution of energetic electrons and protons with good energy and time resolution. Each SEPT instrument consists of two double-ended magnet/foil particle telescopes which cleanly separate and measure electrons in the energy range from 30 keV to 400 keV and protons from 60 keV to 7000 keV. Anisotropy information on a non spinning spacecraft is provided by two separate but identical instruments: SEPT-E aligned along the Parker spiral magnetic field in the ecliptic plane along looking both towards and away from the Sun, and SEPT-NS aligned vertical to the ecliptic plane looking towards North and South. The dual set-up refers to two adjacent sensor apertures for each of the four viewing directions SUN, ANTISUN, NORTH, and SOUTH: one for protons, one for electrons. In this contribution a simulation of SEPT utilizing the GEANT4 toolkit has been set up with an extended instrument model in order to calculate improved response functions of the four different telescopes. This will help to understand and correct instrumental effects in the measurements.

Interpretation of increased energetic particle flux measurements by SEPT aboard the STEREO spacecraft and contamination

S. **Wraase**, B. Heber, S. Böttcher, R. Bucik, N. Dresing, Gómez-Herrero, A. Klassen, R. Müller-Mellin
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https://arxiv.org/pdf/1801.01040.pdf
http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2018/03/aa32063-17/aa32063-17.html

Context. Interplanetary (IP) shocks are known to be accelerators of energetic charged particles observed in-situ in the heliosphere. However, the acceleration of near-relativistic electrons by shocks in the interplanetary medium is often questioned. On **9 August 2011** a Corotating Interaction Region (CIR) passed STEREO B (STB) that resulted in a flux increase in the electron and ion channels of the Solar Electron and Proton Telescope (SEPT). Because electron measurements in the few keV to several 100 keV range rely on the so-called magnet foil technique, which is utilized by SEPT, ions can contribute to the electron channels. Aims. We aim to investigate whether the flux increase in the electron channels of SEPT during the CIR event on 9 August 2011 is caused by ion contamination only. Methods. We compute the SEPT response functions for protons and helium utilizing an updated GEANT4 model of SEPT. The CIR energetic particle ion spectra for protons and helium are assumed to follow a Band function in energy per nucleon with a constant helium to proton ratio. Results. Our analysis leads to a helium to proton ratio of 16.9% and a proton flux following a Band function with the parameters I_0 = 1.24 10^4 / (cm2 s sr MeV/nuc.), E_c = 79 keV/nuc. and spectral indices of \gamma_1 = -0.94 and \gamma_2 = -3.80 which are in good agreement with measurements by the Suprathermal Ion Telescope (SIT) aboard STB. Conclusions. Since our results explain the SEPT measurements, we conclude that no significant amount of electrons were accelerated between 55 keV and 425 keV by the CIR.

Statistical Study of Release Time and Its Energy Dependence of In Situ Energetic Electrons in Impulsive Solar Flares

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Using the fraction velocity dispersion analysis method, it has been shown recently that in two impulsive solar energetic electron (SEE) events, the release times of near-relativistic electrons at the Sun for outward-propagating electrons are energy dependent and are delayed compared to those of the downward-propagating electrons. In this work, we perform a statistical study of the release time and its energy dependence of near-relativistic electrons in impulsive SEE events. We use in situ observations from the WIND spacecraft and remote hard X-ray observations from the RHESSI and/or Fermi spacecraft. The difference in the release times between outward electrons and downward electrons for 29 events is obtained. In all events, the release of the outward-propagating electrons is delayed from those precipitating downward. In 26 of the 29 events, the release times of outward-propagating electrons also show clear energy dependence. In 15 of these 26 events, in situ electron data from more than five energy channels were available. The delay time as a function of energy for nine of these can be fitted by a form proposed by G. Li et al. (2021, https://doi.org/10.1029/2021GL095138). The implication of this energy-dependent release on the Magnetohydrodynamics turbulence property at the electron acceleration site is discussed.

Magnetic Cloud and Sheath in the Ground-level Enhancement Event of 2000 July 14. I. Effects on the Solar Energetic Particles

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2020 ApJ 904 151

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https://iopscience.iop.org/article/10.3847/1538-4357/abc0f2/pdf

Ground-level enhancements generally accompany fast interplanetary coronal mass ejections (ICMEs), and ICME-driven shocks are sources of solar energetic particles (SEPs). Observations of the GLE event of **2000 July 14** show that a very fast and strong magnetic cloud (MC) is behind the ICME shock and the proton intensity-time profiles observed at 1 au had a rapid two-step decrease near the sheath and MC. Therefore, we study the effect of sheath and MC on SEPs accelerated by an ICME shock by numerically solving the focused transport equation. The shock is regarded as a moving source of SEPs with an assumed particle distribution function. The sheath and MC are set to thick spherical caps with enhanced magnetic field, and the turbulence levels in the sheath and MC are set to be higher and lower than those of the ambient solar wind, respectively. The simulation results of proton intensity-time profiles agree well with the observations in energies ranging from ~1 to ~100 MeV, and the two-step decrease is reproduced when the sheath and MC arrived at the Earth. The simulation results show that the sheath-MC structure reduced the proton intensities for about 2 days after the shock passed through the Earth. It is found that the sheath contributed most of the decrease while the MC facilitated the formation of the second step decrease. The simulation also infers that the coordination of magnetic field and turbulence in sheath-MC structure can produce a stronger reduction of SEP intensities.

Penetrating particle ANalyzer (PAN)

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https://www.sciencedirect.com/science/article/pii/S0273117719300201?dgcid=raven_sd_via_email

PAN is a scientific instrument suitable for deep space and interplanetary missions. It can precisely measure and monitor the flux, composition, and direction of highly penetrating particles (>∼100 MeV/nucleon) in deep space, over at least one full solar cycle (11 years). The science program of PAN is multi- and cross-disciplinary, covering cosmic ray physics, solar physics, space weatherand space travel. PAN will fill an observation gap of galactic cosmic rays in the GeV region, and provide precise information of the spectrum, composition and emission time of energetic particle originated from the Sun. The precise measurement and monitoring of the energetic particles is also a unique contribution to space weather studies. PAN will map the flux and composition of penetrating particles, which cannot be shielded effectively, precisely and continuously, providing valuable input for the assessment of the related health risk, and for the development of an adequate mitigation strategy. PAN has the potential to become a standard on-board instrument for deep space human travel.

PAN is based on the proven detection principle of a magnetic spectrometer, but with novel layout and detection concept. It will adopt advanced particle detection technologies and industrial processes optimized for deep space application. The device will require limited mass (20 kg) and power (20 W) budget. Dipole magnet sectors built from high field permanent magnet Halbach arrays, instrumented in a modular fashion with high resolution silicon strip detectors, allow to reach an energy resolution better than 10% for nuclei from H to Fe at 1 GeV/n. The charge of the particle, from 1 (proton) to 26 (Iron), can be determined by scintillating detectors and silicon strip detectors, with readout ASICs of large dynamic range. Silicon pixel detectors used in a low power setting will maintain the detection capabilities for even the strongest solar events. A fast scintillator with silicon photomultiplier (SiPM) readout will provide timing information to determine the entering direction of the particle, as well as a high rate particle counter. Low noise, low power and high density ASIC will be developed to satisfy the stringent requirement of the position resolution and the power consumption of the tracker.

Model of energy spectrum parameters of ground level enhancement events in solar cycle 23†

S.-S. **Wu**, G. Qin

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http://sci-hub.tw/10.1002/2017JA024638

Mewaldt et al. 2012 fitted the observations of the ground level enhancement (GLE) events during solar cycle 23 to the double power-law equation to obtain the four spectral parameters, the normalization constant C, low-energy power-law slope γ1, high-energy power-law slope γ2, and break energy E0. There are 16 GLEs from which we select 13 for study by excluding some events with complicated situation. We analyze the four parameters with conditions of the corresponding solar events. According to solar event conditions we divide the GLEs into two groups, one with strong acceleration by interplanetary (IP) shocks and another one without strong acceleration. By fitting the four parameters with solar event conditions we obtain models of the parameters for the two groups of GLEs separately. Therefore, we establish a model of energy spectrum of solar cycle 23 GLEs which may be used in prediction in the future. **1997/11/07, 1998/05/02-04, 1998/05/06-08, 1998/08/25-26, 2000/07/14, 2001/04/15, 2001/04/18, 2001/11/04-06, 2001/12/26, 2002/08/24, 2003/10/28-29, 2003/11/02, 2005/01/17, 2005/01/20, 2006/12/13**

Table 1. Some related parameters of solar cycle 23 GLEs.

Global magnetohydrodynamic simulation of the 15 March 2013 coronal mass ejection event—Interpretation of the 30–80 MeV proton flux

Chin-Chun **Wu**, Kan Liou, Angelos Vourlidas, Simon Plunkett, Murray Dryer, S. T. Wu, Richard A. Mewaldt

JGR Volume 121, Issue 1 January **2016** Pages 56–76

The coronal mass ejection (CME) event on **15 March 2013** is one of the few solar events in Cycle 24 that produced a large solar energetic particle (SEP) event and severe geomagnetic activity. Observations of SEP from the ACE spacecraft show a complex time-intensity SEP profile that is not easily understood with current empirical SEP models. In this study, we employ a global three-dimensional (3-D) magnetohydrodynamic (MHD) simulation to help interpret the observations. The simulation is based on the H3DMHD code and incorporates extrapolations of photospheric magnetic field as the inner boundary condition at a solar radial distance (r) of 2.5 solar radii. A Gaussian-shaped velocity pulse is imposed at the inner boundary as a proxy for the complex physical conditions that initiated the CME. It is found that the time-intensity profile of the high-energy (>10 MeV) SEPs can be explained by the evolution of the CME-driven shock and its interaction with the heliospheric current sheet and the nonuniform solar wind. We also demonstrate in more detail that the simulated fast-mode shock Mach number at the magnetically connected shock location is well correlated (rcc ≥ 0.7) with the concurrent 30–80 MeV proton flux. A better correlation occurs when the 30–80 MeV proton flux is scaled by r−1.4(rcc = 0.87). When scaled by r−2.8, the correlation for 10–30 MeV proton flux improves significantly from rcc = 0.12 to rcc = 0.73, with 1 h delay. The present study suggests that (1) sector boundary can act as an obstacle to the propagation of SEPs; (2) the background solar wind is an important factor in the variation of IP shock strength and thus plays an important role in manipulation of SEP flux; (3) at least 50% of the variance in SEP flux can be explained by the fast-mode shock Mach number. This study demonstrates that global MHD simulation, despite the limitation implied by its physics-based ideal fluid continuum assumption, can be a viable tool for SEP data analysis.

Observations of Energetic Particles between a Pair of Corotating Interaction Regions

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2014 ApJ 781 17

We report observations of the acceleration and trapping of energetic ions and electrons between a pair of corotating interaction regions (CIRs). The event occurred in Carrington Rotation 2060. Observed by the STEREO-B spacecraft, the two CIRs were separated by less than 5 days. In contrast to other CIR events, the fluxes of the energetic ions and electrons in this event reached their maxima between the trailing edge of the first CIR and the leading edge of the second CIR. The radial magnetic field (Br) reversed its sense and the anisotropy of the flux also changed from Sunward to anti-Sunward between the two CIRs. Furthermore, there was an extended period of counterstreaming suprathermal electrons between the two CIRs. Similar observations for this event were also obtained with the Advanced Composition Explorer and STEREO-A. We conjecture that these observations were due to a U-shaped, large-scale magnetic field topology connecting the reverse shock of the first CIR and the forward shock of the second CIR. Such a disconnected U-shaped magnetic field topology may have formed due to magnetic reconnection in the upper corona.

First Application of a Theoretically Derived Coupling Function in Cosmic-Ray Intensity for the Case of the 10 September 2017 Ground-Level Enhancement (GLE 72)

L. **Xaplanteris**, M. Gerontidou, H. Mavromichalaki, J. V. Rodriguez, M. Livada, M. K. Georgoulis, T. E. Sarris, V. Spanos & L. Dorman

Solar Physics volume 297, Article number: 73 (**2022**)

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In this work we implement an analytically derived coupling function between ground-level and primary proton particles for the case of ground-level enhancement events (GLEs). The main motivation for this work is to determine whether this coupling function is suitable for the study of both major cases of cosmic-ray (CR) variation events, namely GLEs and Forbush decreases. This version of the coupling function, which relies on formalism used in quantum field theory (QFT) computations, has already been applied to Forbush decreases yielding satisfactory results. In this study, it is applied to a GLE event that occurred on 10 September 2017. For the analytical derivations, normalized ground-level cosmic-ray data were used from seven neutron-monitor stations with low cutoff rigidities. To assess and evaluate the results for the normalized proton intensity, we benchmark them with the time series for the proton flux, as recorded by the GOES 13 spacecraft during the same time period. The theoretically calculated results for proton energy ≥1 GeV≥1 GeV are in general agreement with the recorded data for protons with energy >700 MeV>700 MeV, presenting a least-squares linear best fit with slope 0.75±0.170.75±0.17 and a Pearson correlation coefficient equal to 0.62. We conclude that the coupling function presented in this work is the first coupling function that is well applicable to both cases of cosmic-ray intensity events, namely GLEs and Forbush decreases.

Improved Approach in the Coupling Function Between Primary and Ground Level Cosmic Ray Particles Based on Neutron Monitor Data

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Solar Physics volume 296, Article number: 91 (**2021**)

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In this work an improved approach of existing approximations on the coupling function between primary and ground-level cosmic-ray particles is presented. The proposed coupling function is analytically derived based on a formalism used in Quantum Field Theory calculations. It is upgraded compared to previous versions with the inclusion of a wider energy spectrum that is extended to lower energies, as well as an altitude correction factor, also derived analytically. The improved approximations are applied to two cases of Forbush decreases detected in March 2012 and September 2017. In the analytical procedure for the derivation of the primary cosmic-ray spectrum during these events, we also consider the energy spectrum exponent γγ to be varied with time. For the validation of the findings, we present a direct comparison between the primary spectrum and the amplitude values derived by the proposed method and the obtained time series of the cosmic-ray intensity at the rigidity of 10 GV obtained from the Global Survey Method. The two sets of results are found to be in very good agreement for both events as denoted by the Pearson correlation factors and slope values of their scatter plots. In such way we determine the validity and applicability of our method to Forbush decreases as well as to other cosmic-ray phenomena, thus introducing a new, alternative way of inferring the primary cosmic-ray intensity. **7-15 Mar 2012, 8-11 Sep 2017**

Detection of Energy Cutoffs in Flare-accelerated Electrons

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2021 ApJ 908 111

https://iopscience.iop.org/article/10.3847/1538-4357/abce5c/pdf

Energy cutoffs in electron distribution define the lower and upper limits on the energy range of energetic electrons accelerated in solar flares. They are crucial parameters for understanding particle acceleration processes and energy budgets. Their signatures have been reported in studies of flattened flare X-ray spectra, i.e., the impulsive emission of nonthermal bremsstrahlung from energetic electrons impacting ambient, thermal plasma. However, these observations have not provided unambiguous constraints on the cutoffs. Moreover, other processes may result in similar spectral features. Even the existence and necessity of cutoffs as physical parameters of energetic electrons have been under debate. Here we report a search for their signatures in flare-accelerated electrons with two approaches, i.e., in both X-ray spectra and solar energetic particle (SEP) events. These represent two different electron populations, but may contain information of the same acceleration process. By studying a special group of late impulsive flares, and a group of selected SEP events, we found evidence of cutoffs revealed in both X-ray spectra and SEP electron distributions. In particular, we found for the first time consistent low- and high-energy cutoffs in both hard X-ray-producing and escaping electrons in two events. We also showed the importance of high-energy cutoff in studies of spectral shapes. These results provide evidence of cutoffs in flare-accelerated energetic electrons and new clues for constraining electron distribution parameters and particle acceleration models. **23 Oct 2003, 14 Aug 2004, 7 Nov 2004, 6 Dec 2006, 18 Nov 2012, 16 Apr 2015**

Table 1 Late Impulsive X-Ray Bursts and Two Selected SEP-related Flare Events (2002-2015)

Statistical Study on Multispacecraft Widespread Solar Energetic Particle Events During Solar Cycle 24

H. **Xie** , O. C. St. Cyr , P. Mäkelä, N. Gopalswamy

JGR Volume124, Issue8 Pages 6384-6402 **2019 File**

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019JA026832

We conduct a statistical study on the large three-spacecraft widespread solar energetic particle (SEP) events. Longitudinal distributions of the peak intensities, onset delays, and relation between the SEP intensity, coronal mass ejection (CME) shock speed, width, and the kinetic energy of the CME have been investigated. We apply a Gaussian fit to obtain the SEP intensity I0 and distribution width σ and a forward-modeling fit to determine the true shock speed and true CME width. We found a good correlation between σ and connection angle to the flare site and I0 and the kinetic energy of the CME. By including the true shock speed and true CME widths, we reduce root-mean-square errors on the predicted SEP intensity by ~41% for protons compared to Richardson et al.'s (2014, https://doi.org/10.1007/s11207-014-0524-8) prediction. The improved correlation between the CME kinetic energy and SEP intensity provides strong evidence for the CME-shock acceleration theory of SEPs. In addition, we found that electron and proton release time delays (DTs) relative to Type II radio bursts increase with connection angles. The average electron (proton) DT is ~14 (32) min for strongly anisotropic events and ~2.5 (4.4) hr for weakly anisotropic events. Poor magnetic connectivity and large scattering effects are two main reasons to cause large delays. **5 March 2013**

Table 1 Event Number, Date, Type III Radio Burst Onset Time, Flare Location, CA, A Value, and Coronal Mass Ejection Shock Fit Results

Table 3 Electrons and Protons Release Times and Type II Radio Burst Onset Times

Table 4 Observed Peak Intensities of Electrons and Protons of the Test Sample

Comparison of the CME-shock Acceleration of Three Widespread SEP Events during Solar Cycle 24†

H. **Xie**, P. Mäkelä, O. C. St. Cyr, N. Gopalswamy

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http://sci-hub.cc/10.1002/2017JA024218

https://cdaw.gsfc.nasa.gov/publications/xie/xie2017JGR_final.pdf

We studied three solar energetic particle (SEP) events observed on **August 14, 2010, November 03, 2011, and March 05, 2013** by STEREO A, B and near-Earth (L1) spacecraft with a longitudinal distribution of particles > 90 degree. Using a forward-modeling method combined with extreme ultraviolet and white-light images we determined the angular extent of the shock, the time and location (cobpoint) of the shock intersection with the magnetic field line connecting to each spacecraft, and compute the shock speed at the cobpoint of each spacecraft. We then examine whether the observations of SEPs at each spacecraft were accelerated and injected by the spatially extended shocks or whether another mechanism such as cross-field transport is required for an alternative explanation. Our analyses results indicate that the SEPs observed at the three spacecraft on November 03, STB and L1 on August 14, and the March 05 SEP event at STA can be explained by the direct shock acceleration. This is consistent with the observed significant anisotropies, short time delays between particle release times and magnetic connection times, and sharp rises in the SEP time profiles. Cross-field diffusion is the likely cause for the August 14 SEP event observed by STA and the March 05 SEPs observed by STB and L1 spacecraft, as particle observations featured weak electron aniotropies and slow rising intensity profiles. Otherwise, the wide longitudinal spread of these SEP increases would require an existence of a circumsolar shock, which may not be a correct assumption in the corona and heliosphere.

Energy dependence of SEP electron and proton onset times

H. **Xie**, P. Mäkelä, N. Gopalswamy, O. C. St. Cyr

JGR Volume 121, Issue 7 July **2016** Pages 6168–6183

http://arxiv.org/pdf/1609.08171v1.pdf

We study the large solar energetic particle (SEP) events that were detected by GOES in the >10 MeV energy channel during December 2006 to March 2014. We derive and compare solar particle release (SPR) times for the 0.25–10.4 MeV electrons and 10–100 MeV protons for the 28 SEP events. In the study, the electron SPR times are derived with the time-shifting analysis (TSA) and the proton SPR times are derived using both the TSA and the velocity dispersion analysis (VDA). Electron anisotropies are computed to evaluate the amount of scattering for the events under study. Our main results include (1) near-relativistic electrons and high-energy protons are released at the same time within 8 min for most (16 of 23) SEP events. (2)There exists a good correlation between electron and proton acceleration, peak intensity, and intensity time profiles. (3) The TSA SPR times for 90.5 MeV and 57.4 MeV protons have maximum errors of 6 min and 10 min compared to the proton VDA release times, respectively, while the maximum error for 15.4 MeV protons can reach to 32 min. (4) *For 7 low-intensity events of the 23, large delays occurred for 6.5 MeV electrons and 90.5 MeV protons relative to 0.5 MeV electrons. Whether these delays are due to times needed for the evolving shock to be strengthened or due to particle transport effects remains unsolved.*

13-Dec-06 , 2011 August 4 , 2011 August 9, 26-Nov-11 , 2012-01-27, May 17 2012, 2014 February 20

Table 1. SEP Electrons and Protons Solar Release Times and Associated Solar Eruptive Signatures

Table 2. Electron Anisotropy and Velocity Dispersion Analysis Results for Protons

Composition variation of the May 16 2023 Solar Energetic Particle Event observed by Solar Orbiter and Parker Solar Probe

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ApJ **976** L3 **2024**

https://arxiv.org/pdf/2410.19672

https://iopscience.iop.org/article/10.3847/2041-8213/ad8b18/pdf

In this study, we employ the combined charged particle measurements from Integrated Science Investigation of the Sun (\ISOIS) onboard the Parker Solar Probe (PSP) and Energetic Particle Detector (EPD) onboard the Solar Orbiter (SolO) to study the composition variation of the solar energetic particle (SEP) event occurring on **May 16, 2023**. During the event, SolO and PSP were located at a similar radial distance of ~0.7 au and were separated by ∼60∘ in longitude. The footpoints of both PSP and SolO were west of the flare region but the former was much closer (18∘ vs 80∘). Such a distribution of observers is ideal for studying the longitudinal dependence of the ion composition with the minimum transport effects of particles along the radial direction. We focus on H, He, O, and Fe measured by both spacecraft in sunward and anti-sunward directions. Their spectra are in a double power-law shape, which is fitted best by the Band function. Notably, the event was Fe-rich at PSP, where the mean Fe/O ratio at energies of 0.1 - 10 Mev/nuc was 0.48, higher than the average Fe/O ratio in previous large SEP events. In contrast, the mean Fe/O ratio at SolO over the same energy range was considerable lower at 0.08. The Fe/O ratio between 0.5 and 10 MeV/nuc at both spacecraft is nearly constant. Although the He/H ratio shows energy dependence, decreasing with increasing energy, the He/H ratio at PSP is still about twice as high as that at SolO. Such a strong longitudinal dependence of element abundances and the Fe-rich component in the PSP data could be attributed to the direct flare contribution. Moreover, the temporal profiles indicate that differences in the Fe/O and He/H ratios between PSP and SolO persisted throughout the entire event rather than only at the start.

First Solar energetic particles measured on the Lunar far-side

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ApJ Letter 902 L30 **2020**

https://arxiv.org/pdf/2008.03492.pdf

https://doi.org/10.3847/2041-8213/abbccc

On **2019 May 6**, the Lunar Lander Neutron & Dosimetry (LND) Experiment on board the Chang'E-4 on the far-side of the Moon detected its first small solar energetic particle (SEP) event with proton energies up to 21MeV. Combined proton energy spectra are studied based on the LND, SOHO/EPHIN and ACE/EPAM measurements which show that LND could provide a complementary dataset from a special location on the Moon, contributing to our existing observations and understanding of space environment. Velocity dispersion analysis (VDA) has been applied to the impulsive electron event and weak proton enhancement and the results demonstrate that electrons are released only 22 minutes after the flare onset and ∼15 minutes after type II radio burst, while protons are released more than one hour after the electron release. The impulsive enhancement of the in-situ electrons and the derived early release time indicate a good magnetic connection between the source and Earth. However, stereoscopic remote-sensing observations from Earth and STA suggest that the SEPs are associated with an active region nearly 100∘ away from the magnetic footpoint of Earth. This suggests that the propagation of these SEPs could not follow a nominal Parker spiral under the ballistic mapping model and the release and propagation mechanism of electrons and protons are likely to differ significantly during this event.

The Enhancement of the Energetic Particle Intensities in ICMEs

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2019 ApJ 885 54

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The behavior of energetic particles in interplanetary coronal mass ejections (ICMEs) is of great interest. In general, due to the relatively closed magnetic structures of ICMEs, the energetic-particle intensities are usually depressed in them. However, previous studies have found some counterexamples. In this work, using protons with energies form ~200 keV to ~7 MeV observed by Wind/3dp as a measure, we check the proton intensity signatures of the 487 ICMEs between 1995 and 2017. A total of 12 ICMEs with extraordinary energetic-particle enhancements have been found, 9 of which are shock-interplanetary coronal mass ejection complex structures (S-ICMEs) and 3 that are isolated interplanetary coronal mass ejections (I-ICMEs). Comparing the two kinds of ICMEs, we find that energetic-particle intensities increase more in the S-ICMEs than in the I-ICMEs in all energy channels, especially in the high-energy channels. In addition, shocks inside energetic-particle-enhanced S-ICMEs are relatively fast and strong. These results indicate that shock-ICME interaction may be an effective local acceleration mechanism.

LSTM neural network for solar radio spectrum classification

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RAA **2019** Vol. 19 No. 9, 135(12pp)

http://www.raa-journal.org/raa/index.php/raa/article/view/4379/4860

A solar radio spectrometer records solar radio radiation in the radio waveband. Such solar radio radiation spanning multiple frequency channels and over a short time period could provide a solar radio spectrum which is a two dimensional image. The vertical axis of a spectrum represents frequency channel and the horizontal axis signifies time. Intrinsically, time dependence exists between neighboring columns of a spectrum since solar radio radiation varies continuously over time. Thus, a spectrum can be treated as a time series consisting of all columns of a spectrum, while treating it as a general image would lose its time series property. A recurrent neural network (RNN) is designed for time series analysis. It can explore the correlation and interaction between neighboring inputs of a time series by augmenting a loop in a network. This paper makes the first attempt to utilize an RNN, specifically long short-term memory (LSTM), for solar radio spectrum classification. LSTM can mine well the context of a time series to acquire more information beyond a non-time series model. As such, as demonstrated by our experimental results, LSTM can learn a better representation of a spectrum, and thus contribute better classification.**2010-04-21**

Observations of a Coronal Shock Wave and the Production of Solar Energetic Particles

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2017 ApJ 840 38

http://sci-hub.cc/10.3847/1538-4357/aa6ba2

We present a study that clarifies the acceleration source/mechanism of the solar energetic particle (SEP) event on **2011 August 9**. Based on the assumption of scatter-free propagation of charged particles along the interplanetary magnetic field, the solar particle release times of the electrons and protons are derived and both found to be in the decay phase of the flare emission. Furthermore, we compare the peak-flux spectra of the in situ particles and the remote-sensing hard X-ray photons and find a weak correlation between them. In particular, we note that an extreme ultraviolet shock wave, presumed to be a signature of coronal mass ejection (CME) shock front on the solar surface, and an associated type II radio burst were observed alongside this event. Under the framework of diffusive shock acceleration, the derived shock compression ratio can accelerate particles with a theoretical spectral index , which is comparable to the observational index of ~2.0. Our results appear to support the notion that the coronal shock wave was most likely responsible for the SEP event. Specifically, we find that the electrons were released in a low coronal site at ~0.58 solar radii, and protons were released when the CME-driven shock propagated to ~1.38 solar radii. The multi-spacecraft observations, in addition, reveal the connection between the acceleration of shock waves and the release of SEPs.

An unusual long-lived relativistic electron enhancement event excited by sequential CMEs

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JGR   Volume 119, Issue 11, pages 9038–9050, November **2014**

An unusual long-lived intense relativistic electron enhancement event from July to August 2004 is examined using data from Fengyun-1, POES, GOES, ACE, the Cluster Mission, and geomagnetic indices. During the initial 6 days of this event, the observed fluxes in the outer zone enhanced continuously, and their maximum increased from 2.1×10^2 cm^{-2} sr^{-1} s^{-1} to 3.5×10^4 cm^{-2} sr^{-1} s^{-1}, the region of enhanced fluxes extended from L = 3.5–6.5 to L = 2.5–6.5, and the flux peak location shifted inward from L ~ 4.2 to L ~ 3.3. During the following 7 days, without any locational movement, the flux peak increased slowly and exceeded the prestorm fluxes by about 4 orders of magnitude. Subsequently, the decay rate of relativistic electrons is so slow that the peak remains over 10^4 cm^{-2} sr^{-1} s^{-1} for about 30 days. The drift resonance between ULF waves, which arose from high-speed solar wind and frequent impulses of solar wind dynamic pressure, and energetic electrons injected by substorms could be an important acceleration mechanism in this event. The local acceleration by whistler mode chorus could be another mechanism contributing to this enhancement. The plasmaspheric response to the interplanetary disturbances reveals that the enhanced outer zone is divided into two portions by the plasmapause. Accordingly, the slow loss rate in the plasmasphere due to hiss primarily contributed to the long-lived characteristic of this event. This event reveals that the outer zone population behaviors are dominated by the interplanetary variations together with the responses of geomagnetic field and plasmasphere to these variations.

Sigmoid eruption associated with X9.3 flare from AR 12673 drives gradual SEP event on 2017 September 6

Stephanie L. **Yardley**, David H. Brooks

ApJ   **976** 152   **2024**

https://arxiv.org/pdf/2410.22814

https://iopscience.iop.org/article/10.3847/1538-4357/ad8d5f/pdf

Large gradual solar energetic particle (SEP) events can pose a radiation risk to crewed spaceflight and a significant threat to near-Earth satellites however, the origin of the SEP seed particle population, how these particles are released, accelerated and transported into the heliosphere are not well understood. We analyse NOAA active region (AR) 12673, that was the source responsible for multiple large gradual SEP events during September 2017, and found that almost immediately after each significant eruptive event associated with SEPs an enhanced Si/S abundance ratio was measured by Wind, consistent with the previous work by Brooks et al. Hinode/EIS took data roughly 8~hours before the second SEP event on 2017 September 6 that allowed the regions of enhanced Si/S abundance ratio in the AR to be determined. We have shown that the AR contains plasma with elemental abundance values detected in situ by Wind. In particular, the plasma originates from the core of the AR, similar to Brooks et al., but in the moss (footpoints) associated with hot sigmoidal AR loops. The sigmoid, that contains highly fractionated plasma, erupts and propagates towards an Earth-connected magnetic null point, providing a direct channel for the highly fractionated plasma to escape and be detected in the near-Earth environment.

The magnetic field environment of active region 12673 that produced the energetic particle events of September 2017

Stephanie L. **Yardley**, Lucie M. Green, Alexander W. James, David Stansby, Teodora Mihailescu

ApJ   **937** 57   **2022**

https://arxiv.org/pdf/2208.12774.pdf   **File**

https://iopscience.iop.org/article/10.3847/1538-4357/ac8d69/pdf

Forecasting solar energetic particles (SEPs), and identifying flare/CMEs from active regions (ARs) that will produce SEP events in advance is extremely challenging. We investigate the magnetic field environment of AR 12673, including the AR's magnetic configuration, the surrounding field configuration in the vicinity of the AR, the decay index profile, and the footpoints of Earth-connected magnetic field, around the time of four eruptive events. Two of the eruptive events are SEP-productive (**2017 September 4** at 20:00~UT and **September 6** at 11:56~UT), while two are not (September 4 at 18:05~UT and **September 7** at 14:33~UT). We analysed a range of EUV and white-light coronagraph observations along with potential field extrapolations and find that the CMEs associated with the SEP-productive events either trigger null point reconnection that redirects flare-accelerated particles from the flare site to the Earth-connected field and/or have a significant expansion (and shock formation) into the open Earth-connected field. The rate of change of the decay index with height indicates that the region could produce a fast CME (v> 1500~km~s−1), which it did during events two and three. The AR's magnetic field environment, including sites of open magnetic field and null points along with the magnetic field connectivity and propagation direction of the CMEs play an important role in the escape and arrival of SEPs at Earth. Other SEP-productive ARs should be investigated to determine whether their magnetic field environment and CME propagation direction are significant in the escape and arrival of SEPs at Earth.

Particle Acceleration in a Shock Wave Propagating to an Inhomogeneous Medium

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2020 ApJ 897 50

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We investigate effects of upstream density fluctuations on the diffusive shock acceleration (DSA) by Monte Carlo simulations. The simulations show that particles are reaccelerated in the shock downstream region by a sound wave generated at the shock front. The timescale of turbulent acceleration by the sound wave is estimated. We propose a new back reaction of particles accelerated around the shock front. The accelerated particles generate the upstream density fluctuations by the Drury instability, which are converted to the downstream sound waves by the shock. The downstream sound waves modify the momentum spectrum of particles accelerated around the shock front. This new back reaction affects emission from the accelerated particles, which gives a new constraint on the acceleration efficiency of the DSA.

Energetic Proton Propagation and Acceleration Simulated for the Bastille Day Event of July 14, 2000

Matthew A. **Young**, Nathan A. Schwadron, Matthew Gorby, Jon Linker, Ronald M. Caplan, Cooper Downs, Tibor Török, Pete Riley, Roberto Lionello, Viacheslav Titov, Richard A. Mewaldt, Christina M. S. Cohen

ApJ **909** 160 **2021**

https://arxiv.org/pdf/2012.09078.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/abdf5f/pdf

https://doi.org/10.3847/1538-4357/abdf5f

This work presents results from simulations of the **14 July 2000** ("Bastille Day") solar proton event. We used the Energetic Particle Radiation Environment Model (EPREM) and the CORona-HELiosphere (CORHEL) software suite within the SPE Threat Assessment Tool (STAT) framework to model proton acceleration to GeV energies due to the passage of a CME through the low solar corona, and compared the model results to GOES-08 observations. The coupled simulation models particle acceleration from 1 to 20 R⊙, after which it models only particle transport. The simulation roughly reproduces the peak event fluxes, and timing and spatial location of the energetic particle event. While peak fluxes and overall variation within the first few hours of the simulation agree well with observations, the modeled CME moves beyond the inner simulation boundary after several hours. The model therefore accurately describes the acceleration processes in the low corona and resolves the sites of most rapid acceleration close to the Sun. Plots of integral flux envelopes from multiple simulated observers near Earth further improve the comparison to observations and increase potential for predicting solar particle events. ***Broken-power-law fits to fluence spectra*** agree with diffusive acceleration theory over the low energy range. Over the high energy range, they demonstrate the variability in acceleration rate and mirror the inter-event variability observed solar-cycle 23 GLEs. We discuss ways to improve STAT predictions, including using corrected GOES energy bins and computing fits to the seed spectrum. This paper demonstrates a predictive tool for simulating low-coronal SEP acceleration.

5.2. Broken power laws

Suprathermal Proton Spectra at Interplanetary Shocks in 3D Hybrid Simulations

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2020 ApJ 897 109

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Interplanetary shocks are one of the proposed sources of suprathermal ion populations (i.e., ions with energies of a few times the solar-wind energy). Here we present results from a series of 3D hybrid simulations of collisionless shocks in the solar wind. We focus on the influence of the shock-normal angle, θ_{Bn}, and the shock speed, V_s, on producing protons with energies a few to hundreds of times the thermal energy of the upstream plasma. The combined effects of θ_{Bn} and V_s result in shocks with Alfvén Mach numbers in the range 3.0–6.0 and fast magnetosonic Mach numbers in the range 2.5–5.0, representing moderate to strong interplanetary shocks. We find that θ_{Bn} largely organizes the shape of proton energy spectra, while shock speed controls acceleration efficiency. All shocks accelerate protons at the shock front, but the spectral evolution depends on θ_{Bn}. Shocks with $\theta_{Bn} \geq 60°$ produce isolated bursts of suprathermal protons at the shock front, while shocks with $\theta_{Bn} \leq 45°$ create suprathermal beams upstream of the shock. Downstream proton energy spectra have exponential or smoothed broken power-law forms when θ Bn ≥ 45° and a single power-law form when θ Bn ≤ 30°. Protons downstream of the strongest shocks have energies at least 100 times the upstream thermal energy, with θ Bn ≤ 30° shocks producing the highest-energy protons and θ Bn ≥ 60° shocks producing the largest number of protons with energies at least a few times the thermal energy.

A Comparative Study of Two Contrasting Cosmic-Ray Events Caused by Solar Eruptions from NOAA AR 12673 in 2017 September

Xiao Xia **Yu**1, Shuang Nan Zhang1, Hong Lu1, Hong Bo Hu1, Ping Zhang2,3, and Wei Kang Gao1

2024 ApJ 960 85

https://iopscience.iop.org/article/10.3847/1538-4357/ad0550/pdf

Two major solar eruptions on AR 12673 produced a Forbush decrease (FD) event (reduction of cosmic rays) on 2017 September 8 and ground-level enhancement (GLE; enhancement of cosmic rays) on 2017 September 10. The occurrence of two contrasting cosmic-ray events within 2 days that are associated with two similar X-class solar flares (X9.3 and X8.2) and share the same active region on the Sun provides us a rare opportunity to understand the dominant factors in determining the properties of transient cosmic-ray events. Using a suite of modern-day instruments continuously tracking solar eruptions from the Sun to the Earth with ground-based cosmic-ray detectors, we reveal the complete cause–effect chain of activities for these two events. We conclude that the different consequences on the ground arise from two effects of the eruptions near the Sun: (1) the geometric effect of CMEs and (2) the intensity effect of CME-driven shocks. The first eruption, which originated at the heliographic longitude of W34° on 2017 September 6, had its CME ejecta and CME-driven shock intercept the Earth, leading to the FD event. The second eruption, which occurred on September 10 at W88°, only had its far flank reach the Earth. The peak shock speed of 3344 km s−1 of the second eruption, much faster than the 2175 km s−1 of the first eruption, is the dominant factor producing the GLE event, even though the first eruption is better connected magnetically to the Earth and has a similar flare. *The results indicate that the production of GLE particles can be dominated by fast-enough CME-driven shocks*. **6 Sep 2017**

Double-power-law feature of energetic particles accelerated at coronal shocks

Feiyu **Yu**, Xiangliang Kong, Fan Guo, Wenlong Liu, Zelong Jiang, Yao Chen, Joe Giacalone

ApJL **2022**

https://arxiv.org/pdf/2201.06712.pdf

Recent observations have shown that in many large solar energetic particle (SEP) events the event-integrated differential spectra resemble double power laws. We perform numerical modeling of particle acceleration at coronal shocks propagating through a streamer-like magnetic field by solving the Parker transport equation, including protons and heavier ions. We find that for all ion species the energy spectra integrated over the simulation domain can be described by a double power law, and the break energy depends on the ion charge-to-mass ratio as EB∼(Q/A)α, with α varying from 0.16 to 1.2 by considering different turbulence spectral indices. We suggest that the double power law distribution may emerge as a result of the superposition of energetic particles from different source regions where the acceleration rates differ significantly due to particle diffusion. The diffusion and mixing of energetic particles could also provide an explanation for the increase of Fe/O at high energies as observed in some SEP events. Although further mixing processes may occur, our simulations indicate that either power-law break or rollover can occur near the Sun and predict that the spectral forms vary significantly along the shock front, which may be examined by upcoming near-Sun SEP measurements from Parker Solar Probe and Solar Orbiter.

Comparisons of High-Linear Energy Transfer Spectra on the ISS and in Deep Space

C. **Zeitlin** , L. Narici, R. R. Rios, A. Rizzo, N. Stoffle, D. M. Hassler et al.

Space Weather Volume17, Issue3 March 2019 Pages 396-418

sci-hub.se/10.1029/2018SW002103

In deep space, personnel and equipment are exposed to the space radiation environment in the form of energetic particles, specifically galactic cosmic rays and sporadic solar energetic particle events. Radiation fields resulting from these particles are modified by shielding, but most radiation measurements in deep space have been made with detectors that were unshielded or very lightly shielded. In contrast, the space radiation environment on the International Space Station (ISS) is more complicated, with time-dependent modification of the incident flux by the geomagnetic field and complex bulk shielding distributions; measured particle spectra inside the ISS are affected by both types of shielding. The geomagnetic field is also responsible for the existence of the South Atlantic Anomaly, a region of trapped energetic protons and electrons, and hence enhanced radiation dose, through which the ISS travels several times per day on average. Here our primary aim is to compare charged-particle spectra at high linear energy transfer obtained by the Anomalous Long-Term Effects in Astronauts instrument on ISS during high-latitude portions of the orbit to data acquired at the same time by the Cosmic Ray Telescope for the Effects of Radiation and

Radiation Assessment Detector instruments, both in deep space. The hypothesis being tested is that these spectra are the same, modulo shielding differences, since the effects of the geomagnetic field are expected to be minimal at high latitudes.

Quiet-time 0.04--2 MeV/nucleon0.04--2 MeV/nucleon Ions at 1 AU in Solar Cycles 23 and 24

M. A. **Zeldovich**, Y. I. Logachev, K. Kecskeméty
Solar Physics January **2018**, 293:3
https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1170-8.pdf
The fluxes of 3He, 4He, C, O, and Fe ions at low energies (about 0.04--2 MeV/nucleon0.04--2 MeV/nucleon) are studied during quiet periods in Solar Cycles (SC) 23 and 24 using data from the ULEIS/ACE instrument. In selecting quiet periods (the definition is given in Section 2.1), additional data from EPHIN/SOHO and EPAM/ACE were also used. The analysis of the ion energy spectra and their relative abundances shows that their behavior is governed by their first-ionization potential. Substantial differences in the ion energy spectra in two consecutive solar cycles are observed during the quiet periods selected. Quiet-time fluxes are divided into three distinct types according to the ~80--320 keV/nucleon~80--320 keV/nucleon Fe/O ratio. Our results confirm the earlier observation that these types of suprathermal particles have different origins, that is, they represent different seed populations that are accelerated by different processes. Except for the solar activity minimum, the Fe/O ratio during quiet-time periods correspond either to the abundances of ions in particle fluxes accelerated in impulsive solar flares or to the mean abundances of elements in the solar corona. At the activity minimum, this ratio takes on values that are characteristic for the solar wind. These results indicate that the background fluxes of low-energy particles in the ascending, maximum, and decay phases of the solar cycle include significant contributions from both coronal particles accelerated to suprathermal energies and ions accelerated in small impulsive solar flares rich in Fe, while the contribution of remnants from earlier SEP events cannot be excluded. The comparison of suprathermal ion abundances during the first five years of SC 23 and SC 24 suggests that the quiet-time and non-quiet fluxes of Fe and 3He were lower in SC 24. **Table**

Time Evolution of Elemental Ratios in Solar Energetic Particle events

P. **Zelina**, S. Dalla, C. M. S. Cohen, R. A. Mewaldt
ApJ 835 71 **2016**
https://arxiv.org/pdf/1612.00758v1.pdf
Heavy ion ratio abundances in Solar Energetic Particle (SEP) events, e.g.~Fe/O, often exhibit decreases over time. Using particle instruments on the ACE, SOHO and STEREO spacecraft, we analysed heavy ion data from 4 SEP events taking place between December 2006 and December 2014. We constructed 36 different ionic pairs and studied their time evolution in each event. We quantified the temporal behaviour of abundant SEP ratios by fitting the data to derive a decay time constant B. We also considered the ratio of ionic mass--to--charge for each pair, the S value given e.g.~for Fe/O by SFe/O=(M/Q)Fe/(M/Q)O. We found that the temporal behaviour of SEP ratios is ordered by the value of S: ratios with S>1 showed decreases over time (i.e.~B<0) and those with S<1 showed increases (B>0). We plotted B as a function of S and observed a clear monotonic dependence: ratios with a large S decayed at a higher rate. A prominent discontinuity at S=2.0 (corresponding to He/H) was found in 3 of the 4 events, suggesting anomalous behaviour of protons. The X/H ratios often show an initial increase followed by a decrease, and decay at a slower rate. We discuss possible causes of the observed B versus S trends within current understanding of SEP propagation. **13 Dec 2006, 31 Aug 2012, 25 Feb 2014, 01 Sept 2014**
See Introduction.
UK Solar Physics (UKSP) – Nuggets #81 **2017** www.uksolphys.org/?p=13204

A Real-Time Prediction System of the Intensity of Solar Energetic Proton Events Based on a Solution of the Diffusion Equation

Y. **Zhang**, Y. Wang, X. Li, P. B. Zuo
Space Weather Volume22, Issue8 August **2024** e2023SW003725
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003725
https://doi.org/10.1029/2023SW003725
In this study, based on solar energetic particle (SEP) events classification and a solution of the diffusion equation, we present an efficient system, HITSEP, to predict the intensities in different energy channels (P4 15.0–44.0 MeV, P5 40.0–80.0 MeV, and P6 80.0–165.0 MeV) of energetic proton events observed by GOES spacecraft. The system can predict the rising phase (especially the peak time and peak intensity) of the energetic proton events using only a small amount of data at the beginning of the solar energetic proton events. Among the events that meet the conditions for the use of our prediction system from 2003 to 2017, for P4, P5, and P6 channels, the median Warning Times are 3.70, 2.52, and 1.69 hr; the median Error of the Intensity for events are 0.43, 0.23, 0.34 orders of magnitude; the median Error of the Peak Time for events are 2.53, 0.55, 0.43 hr, respectively. Our system is based on physical mechanisms and has a high accuracy in forecasting the peak intensity with a strict definition of the error.

The HITSEP system has huge potential to apply in the space weather forecast. The application of the HITSEP system in space weather forecasting is very promising.
Table 1 The Statistics Result of SEP Events Observed by GOES During 2003–2017

A data-driven physics-based transport model of solar energetic particles accelerated by coronal mass ejection shocks propagating through the solar coronal and heliospheric magnetic fields

Ming **Zhang**, Lei Cheng, Ju Zhang, Pete Riley, Ryun Young Kwon, David Lario, Laura Balmaceda, Nikolai Pogorelov

2023 *ApJS* **266** 35
https://arxiv.org/pdf/2212.07259.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/accb8e/pdf

In an effort to develop computational tools for predicting radiation hazards from solar energetic particles (SEPs), we have created a data-driven physics-based particle transport model to calculate the injection, acceleration and propagation of SEPs from coronal mass ejection (CME) shocks traversing through the solar corona and interplanetary magnetic fields. The model runs on an input of corona and heliospheric plasma and magnetic field configuration from an MHD model driven by solar photospheric magnetic field measurements superposed with observed CME shocks determined from coronagraph images. Using several advanced computation techniques involving stochastic simulation and integration, it rigorously solves the time-dependent 5-dimensional focus transport equation in the phase space that includes pitch-angle scattering, diffusion across magnetic field line, and particle acceleration by CME shocks. We apply the model to the **2011 November 3** CME event. The calculation results reproduce multi-spacecraft SEP observations reasonably well without normalization of particle flux. This circumsolar SEP event seen by spacecraft at Earth, STEREO-A and STEREO-B at widely separated longitudes can be explained by diffusive shock acceleration by a single CME shock with a moderate speed.

A Study of the Possible Mechanism of the Ground Level Enhancement on 28 October 2021

YunFeng **Zhang**, Kazi A. Firoz, WeiQun Gan, YouPing Li & HuanYu Jia

Solar Physics volume 297, Article number: 155 (**2022**)
https://doi.org/10.1007/s11207-022-02087-1

We have analyzed the particle acceleration processes and energy spectra for the ground level enhancement (GLE) event on 28 October 2021 using the in situ data registered by ground-based and space-borne instruments. It is found that the onset of the soft X-ray flare component (1 – 8 Å) lies close to the onset of the GLE (≥1 GeV) and high-energy (>500 MeV) proton fluxes, indicating that the GLE event might have been initiated by the flare acceleration process. It is observed that the coronal shock traced in m-Type II burst that operates over the flare acceleration phase plays a role on the impulsive phase of high energy particles. However, the coronal shock traced in DH-Type II burst that operates over the coronal mass ejection (CME) propagation phase plays a more important role in the reacceleration of the protons of low energy (≤80 MeV) than those of high energy (>80 MeV), thus supporting previous suggestions that the CME shock prolongs the temporal evolution of low-energy proton fluxes. The finding is supported by the analyses of proton energy spectra. For instance, the peak energy spectrum after the flare follows a double power-law, exhibiting that the break energy appeared at ∼80 MeV whilst the peak spectrum of the low-energy proton fluxes is harder than that of the high-energy proton fluxes.

Multi-species Ion Acceleration in 3D Magnetic Reconnection

Qile **Zhang**, Fan Guo, William Daughton, Hui Li, Ari Le, Tai Phan, Mihir Desai

2022
https://arxiv.org/pdf/2210.04113.pdf

Magnetic reconnection drives explosive particle acceleration in a wide range of space and astrophysical applications. The energized particles often include multiple species (electrons, protons, heavy ions), but the underlying acceleration mechanism is poorly understood. In-situ observations of these minority heavy ions offer a more stringent test of acceleration mechanisms, but the multi-scale nature of reconnection hinders studies on heavy-ion acceleration. Here we employ hybrid simulations (fluid electron, kinetic ions) to capture 3D reconnection over an unprecedented range of scales. For the first time, our simulations demonstrate nonthermal acceleration of all available ion species into power-law spectra. The reconnection layers consist of fragmented kinking flux ropes as part of the reconnection-driven turbulence, which produces field-line chaos critical for accelerating all species. The upstream ion velocities influence the first Fermi reflection for injection. Then lower charge/mass species initiate Fermi acceleration at later times as they interact with growing flux ropes. The resulting spectra have similar power-law indices (p∼4.5), but different maximum energy/nucleon ∝(charge/mass)α, with α∼0.6 for low plasma β, and with p and α increasing as β approaches unity. These findings are consistent with observations at heliospheric current sheets and the magnetotail, and provide strong evidence suggesting Fermi acceleration as the dominant ion-acceleration mechanism.

Study of Temporal Profile and Flux Variation of GLE Events During Solar Cycles 23 and 24 Using GOES Data

YunFeng **Zhang**, HuanYu Jia, YongLin Feng & ChangBei Wang

Solar Physics volume 297, Article number: 75 (**2022**)

https://doi.org/10.1007/s11207-022-02010-8

A ground level enhancement (GLE) event of solar cosmic rays refers to the sudden, sharp, and short-lived enhancement of energetic particles at ground level generated from a solar flare accompanied by a coronal mass ejection (CME). The study of GLE events not only provides the basis for the research of the origin, propagation, and acceleration of cosmic rays but also has important significance for space-weather research. In this article, we analyzed the temporal profile and flux variation of the electrons, X rays, and protons of 18 GLE events during Solar Cycles 23 and 24 using GOES series spacecraft data. The results suggested that the release time, onset time, peak time, and end time of the GLEs depend upon the energy and species of particles. The release time of protons with higher energies is later than for those with lower energies; the opposite is true for the onset time, peak time, and end time. The rise time decreases with the energy, and the recovery time increases first and then decreases with increasing energy. The energy spectrum of particles at onset time is harder than the peak spectrum. The energy spectrum at onset time is most affected by the CME speed, and the correlation of the peak energy spectrum and the flare longitude is strongest. The acceleration ability of CME-driven shock to low-energy particles is stronger than that of high-energy particles.

Earth-affecting Solar Transients: A Review of Progresses in Solar Cycle 24

Jie **Zhang**, Manuela Temmer, Nat Gopalswamy, Olga Malandraki, Nariaki V. Nitta, Spiros Patsourakos, Fang Shen, Bojan Vršnak, Yuming Wang, David Webb, Mihir I. Desai, Karin Dissauer, Nina Dresing, Mateja Dumbović, Xueshang Feng, Stephan G. Heinemann, Monica Laurenza, Noé Lugaz, Bin Zhuang

Progress in Earth and Planetary Science, Volume 8, Issue 1, article id.56, **2021** **File**

https://progearthplanetsci.springeropen.com/counter/pdf/10.1186/s40645-021-00426-7.pdf

https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf **2021**

2020 https://arxiv.org/abs/2012.06116

https://arxiv.org/ftp/arxiv/papers/2012/2012.06116.pdf

https://doi.org/10.1186/s40645-021-00426-7

This review article summarizes the advancement in the studies of Earth-affecting solar transients in the last decade that encompasses most of solar cycle 24. The Sun Earth is an integrated physical system in which the space environment of the Earth sustains continuous influence from mass, magnetic field and radiation energy output of the Sun in varying time scales from minutes to millennium. This article addresses short time scale events, from minutes to days that directly cause transient disturbances in the Earth space environment and generate intense adverse effects on advanced technological systems of human society. Such transient events largely fall into the following four types: (1) solar flares, (2) coronal mass ejections (CMEs) including their interplanetary counterparts ICMEs, (3) solar energetic particle (SEP) events, and (4) stream interaction regions (SIRs) including corotating interaction regions (CIRs). In the last decade, the unprecedented multi viewpoint observations of the Sun from space, enabled by STEREO Ahead/Behind spacecraft in combination with a suite of observatories along the Sun-Earth lines, have provided much more accurate and global measurements of the size, speed, propagation direction and morphology of CMEs in both 3-D and over a large volume in the heliosphere. Several advanced MHD models have been developed to simulate realistic CME events from the initiation on the Sun until their arrival at 1 AU. Much progress has been made on detailed kinematic and dynamic behaviors of CMEs, including non-radial motion, rotation and deformation of CMEs, CME-CME interaction, and stealth CMEs and problematic ICMEs. The knowledge about SEPs has also been significantly improved**. 2008-11-03, 7 March 2011 , June 30, 2012, 12-14 July 2012, 2012.10.04-05, 8-10 October 2012, 29 May 2013, 2014-06-24**

Precipitation and Release of Solar Energetic Particles from the Solar Coronal Magnetic Field

Ming **Zhang** and Lulu Zhao

2017 ApJ 846 107

https://iopscience.iop.org/article/10.3847/1538-4357/aa86a8/pdf

Most solar energetic particles (SEPs) are produced in the corona. They propagate through complex coronal magnetic fields subject to scattering and diffusion across the averaged field lines by turbulence. We examine the behaviors of particle transport using a stochastic 3D focused transport simulation in a potential field source surface model of coronal magnetic field. The model is applied to an SEP event on **2010 February 7**. We study three scenarios of particle injection at (i) the compact solar flare site, (ii) the coronal mass ejection (CME) shock, and (iii) the EUV wave near the surface. The majority of particles injected on open field lines are able to escape the corona. We found that none of our models can explain the observations of wide longitudinal SEP spread without perpendicular diffusion. If the perpendicular diffusion is about 10% of what is derived from the random walk of field lines at the rate of supergranular diffusion, **particles injected at the compact solar flare site can spread to a wide range of longitude and latitude, very similar to the behavior of particles injected at a large CME shock.** Stronger pitch-angle scattering results in a little more lateral spread by holding the particles in the corona for longer periods of time. Some injected particles eventually end up precipitating onto the solar surface. Even with a very small perpendicular diffusion, the pattern of the particle precipitation can be quite complicated depending on the detailed small-scale coronal magnetic field structures, which could be seen with future sensitive gamma-ray telescopes.

MHD Simulations for the Origin and Magnetic Topology of Solar 3He Events

T. X. **Zhang**

The Astrophysical Journal, Vol. 677, No. 1: 692-698, **2008**.

http://www.journals.uchicago.edu/doi/abs/10.1086/529403

The origin and magnetic topology of impulsive solar energetic particle (SEP) events (also called solar 3He-rich events) are numerically investigated by using a three-dimensional axisymmetric time-dependent self-consistent magnetohydrodynamic (MHD) model. The results indicate that when a counterclockwise (or normal) magnetic flux rope is emerged from the photosphere at the open field region near the closed magnetic field lines, the magnetic topology produced by the MHD simulation is that proposed by Reames to lead to impulsive SEP events. The flux emergence initiates the magnetic configuration which produces the magnetic reconfiguration and reconnection at the coronal base. The magnetic reconnection at the coronal base strongly disturbs the magnetic fields in the solar corona and interplanetary space, and generates fast jet-like plasma outflows (or nonYflux-rope coronal mass ejections). The magnetic field line disturbances could scatter charged particles and therefore accelerate them to high energies through the Fermi acceleration mechanism.

Solar Wind With Field Lines and Energetic Particles (SOFIE) Model: Application to Historical Solar Energetic Particle Events

Lulu **Zhao**, Igor Sokolov, Tamas Gombosi, David Lario, Kathryn Whitman, Zhenguang Huang, Gabor Toth, Ward Manchester, Bart van der Holst … See all authors

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https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003729 **File**

In this paper, we demonstrate the applicability of the data-driven solar energetic particle (SEP)model, SOlar-wind with FIeld-lines and Energetic-particles (SOFIE), to simulate the acceleration and transportprocesses of SEPs and make forecast of the energetic proton flux at energies ≥10 MeV that will be observednear 1 AU. The SOFIE model is built upon the Space Weather Modeling Framework developed at theUniversity of Michigan. In SOFIE, the background solar wind plasma in the solar corona and interplanetaryspace is calculated by the Stream-Aligned Aflvén Wave Solar-atmosphere Model(-Realtime) driven by thenear-real-time hourly updated Global Oscillation Network Group solar magnetograms. In the background solarwind, coronal mass ejections (CMEs) are launched by placing an force-imbalanced magnetic flux rope on top ofthe parent active region, using the Eruptive Event Generator using Gibson-Low model. The acceleration andtransport processes are modeled by the Multiple-Field-Line Advection Model for Particle Acceleration. In thiswork, nine SEP events (Solar Heliospheric and INterplanetary Environment challenge/campaign events) aremodeled. The three modules in SOFIE are validated and evaluated by comparing with observations, includingthe steady-state background solar wind properties, the white-light image of the CMEs, and the flux of solarenergetic protons, at energies of ≥10 MeV. **7 March 2012, 17 May 2012, 12 July 2012, 11 April 2013, 7 January 2014, 14 July 2017; 4, 6, 10 Sep 2017**

Table 1 Observational Facts of the Nine Solar Energetic Particle Events

CLEAR Space Weather Center of Excellence: All-Clear Solar Energetic Particle Prediction

Lulu **Zhao**

Space Weather **2023**

https://arxiv.org/pdf/2310.14677.pdf

The CLEAR Space Weather Center of Excellence (CLEAR center) is a five year project that is funded by the NASA Space Weather Center of Excellence program. The CLEAR center will build a comprehensive prediction framework for solar energetic particles (SEPs) focusing on the timely and accurate prediction of low radiation periods (``all clear forecast'') and the occurrence and characteristics of elevated periods. This will be accomplished by integrating empirical, first-principles based and machine learning (ML)-trained prediction models. In this paper, the motivation, overview, and tools of the CLEAR center will be discussed.

Solar Wind with Field Lines and Energetic Particles (SOFIE) Model: Application to Historical Solar Energetic Particle Events

Lulu **Zhao**, Igor Sokolov, Tamas Gombosi, David Lario, Kathryn Whitman, Zhenguang Huang, Gabor Toth, Ward Manchester, Bart van der Holst, Nishtha Sachdeva

Space Weather **2023**

https://arxiv.org/pdf/2309.16903.pdf

In this paper, we demonstrate the applicability of the data-driven and self-consistent solar energetic particle model, Solar-wind with FIeld-lines and Energetic-particles (SOFIE), to simulate acceleration and transport processes of solar energetic particles. SOFIE model is built upon the Space Weather Modeling Framework (SWMF) developed at the University of Michigan. In SOFIE, the background solar wind plasma in the solar corona and interplanetary space is calculated by the Aflvén Wave Solar-atmosphere Model(-Realtime) (AWSoM-R) driven by the near-real-time hourly updated Global Oscillation Network Group (GONG) solar magnetograms. In the background solar wind, coronal mass ejections (CMEs) are launched by placing an imbalanced magnetic flux rope on top of the parent active region, using the Eruptive Event Generator using Gibson-Low model (EEGGL). The acceleration and transport processes are modeled by the Multiple-Field-Line Advection Model for Particle Acceleration (M-FLAMPA). In this work, nine solar energetic particle events (Solar Heliospheric and INterplanetary Environment (SHINE) challenge/campaign events) are modeled. The three modules in SOFIE are validated and evaluated by comparing with observations, including the steady-state background solar wind properties, the white-ligh, image of the CME, and the flux of solar energetic protons, at energies of > 10 MeV. **2012-Mar-07, 2012-May-17, 2012-Jul-12, 2013-Apr-11, 2014-Jan-07, 2017-Jul-14, 2017-Sep-04, 2017-Sep-06, 2017-Sep-10**

Modeling the Transport Processes of a Pair of Solar Energetic Particle Events Observed by Parker Solar Probe Near Perihelion

Lulu **Zhao**1, Ming Zhang1, and David Lario2

2020 ApJ 898 16

https://doi.org/10.3847/1538-4357/ab97b3

We present model calculations of the transport processes of solar energetic particles in the corona and interplanetary medium for two events detected by Parker Solar Probe near its second perihelion on **2019 April 2 and April 4**. In the 2019 April 2 event, the <100 keV proton differential intensity measured by the Integrated Science Investigation of the Sun Low-Energy Energetic Particle instrument increased by more than a factor of 10 above the pre-event intensity, whereas the ~1 MeV proton differential intensity detected by the High-Energy Energetic Particle Instrument did not show any intensity enhancement. In the 2019 April 4 event, the ~1 MeV proton intensity showed an increase of more than a factor of 100 above the pre-event intensity, but the <100 keV proton intensity enhancement was rather low and gradual. The observational fact that only the 2019 April 4 event displayed a high-energy intensity enhancement indicates that the associated acceleration process in the second event was more energetic than the first event. However, the gradual and low enhancement of the low-energy proton intensity in the second event is at odds with this scenario. In this paper, we investigate the injection and transport processes of protons in the corona and interplanetary magnetic fields with numerical model simulations. Our model calculations suggest that the gradual and low rise of the low-energy protons in the April 4 event was probably due to the different diffusion conditions in these two events and the fact that the spacecraft was moving away from the source region during these two events.

A study on the dynamic spectral indices for SEP events on 2000 July 14 and 2005 January 20

Ming-Xian **Zhao**, Gui-Ming Le

Research in Astronomy and Astrophysics **2019**

https://arxiv.org/pdf/1910.07286.pdf

We have studied the dynamic proton spectra for the two solar energetic particle (SEP) events on **2000 July 14** (hereafter GLE59) and **2005 January 20** (hereafter GLE69). The source locations of GLE59 and GLE69 are N22W07 and N12W58 respectively. Proton fluxes >30 MeV have been used to compute the dynamic spectral indices of the two SEP events. The results show that spectral indices of the two SEP events increased more swiftly at early times, suggesting that the proton fluxes >30 MeV might be accelerated particularly by the concurrent flares at early times for the two SEP events. For the GLE69 with source location at N12W58, both flare site and shock nose are well connected with the Earth at the earliest time. However, only the particles accelerated by the shock driven by eastern flank of the CME can propagate along the interplanetary magnetic field line to the Earth after the flare. For the GLE59 with source location at N22W07, only the particles accelerated by the shock driven by western flank of the associated CME can reach the Earth after the flare. Results show that there was slightly more than one hour during which the proton spectra for GLE69 are softer than that for GLE59 after the flares, suggesting that the shock driven by eastern flank of the CME associated with GLE69 is weaker than the shock driven by the western flank of the CME associated with GLE59. The results support that quasi-perpendicular shock has stronger potential in accelerating particles than the quasi-parallel shock. The results also suggest that only a small part of the shock driven by western flank of the CME associated with the GLE59 is quasi-perpendicular.

Statistical analysis of interplanetary magnetic field path lengths from solar energetic electron events observed by WIND
Lulu **Zhao**, Gang Li, Ming Zhang, Linghua Wang, Ashraf Moradi, Frederic Effenberger
2019 *ApJ* **878** 107
https://arxiv.org/pdf/1905.03755.pdf
sci-hub.se/10.3847/1538-4357/ab2041
We calculate the interplanetary magnetic field path lengths traveled by electrons in solar electron events detected by the WIND 3DP instrument from 1994 to 2016. The velocity dispersion analysis method is applied for electrons at energies of ~ 27 keV to 310 keV. Previous velocity dispersion analyses employ the onset times, which are often affected by instrumental effects and the pre-existing background flux, leading to large uncertainties. We propose a new method here. Instead of using the peak or onset time, we apply the velocity dispersion analysis to the times that correspond to the rising phase of the fluxes that are a fraction, η, of the peak flux. We perform statistical analysis on selected events whose calculated path lengths have uncertainties smaller than 0.1 AU. The mean and standard deviation, (μ, σ), of the calculated path lengths corresponding to η= 3/4, 1/2, and 1/3 of the peak flux is (1.17 AU, 0.17 AU), (1.11 AU, 0.14 AU), and (1.06 AU, 0.15 AU). The distribution of the calculated path lengths is also well fitted by a Gaussian distribution for the η=3/4 and 1/3 cases. These results suggest that in these electron events the interplanetary magnetic field topology is close to the nominal Parker spiral with little field line meandering. Our results have important implications for particles' perpendicular diffusion.
Table 1. Electron Event Data (1998-2016)

Effects of Coronal Magnetic Field Structures on the Transport of Solar Energetic Particles
Lulu **Zhao** and Ming Zhang
2018 ApJL 859 L29 DOI 10.3847/2041-8213/aac6cf
This Letter presents a model calculation of solar energetic particle (SEP) transport to test the sensitivity of the distribution of escaped SEPs in interplanetary space and dependence upon the details of the magnetic field structure in the corona. It is applied to a circumsolar event on **2011 November 3**, in which SEPs are observed promptly after the solar event eruption by three spacecraft (the twin Solar TErrestrial RElations Observatories (STEREO-A and STEREO-B) and ACE) separated by more than 100° in longitude from each other. The corona magnetic field reconstructed from photosphseric field measurements using the PFSS method changes substantially before and after the solar eruption, especially around the active region. The locations of open field regions, separatrix surfaces including the heliospheric current sheet, and footpoints of magnetic field lines connected to the spacecraft location have shifted substantially. We inject 100 keV energetic electrons on the open field lines at 1.5 R s within the size of observed coronal mass ejections (CMEs) and follow their propagation in the corona and the interplanetary space. We find that with a perpendicular diffusion due to field line random walk equal to 10% of the supergranular diffusion rate, the overall distribution of escaped SEPs does not change much even though the region of open field lines from SEPs has changed. The result suggests that detailed small-scale coronal magnetic field structures and the exact magnetic field connection are not crucially important for observing SEPs in the interplanetary space.

Investigation of the possible source for solar energetic particle event of 2017 September 10
Ming-Xian **Zhao**, Gui-Ming Le, Yu-Tian Chi
Research in Astronomy and Astrophysics (RAA) **18** 074 **2018**
https://arxiv.org/pdf/1805.01082.pdf
https://iopscience.iop.org/article/10.1088/1674-4527/18/7/74/pdf
According to the solar protons' data observed by Geostationary Operational Environmental Satellites (GOES) and neutron monitors on the ground of the Earth, and near-relativistic electrons data measured by the ACE spacecraft, the onset times of protons with different energies and near-relativistic electrons have been estimated and compared with the time of solar soft and hard X-ray and radio burst data. *The results show that first arriving relativistic and non-relativistic protons and electrons may be accelerated by the concurrent flare. The results also suggest that release times of protons with different energies may be different, and the protons with lower energy may release earlier than those with higher energy. Some protons accelerated by concurrent flares may be further accelerated by CME-driven shock.*

The Effects of Interplanetary Transport in the Event-intergrated Solar Energetic Particle Spectra
Lulu **Zhao**, Ming Zhang, and Hamid K. Rassoul
2017 ApJ 836 31
http://sci-hub.cc/10.3847/1538-4357/836/1/31

Previous investigations on the energy spectra of solar energetic particle (SEP) events revealed that the energy spectra observed at 1 au often show double power laws with break energies from one to tens of MeV/nuc. In order to determine whether the double power-law features result from the SEP source or the interplanetary transport process from the Sun to 1 au, we separately analyze the SEP spectra in the decay phase, during which the transport effect is minimum. In this paper, we reported three events observed by the Interplanetary Monitory Platform 8 spacecraft, which occurred on **1977 September 19, November 22, and 1979 March 1**. For the first two events, the event-integrated spectra of protons possess double power-law profiles with break energies in a range of several MeV to tens of MeV, while the spectra integrated in the decay (reservoir) phase yield single power laws. Moreover, a general trend from a double power law at the rising phase to a single power law at the decay phase is observed. For the third event, both the event-integrated and the reservoir spectra show double power-law features. However, the difference between the low- and high-energy power-law indices is smaller for the reservoir spectrum than the event-integrated spectrum. These features were reproduced by solving the 1D diffusion equation analytically and we suggest that the transport process, especially the diffusion process, plays an important role in breaking the energy spectra.

Probing shock geometry via the charge to mass ratio dependence of heavy ion spectra from multiple spacecraft observations of the 2013 November 4 event

Lulu **Zhao**, Gang Li, G. M. Mason, C. Cohen, R. A. Mewaldt, M. I. Desai, R. W. Ebert, M. A. Dayeh
Research in Astron. Astrophys. **2016**
https://arxiv.org/pdf/1609.09479v1.pdf

In large SEP events, ions can be accelerated at CME-driven shocks to very high energies. Spectra of heavy ions in many large SEP events show features such as roll-overs or spectral breaks. In some events when the spectra are plotted in energy/nucleon they can be shifted relative to each other to make the spectral breaks align. The amount of shift is charge-to-mass ratio (Q/A) dependent and varies from event to event. This can be understood if the spectra of heavy ions are organized by the diffusion coefficients (Cohen et al., 2005). In the work of Li et al. (2009), the Q/A dependences of the scaling is related to shock geometry when the CME-driven shock is close to the Sun. For events where multiple in-situ spacecraft observations exist, one may expect that different spacecraft are connected to different portions of the CME-driven shock that have different shock geometries, therefore yielding different Q/A dependence. In this work, we examine one SEP event which occurred on **2013 November 4.** We study the Q/A dependence of the energy scaling for heavy ion spectra using Helium, oxygen, and iron ions. Observations from STEREO-A, STEREO-B and ACE are examined. We find that the scalings are different for different spacecraft. We suggest that this is because ACE, STEREO-A and STEREO- B are connected to different parts of the shock that have different shock geometries. Our analysis indicates that studying the Q/A scaling of in-situ particle spectra can serve as a powerful tool to remotely examine the shock geometry for large SEP events.

DOUBLE POWER LAWS IN THE EVENT-INTEGRATED SOLAR ENERGETIC PARTICLE SPECTRUM

Lulu **Zhao**, Ming Zhang, and Hamid K. Rassoul
2016 ApJ 821 62
https://iopscience.iop.org/article/10.3847/0004-637X/821/1/62/pdf

A double power law or a power law with exponential rollover at a few to tens of MeV nucleon^{-1} of the event-integrated differential spectra has been reported in many solar energetic particle (SEP) events. The rollover energies per nucleon of different elements correlate with a particle's charge-to-mass ratio (Q/A). The probable causes are suggested as residing in shock finite lifetimes, shock finite sizes, shock geometry, and an adiabatic cooling effect. In this work, we conduct a numerical simulation to investigate a particle's transport process in the inner heliosphere. We solve the focused transport equation using a time-backward Markov stochastic approach. The convection, magnetic focusing, adiabatic cooling effect, and pitch-angle scattering are included. The effects that the interplanetary turbulence imposes on the shape of the resulting SEP spectra are examined. By assuming a pure power-law differential spectrum at the Sun, a perfect double-power-law feature with a break energy ranging from 10 to 120 MeV nucleon^{-1} is obtained at 1 au. We found that the double power law of the differential energy spectrum is a robust result of SEP interplanetary propagation. It works for many assumptions of interplanetary turbulence spectra that give various forms of momentum dependence of a particle's mean free path. The different spectral shapes in low-energy and high-energy ends are not just a transition from the convection-dominated propagation to diffusion-dominated propagation.

Particle acceleration in 3D single current sheets formed in the solar corona and heliosphere: PIC approach

Zharkova V.V. and Siversky T

Journal of Physics, Conference Series (JPCS), **2015**, 642, 012032
http://computing.unn.ac.uk/staff/slmv5/kinetics/zharkova_aiac15_v3.pdf
Acceleration of protons and electrons in a reconnecting current sheet (RCS) is investigated with the test particle and particle-in-cell (PIC) approaches in a 3D magnetic topology. PIC simulations confirm a spatial separation of electrons and protons with respect to the midplane depending on the guiding field. Simulation reveals that the separation occurs in magnetic topologies with strong guiding fields and lasts as long as the particles are kept dragged into a current sheet. This separation produces a polarisation electric field induced by the plasma feedback to a presence of accelerated particles, which shape can change from symmetric towards the midplane (for weak guiding field) to fully asymmetric (for strong guiding field). Particles are found accelerated at a midplane of any current sheets present in the heliosphere to the energies up to hundred keV for electrons and hundred MeV for protons. The maximum energy gained by particles during their motion inside the current sheet is defined by its magnetic field topology (the ratio of magnetic field components), the side and location from the X-nullpoint, where the particles enter a current sheet. In strong magnetic fields of the solar corona with weaker guiding fields, electrons are found circulating about the midplane to large distances where proton are getting accelerated, creating about the current sheet midplane clouds of high energy electrons, which can be the source of hard X-ray emission in the coronal sources of flares. These electrons are ejected into the same footpoint as protons after the latter reach the energy sufficient to break from a current sheet. In a weaker magnetic field of the heliosphere the bounced electrons with lower energies cannot reach the midplane turning instead at some distance D before the current sheet midplane by 180 degrees from their initial motion. Also the beams of accelerated transit and bounced particles are found to generate turbulent electric fields in a form of Langmuir waves (electrons) or ion-acoustic waves (protons).

Recent Advances in Understanding Particle Acceleration Processes in Solar Flares **Review**

V.V. **Zharkova** · K. Arzner · A.O. Benz · P. Browning · C. Dauphin · A.G. Emslie · L. Fletcher · E.P. Kontar · G. Mann · M. Onofri · V. Petrosian · R. Turkmani · N. Vilmer · L. Vlahos
Space Sci Rev (**2011**) 159:357–420, **File**

We **review** basic theoretical concepts in particle acceleration, with particular emphasis on processes likely to occur in regions of magnetic reconnection. Several new developments are discussed, including detailed studies of reconnection in three-dimensional magnetic field configurations (e.g., current sheets, collapsing traps, separatrix regions) and stochastic acceleration in a turbulent environment. Fluid, test-particle, and particle-in-cell approaches are used and results compared. While these studies show considerable promise in accounting for the various observational manifestations of solar flares, they are limited by a number of factors, mostly relating to available computational power. Not the least of these issues is the need to explicitly incorporate the electrodynamic feedback of the accelerated particles themselves on the environment in which they are accelerated. A brief prognosis for future advancement is offered.

The Mean Free Path of 13–64 MeV Protons Derived from Statistical Results of Solar Energetic Particle Events

Yushui **Zhong**1,2, Yang Wang1,2, and Gang Qin1,2
2024 ApJ 974 228
https://iopscience.iop.org/article/10.3847/1538-4357/ad70aa/pdf
A recent study by Wang et al. investigated gradual solar proton events with energies >10 MeV, as observed by STEREO-A, STEREO-B, and the Solar and Heliospheric Observatory spacecraft. For each event, the spacecraft with the best magnetic connection to the source region among the three spacecraft was identified, and energetic proton intensities observed by the spacecraft were analyzed through fitting. The fitting process produced two parameters, b and c, for four energy channels (13–16 MeV, 20–25 MeV, 32–40 MeV, and 40–64 MeV) in each event. Parameters b and c govern the rise and decay of particle intensities, respectively. Statistical analysis revealed a power-law correlation between b and c, expressed as $c \sim b^{-\gamma}$. In this study, in order to explain the relation between the two parameters, we investigate the model of particle diffusion coefficients in the interplanetary space. In our simulations, the radial mean free path is modeled as a power function of radial distance, successfully reproducing the b–c relation. Consequently, the observations demonstrate that the radial mean free path varies with radial distance in a power law. In future research, the model of diffusion coefficients holds promise in determining the mean free path of energetic protons.

Numerical Simulation of Equal Ratio Relations for the Peak Intensities of >10 MeV Energetic Protons

Yushui **Zhong**1,2, Yang Wang1,2,3, and Gang Qin1,2,3

2024 ApJ 969 135
https://iopscience.iop.org/article/10.3847/1538-4357/ad5721/pdf
Previous studies have highlighted the significance of perpendicular diffusion in the decay phase of particle intensities for >10 MeV energetic protons. Recently, an observational study has indicated that the peak intensity ratios across different energy channels (13−64 MeV protons) remain almost constant as the spacecraft location varies in many solar proton events. This interesting phenomenon is referred to as equal ratio relations. These findings suggest that perpendicular diffusion not only affects particle intensity during the decay phase but also throughout the rising phase. In this study, we perform numerical simulations of >10 MeV energetic proton events observed by STEREO A, STEREO B, and the Solar and Heliospheric Observatory. Our findings demonstrate that perpendicular diffusion strongly affects the entire time profile of particle intensity for spacecraft not magnetically connected to the source region. The numerical simulation results indicate that in order to reproduce observations, we need to include perpendicular diffusion near the source region and in interplanetary space. Perpendicular diffusion leads to nearly uniform peak ratios at different locations and contributes to the formation of the reservoir phenomenon during the decay phase. Consequently, these numerical results support the significant role of perpendicular diffusion in the formation of the longitudinal distribution of >10 MeV proton events. **2010-08-14, 2011-11-04, 2012-10-14**

Modeling the Transport of Solar Energetic Particles in a Corotating Interaction Region
Y.-S. **Zhong**1, G. Qin3,1,2, and S.-S. Wu1
2024 ApJ 968 75
https://iopscience.iop.org/article/10.3847/1538-4357/ad3fb0/pdf
We present a new three-dimensional (3D) magnetohydrodynamic (MHD) model and a new 3D energetic particle transport (EPT) model. The 3D MHD model numerically solves the ideal MHD equations using the relaxing total variation diminishing scheme. In the 3D MHD simulations, we use simple boundary conditions with a high-speed flow, and we can clearly identify a corotating interaction region (CIR) with the characteristics of forward shock and reverse shock. The 3D EPT model solves the Fokker–Planck transport equation for the solar energetic particles (SEPs) using backward stochastic processes, with the magnetic field and solar wind velocity field from MHD results. For comparison, the 3D EPT model results with Parker fields are also obtained. We investigate the transport of SEPs with particle sources and observers in different positions in MHD fields with a CIR, and we compare the results with those in the Parker fields. Our simulation results show that the compression region with local enhancement of the magnetic field, i.e., CIR, can act as a barrier to scatter energetic particles back, and particles can struggle to diffuse through the strong magnetic field regions. Usually, a normal anisotropy profile is commonly present in SEP simulation results with Parker fields, and it is also typically present in that with MHD fields. However, because of the compression region of the magnetic field, energetic particles may exhibit anomalous anisotropy. This result may be used to replicate the spacecraft observation phenomena of the anomalous anisotropy.

Prediction Model for Solar Energetic Proton Events: Analysis and Verification
Qiuzhen **Zhong** , Jingjing Wang , Xuejie Meng, Siqing Liu, Jiancun Gong
Space Weather **Volume17, Issue5** Pages 709-726 **2019**
sci-hub.se/10.1029/2018SW001915
Solar energetic protons (SEPs) can cause radiation damage to satellites. The Space Environment Prediction Center of China defines the start of an SEP event as the time when three consecutive instances of the 5 min averaged integral flux of >10 MeV protons equal or exceed the 10 proton flux unit threshold. In this study, we analyzed the 5 min averaged soft X-ray flux and the differential and integral proton flux obtained by the Geostationary Operational Environmental Satellites for the period from January 1990 to September 2017 and developed SEP prediction models and their products. The statistical models take one or two data products and the given thresholds as the predictor and predict whether a SEP event will occur or not in the next 24 hours. The quality of the forecast models was measured by comparing the model results against certain verification metrics. Our model taking the products of 5 min averaged integral flux of >10 MeV protons and long wavelength of soft X-ray flux as predictors can provide a probability of detection of 0.80 (152/190), a false alarm ratio of 0.26 (53/205), and an average warning time of 2.6 h for the correctly predicted events. In addition, the model can provide a critical success index of 0.63, a Gilbert skill score of 0.62, and a Heidke skill score of 0.76.
Table 1. SEP events list (1990-2017)

Spectral Curvature of Shock-accelerated Particles in Solar Cycle 23
Connie **Zhou**1,2, Federico Fraschetti3,4, Jeremy J. Drake5, and Martin Pohl6,7
Research Notes of the AAS, Volume 2, Number 3 145 **2018**
http://iopscience.iop.org/article/10.3847/2515-5172/aad8be
https://arxiv.org/pdf/1808.04812.pdf

We have fitted the protons momentum distribution of the 16 GLEs of solar cycle 23 with a log-parabola and have found a correlation between the previously determined energy break and the global spectral curvature of the log-parabola.
In summary, our finding shows for most of the 16 GLE events of cycle 23 an anti-correlation . Such an anti-correlation results from the fact that a shock structure confining higher-energy particles (higher E0) enables particle acceleration via the diffusive mechanism up to higher energies with a spectrum closer to a power-law (smaller β). A log-parabola fit allows also for a reduced number of free parameters, modulo a normalization: one power-law index (α) and a global spectral curvature (β) as opposed to two power-laws indexes and the break E0. Thus, we propose to replace the single energy value of the break E0 with the parameter β that describes a global spectral behavior.

Comparison of JPL and ESP Solar Proton Fluence Models Using the Background-Subtracted RDSv2.0 Data Set

B. X. **Zhu**, K. Whitman, I. Jun, J. M. Ratliff
Space Weather Volume21, Issue3 e2022SW003311 **2023**
https://doi.org/10.1029/2022SW003311
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022SW003311
High energy protons from solar energetic particle (SEP) events are a hazard to spacecraft systems and instruments. For interplanetary and geosynchronous-Earth-orbiting spacecraft, a mission's cumulative SEP fluence is an important consideration for hardware design. The total solar proton fluence for a mission can be dominated by a small number of very high-fluence events. Because of the sporadic and unpredictable nature of these large events, data sets collected over multiple solar cycles are needed to construct a statistical model that can predict a mission's risk of seeing a given fluence exposure during its mission. Several statistical models have been developed, including the JPL model and the Emission of Solar Protons (ESP) model. The models produce somewhat different results, which could be due in part to the different data sets from which they were derived. To understand the sensitivity of predicted mission fluence to the choice of data set and to the statistical distribution to which that data set is fit, we present a comparison of the JPL and ESP cumulative fluence models as reformulated from the same SEP data set, a background-subtracted version of the Reference Data Set Version 2.0 (RDSv2.0) based on data from IMP-8 and GOES, covering 41 years of SEP events from 1974 to 2015 with proton energies between 5 and 289 MeV. The comparisons show that different modeling approaches can produce a factor of 2 or greater difference in the mission fluences even when the same data set is used for model development. **20-29 Feb 2012, 19 Feb-4 Mar 2014**

Shock Properties and Associated Characteristics of Solar Energetic Particles in the 2017 September 10 Ground-level Enhancement Event

Bei **Zhu**1,2, Ying D. Liu3,4, Ryun-Young Kwon5, Meng Jin6, L. C. Lee1, and Xiaojun Xu1,2
2021 ApJ 921 26
https://iopscience.iop.org/article/10.3847/1538-4357/ac106b/pdf
https://doi.org/10.3847/1538-4357/ac106b
The solar eruption on **2017 September 10** was accompanied by a fast coronal mass ejection (∼3000 km s−1) and produced a ground-level enhancement (GLE) event at Earth. Multiple-viewpoint remote sensing observations are used to find the three-dimensional (3D) structure of the shock. We determine the shock parameters by combining the 3D shock kinematics and the solar wind properties obtained from a global magnetohydrodynamic (MHD) simulation, in order to compare them with the characteristics of the solar energetic particles (SEPs). We extract the magnetic connectivities of the observers from the MHD simulation and find that L1 was magnetically connected to the shock flank (rather than the nose). Further analysis shows that this shock flank propagates through the heliospheric current sheet (HCS). The weak magnetic field and relatively dense plasma around the HCS result in a large Mach number of the shock, which leads to efficient particle acceleration even at the shock flank. We conclude that the interaction between the shock and HCS provides a potential mechanism for production of the GLE event. The comparison between the shock properties and the characteristics of SEPs suggests an efficient particle acceleration in a wide spatial range by the shock propagating through the highly inhomogeneous coronal medium.

Investigation of energetic particle release using multi-point imaging and in situ observations

Bei **Zhu**, Ying D. Liu, Ryun-Young Kwon, Rui Wang
ApJ **865** 138 **2018**
https://arxiv.org/pdf/1808.04934.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/aada80/pdf
The solar eruption on **2012 January 27** resulted in a wide-spread solar energetic particle (SEP) event observed by STEREO A and the near-Earth spacecraft (separated by 108\degree). The event was accompanied by an X-class flare, extreme-ultraviolet (EUV) wave and fast coronal mass ejection (CME). We investigate the particle release by comparing the release times of particles at the spacecraft and the times when magnetic connectivity between the

source and the spacecraft was established. The EUV wave propagating to the magnetic footpoint of the spacecraft in the lower corona and the shock expanding to the open field line connecting the spacecraft in the upper corona are thought to be responsible for the particle release. We track the evolution of the EUV wave and model the propagation of the shock using EUV and white-light observations. No obvious evidence indicates that the EUV wave reached the magnetic footpoint of either STEREO A or L1-observers. Our shock modeling shows that the release time of the particles observed at L1 was consistent with the time when the shock first established contact with the magnetic field line connecting L1-observers. The release of the particles observed by STEREO A was delayed relative to the time when the shock was initially connected to STEREO A via the magnetic field line. We suggest that the particle acceleration efficiency of the portion of the shock connected to the spacecraft determines the release of energetic particles at the spacecraft.

Solar Energetic Particle Event Associated with the 2012 July 23 Extreme Solar Storm
Bei **Zhu**, Ying D. Liu, Janet G. Luhmann, Huidong Hu, Rui Wang, Zhongwei Yang
2016 *ApJ* **827** 146
http://arxiv.org/pdf/1607.01585v1.pdf **File**
https://iopscience.iop.org/article/10.3847/0004-637X/827/2/146/pdf
We study the solar energetic particle (SEP) event associated with the **2012 July 23** extreme solar storm, for which STEREO and the spacecraft at L1 provide multi-point remote sensing and in situ observations. The extreme solar storm, with a superfast shock and extremely enhanced ejecta magnetic fields observed near 1 AU at STEREO A, was caused by the combination of successive coronal mass ejections (CMEs). Meanwhile, energetic particles were observed by STEREO and near-Earth spacecraft such as ACE and SOHO, suggestive of a wide longitudinal spread of the particles at 1 AU. Combining the SEP observations with in situ plasma and magnetic field measurements we investigate the longitudinal distribution of the SEP event in connection with the associated shock and CMEs. Our results underscore the complex magnetic configuration of the inner heliosphere formed by solar eruptions. The examinations of particle intensities, proton anisotropy distributions, element abundance ratios, magnetic connectivity and spectra also give important clues for the particle acceleration, transport and distribution.

Acceleration and Release of Solar Energetic Particles Associated with a Coronal Shock on 2021 September 28 Observed by Four Spacecraft
Bin **Zhuang**, Noé Lugaz, David Lario, Ryun-Young Kwon, Nicolina Chrysaphi, Jonathan Niehof, Tingyu Gou, Lulu Zhao
ApJ **963** 119 **2024**
https://arxiv.org/pdf/2401.10388.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ad1e57/pdf
Extreme ultraviolet (EUV) waves are thought to be the propagating footprint of the shock on the solar surface. One of the key questions in SEP research is the timing of the SEP release with respect to the time when the EUV wave magnetically connects with an observer. Taking advantage of close-to-the-Sun measurements by Parker Solar Probe (PSP) and Solar Orbiter (SolO), we investigate an SEP event that occurred on **2021 September 28** and was observed at different locations by SolO, PSP, STEREO-A, and near-Earth spacecraft. During this time, SolO, PSP and STEREO-A shared similar nominal magnetic footpoints relative to the SEP source region but were at different heliocentric distances. We find that the SEP release times estimated at these four locations were delayed compared to the times when the EUV wave intercepted the footpoints of the nominal magnetic fields connecting to each spacecraft by around 30 to 60 minutes. Combining observations in multiple wavelengths of radio, white-light, and EUV, with a geometrical shock model, we analyze the associated shock properties, and discuss the acceleration and delayed release processes of SEPs in this event as well as the accuracy and limitations of using EUV waves to determine the SEP acceleration and release times.

Widespread 1-2 MeV Energetic Particles Associated with Slow and Narrow Coronal Mass Ejections: Parker Solar Probe and STEREO Measurements
Bin **Zhuang**, Noé Lugaz, David Lario
ApJ **925** 96 **2021**
https://arxiv.org/pdf/2111.09711.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac3af2/pdf
Suprathermal ions in the corona are thought to serve as seed particles for large gradual solar energetic particle (SEP) events associated with fast and wide coronal mass ejections (CMEs). A better understanding of the role of suprathermal particles as seed populations for SEP events can be made by using observations close to the Sun. We study a series of SEP events observed by the Integrated Science Investigation of the Sun (IS⊙IS) suite on board the Parker Solar Probe (PSP) from **2020 May 27 to June 2**, during which PSP was at heliocentric distances between ~0.4 and ~0.2 au. These events were also observed by the Ahead Solar TErrestrial RElations Observatory

(STEREO-A) near 1 au, but the particle intensity magnitude was much lower than that at PSP. We find that the SEPs should have spread in space as their source regions were distant from the nominal magnetic footpoints of both spacecraft, and the parent CMEs were slow and narrow. We study the decay phase of the SEP events in the ∼1-2 MeV proton energy range at PSP and STEREO-A, and discuss their properties in terms of both continuous injections by successive solar eruptions and the distances where the measurements were made. This study indicates that seed particles can be continuously generated by eruptions associated with slow and narrow CMEs, spread over a large part of the inner heliosphere, and remain there for tens of hours, even if minimal particle intensity enhancements were measured near 1 au**. 27,28,29 May 2020, 1 Jun 2020**

Successive Coronal Mass Ejections Associated with Weak Solar Energetic Particle Events

Bin **Zhuang**, Noé Lugaz, Tingyu Gou, Liuguan Ding

ApJ **921** 6 **2021**

https://arxiv.org/pdf/2109.02225.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac17e9/pdf

https://doi.org/10.3847/1538-4357/ac17e9

The scenario of twin coronal mass ejections (CMEs), i.e., a fast and wide primary CME (priCME) preceded by previous CMEs (preCMEs), has been found to be favorable to a more efficient particle acceleration in large solar energetic particle (SEP) events. Here, we study 19 events during 2007--2014 associated with twin-CME eruptions but without large SEP observations at L1 point. We combine remote-sensing and in situ observations from multiple spacecraft to investigate the role of magnetic connectivity in SEP detection and the CME information in 3-dimensional (3D) space. We study one-on-one correlations of the priCME 3D speed, flare intensity, suprathermal backgrounds, and height of CME-CME interaction with the SEP intensity. Among these, the priCME speed is found to correlate with the SEP peak intensity at the highest level. We use the projection correlation method to analyze the correlations between combinations of these multiple independent factors and the SEP peak intensity. We find that the only combination of two or more parameters that has higher correlation with the SEP peak intensity than the CME speed is the CME speed combined with the propagation direction. This further supports the dominant role of the priCME in controlling the SEP enhancements, and emphasizes the consideration of the latitudinal effect. Overall, the magnetic connectivity in longitude as well as latitude and the relatively lower priCME speed may explain the existence of the twin-CME SEP-poor events. The role of the barrier effect of preCME(s) is discussed for an event on **2013 October 28.**

Table 1:: Twin-CME (L1-point) SEP-poor events during 2007– 2014

Table 2:: Twin-CME (L1-point) large SEP events in solar cycle 24

The Role of Successive and Interacting CMEs in the Acceleration and Release of Solar Energetic Particles: Multi-viewpoint Observations

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2020 ApJ 901 45

https://doi.org/10.3847/1538-4357/abaef9

Gradual and large solar energetic particle (SEP) events (flux of ions with energy >10 MeV above 10 pfu) are primarily produced in shocks driven by fast and wide coronal mass ejections (CMEs). Past research, both in theory and statistics, has found that the situation where a fast primary CME (priCME) is preceded by previous CMEs (preCMEs) is favorable to a more efficient particle acceleration. However, the physical causes of this association is still a matter of debate, including the association of the acceleration and release of SEPs with the interaction of successive CMEs. Taking advantage of the twin Solar TErrestrial RElations Observatory spacecraft, we study 41 large SEP events in solar cycle 24 by multi-viewpoint observations. Although 21 events (~51%) have a preCME identifiable in the Large Angle and Spectrometric Coronagraph, we determine that the priCMEs overlap the preCMEs in three dimension (3D) for only 11 events (~27%). We further investigate the acceleration (using type II radio bursts) and release (using velocity dispersion analysis) of the particles for all potential instances of CME–CME interaction in 3D. We find that, for six of 11 events, the priCME is far away from catching up with the preCME when the particles are released. However, for the limited samples, the SEP peak intensity is significantly higher in the events in which the priCME is closest to impacting the preCME, indicating the potential for the increased seed population or more enhanced turbulence levels occurring closer to the preCME.

Exploring the potential of microwave diagnostics in SEP forecasting: The occurrence of SEP events

Pietro **Zucca**, Marlon Núñez and Karl-Ludwig Klein

J. Space Weather Space Clim., 7, A13 (**2017**)

https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170001.pdf

https://doi.org/10.1051/swsc/2017011.

Solar energetic particles (SEPs), especially protons and heavy ions, may be a space-weather hazard when they impact spacecraft and the terrestrial atmosphere. Forecasting schemes have been developed, which use earlier signatures of particle acceleration to predict the arrival of solar protons and ions in the space environment of the Earth. The UMASEP (University of MAlaga Solar particle Event Predictor) scheme forecasts the occurrence and the importance of an SEP event based on combined observations of soft X-rays, their time derivative and protons above 10 MeV at geosynchronous orbit. We explore the possibility to replace the derivative of the soft X-ray time history with the microwave time history in the UMASEP scheme. To this end we construct a continuous time series of observations for a 13-month period from December 2011 to December 2012 at two microwave frequencies, 4.995 and 8.8 GHz, using data from the four Radio Solar Telescope Network (RSTN) patrol stations of the US Air Force, and feed this time series to the UMASEP prediction scheme. During the selected period the Geostationary Operational Environmental Satellites (GOES) detected nine SEP events related to activity in the western solar hemisphere. We show that the SEP forecasting using microwaves has the same probability of detection as the method using soft X-rays, but no false alarm in the considered period, and a slightly increased warning time. A detailed analysis of the missed events is presented. We conclude that microwave patrol observations improve SEP forecasting schemes that employ soft X-rays. High-quality microwave data available in real time appear as a significant addition to our ability to predict SEP occurrence. **2012 May 17, 2012 July 07, 2012 July 17, 2012 September 27**

Table 1. Forecast results for each of the SEP events that occurred from November 2011 to December 2012

CESRA Highlight #1540 Oct **2017** http://www.astro.gla.ac.uk/users/eduard/cesra/?p=1540

Microwave observations for forecasting energetic particles from the Sun

Pietro **Zucca**_y1, Karl-Ludwig Klein1, Marlon Nu~nez2, and Rositsa Miteva3

CESRA **2016**, p.87

http://cesra2016.sciencesconf.org/conference/cesra2016/pages/CESRA2016_prog_abs_book_v3.pdf

Predicting when solar energetic particles (SEPs) will hit Earth, and in what concentrations and energies, is important to mitigating space weather hazards ranging from communications outages to high radiation levels on polar aircraft routes. The university of Malaga developed a forecast tool for SEPs called UMASEP. This tool uses time derivatives of the proton pro_le observed in space and of the soft X-ray ux to predict if a SEP event is to occur, and how it will evolve. In the frame of the HESPERIA project, funded by the Horizon 2020 programme of the European Union, we conduct an extensive study on the use of microwave observations to replace or accompany the soft X-ray _rst derivative in the SEP forecast. In addition, we are conducting a study to predict the hardness of the energy spectrum of the incoming protons at Earth employing microwave spectral properties, using a method devised by I. Chertok and collaborators. This contribution is to present _rst results on the two subjects, using a sample microwave observational period of 3 months and a sample of 15 test events: (1) We constructed an uninterrupted time pro_le over three months using the four RSTN stations of the US Air Force, and fed this pro_le into the UMASEP scheme instead of the soft X-ray observations. (2) We tested the capability of the microwave spectral characteristics on the incoming proton energy forecast by comparing predicted and observed proton spectra in interplanetary space for 15 events between 2003 and 2006. These tests are preliminary, and are to be extended to a large data set in the coming months.

ENERGY SPECTRUM OF ENERGETIC PARTICLES ACCELERATED BY SHOCK WAVES: FROM FOCUSED TRANSPORT TO DIFFUSIVE ACCELERATION

Pingbing **Zuo**1,2, Ming Zhang1, Konstantin Gamayunov1, Hamid Rassoul1 and Xi Luo

2011 ApJ 738 168

The focused transport equation (FTE) includes all the necessary physics for modeling the shock acceleration of energetic particles with a unified description of first-order Fermi acceleration, shock drift acceleration, and shock surfing acceleration. It can treat the acceleration and transport of particles with an anisotropic distribution. In this study, the energy spectrum of pickup ions accelerated at shocks of various obliquities is investigated based on the FTE. We solve the FTE by using a stochastic approach. The shock acceleration leads to a two-component energy spectrum. The low-energy component of the spectrum is made up of particles that interact with shock one to a few times. For these particles, the pitch angle distribution is highly anisotropic, and the energy spectrum is variable depending on the momentum and pitch angle of injected particles. At high energies, the spectrum approaches a power law consistent with the standard diffusive shock acceleration (DSA) theory. For a parallel shock, the high-energy component of the power-law spectrum, with the spectral index being the same as the prediction of DSA theory, starts just a few times the injection speed. For an oblique or quasi-perpendicular shock, the high-energy component of the spectrum exhibits a double power-law distribution: a harder power-law spectrum followed by another power-law spectrum with a slope the same as the spectral index of DSA. The shock acceleration will eventually go into the DSA regime at higher energies even if the anisotropy is not small. The intensity of the energy spectrum given by the FTE, in the high-energy range where particles get efficient acceleration in the DSA regime, is different from that given by the standard DSA theory for the same injection source. We define the injection efficiency η as the ratio between them. For a parallel shock, the injection efficiency is less than 1, but for an oblique shock or a quasi-perpendicular shock it could be greater.

COMPOSITION OF CORONAL MASS EJECTIONS

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2016 ApJ 826 10   DOI 10.3847/0004-637X/826/1/10

We analyze the physical origin of plasmas that are ejected from the solar corona. To address this issue, we perform a comprehensive analysis of the elemental composition of interplanetary coronal mass ejections (ICMEs) using recently released elemental composition data for Fe, Mg, Si, S, C, N, Ne, and He as compared to O and H. We find that ICMEs exhibit a systematic abundance increase of elements with first ionization potential (FIP) < 10 eV, as well as a significant increase of Ne as compared to quasi-stationary solar wind. ICME plasmas have a stronger FIP effect than slow wind, which indicates either that an FIP process is active during the ICME ejection or that a different type of solar plasma is injected into ICMEs. The observed FIP fractionation is largest during times when the Fe ionic charge states are elevated above Q Fe > 12.0. For ICMEs with elevated charge states, the FIP effect is enhanced by 70% over that of the slow wind. We argue that the compositionally hot parts of ICMEs are active region loops that do not normally have access to the heliosphere through the processes that give rise to solar wind. ***We also discuss the implications of this result for solar energetic particles accelerated during solar eruptions and for the origin of the slow wind itself.***

ПОИСКИ ИСТОЧНИКОВ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В СОБЫТИЯХ МАЛОЙ МОЩНОСТИ

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Изв. РАН Том: 87Номер: 7 Год: 2023 Страницы: 1002-1004

Некоторые слабые солнечные протонные события, регистрируемые земным наблюдателем, в которых наблюдались протоны с энергией $E \geq 10$ МэВ, являются частицами, ускоренными ударной волной в межпланетном пространстве. Им можно сопоставить вспышку и корональный выброс массы за десятки часов до наблюдаемого возрастания потоков протонов, которые обеспечивают инжекцию частиц в процесс их последующего ускорения в межпланетном пространстве.

ИЗОЛИРОВАННЫЕ СОБЫТИЯ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ, ОБУСЛОВЛЕННЫЕ ПРИХОДОМ БЫСТРЫХ ШТОРМОВЫХ ЧАСТИЦ (ESP)

БАЗИЛЕВСКАЯ Г. А. *[1], **ДАЙБОГ Е. И.** *[2], **ЛОГАЧЕВ Ю. И.** *[2]

Г и А Том: 63Номер: 4 Год: **2023** Страницы: 503-510

По данным Каталогов солнечных протонных событий за 23-й и 24-й циклы солнечной активности выбраны события, не отождествленные с надежным источником частиц, но сопровождаемые межпланетными и геомагнитными возмущениями. Как правило, это события с малыми потоками протонов, зарегистрированных около Земли. Все выбранные события происходили во время прихода ударных волн на Землю и, таким образом, скорее всего были обусловлены приходом к Земле быстрых штормовых частиц. Показано, что источником этих событий могли быть вспышки, сопровождаемые корональными выбросами массы, произошедшие за десятки часов до начала возрастания потоков частиц на орбите Земли. Выбранные события обладают рядом особенностей. Только одно из них сопровождалось единственным ударным фронтом, тогда как во время остальных пришли 2 или 3 ударные волны. Временно́й профиль исследованных событий напоминал структуру, ограниченную двумя ударными фронтами. Таким образом, ударные волны, по-видимому, ускоряли и удерживали частицы в ограниченной области пространства.

СТАТИСТИЧЕСКИЕ СВЯЗИ МЕЖДУ СОЛНЕЧНЫМИ КОСМИЧЕСКИМИ ЛУЧАМИ, РАДИОИЗЛУЧЕНИЕМ II ТИПА И КОРОНАЛЬНЫМИ ВЫБРОСАМИ МАССЫ

Базилевская Г.А., Логачёв Ю.И., Дайбог Е.И., Власова Н.А., Гинзбург Е.А., Ишков В.Н., Лазутин Л.Л., Нгуен М.Д., Сурова Г.М., Яковчук О.С.

Г и А Том: 61Номер: 5 Год: 2021 Страницы: 672-679
DOI: 10.31857/S0016794021050035

Радиоизлучение II типа часто сопровождает события в солнечных космических лучах и является индикатором распространения ударной волны в короне Солнца. С другой стороны, важную роль в ускорении солнечных протонов играет ударная волна, связанная с выбросами коронального вещества. Оба эти явления могут происходить без сопровождения солнечными космическими лучами, в то же время не все события солнечных космических лучей сопровождаются радиоизлучением II типа. Статистические связи между этими явлениями рассмотрены на базе Каталогов солнечных протонных событий 23 и 24-го циклов солнечной активности. Показано, что события солнечных космических лучей, сопровождаемые радиоизлучением II типа, относятся к наиболее мощным как по характеристикам частиц, так и по характеристикам источников.

ХАРАКТЕРНЫЕ ОСОБЕННОСТИ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В 21–24-М ЦИКЛАХ СОЛНЕЧНОЙ АКТИВНОСТИ ПО ДАННЫМ КАТАЛОГОВ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ

БАЗИЛЕВСКАЯ Г. А.[*1], **ДАЙБОГ Е. И.**[2], **ЛОГАЧЁВ Ю. И.**[2], **ВЛАСОВА Н. А.**[2], **ГИНЗБУРГ Е.**[3], **ИШКОВ В. Н.**[4], **ЛАЗУТИН Л. Л.**[2], **НГУЕН М. Д.**[2], **СУРОВА Г. М.**[2], **ЯКОВЧУК О. С.**

ГЕОМАГНЕТИЗМ И АЭРОНОМИЯ Том: 61 Номер: 1 Год: **2021** Страницы: 8-15

Рассмотрены однородные ряды событий солнечных космических лучей за 4 цикла солнечной активности на фоне ее уменьшения в циклах 23 и 24. Число событий солнечных космических лучей с энергией выше 10 МэВ уменьшилось незначительно, тогда как число наземных возрастаний при сравнении циклов 23 и 24 снизилось в 8 раз. Показано, что при переходе от цикла 23 к циклу 24 средний вклад вспышек в генерацию наземных возрастаний уменьшился в 3 раза, а средний вклад корональных выбросов вещества – в 5 раз; средний вклад вспышек в генерацию солнечных космических лучей с энергией >10 МэВ уменьшился в 1.3 раза, а средний вклад корональных выбросов вещества – возрос в 1.4 раза.

НЕКОТОРЫЕ ОСОБЕННОСТИ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ И ДЛИТЕЛЬНЫХ ГАММА-ВСПЫШЕК В 24-М ЦИКЛЕ СОЛНЕЧНОЙ АКТИВНОСТИ

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Известия РАН **2021**

Проведено сравнение характеристик солнечных космических лучей на базе Каталога солнечных протонных событий 24-го цикла солнечной активности и солнечных событий с длительным высокоэнергичным гамма-излучением по данным измерений на гамма-телескопе Ферми. Высокоэнергичные γ-кванты являются в основном продуктом распада πо, которые возникают при взаимодействии на Солнце протонов высокой энергии. Источники гамма-вспышек, не сопровождавшихся солнечными протонами, находились в восточной полусфере Солнца, и связанные с ними выбросы коронального вещества двигались не в сторону Земли. Солнечные протоны от таких источников не регистрируются земным наблюдателем.

СОЛНЕЧНЫЕ ПРОТОННЫЕ СОБЫТИЯ В ЦИКЛАХ СОЛНЕЧНОЙ АКТИВНОСТИ 21–24

БАЗИЛЕВСКАЯ Г.А.1, ЛОГАЧЁВ Ю.И.2, ВАШЕНЮК Э.В.3, ДАЙБОГ Е.И.2, ИШКОВ В.Н.4, ЛАЗУТИН Л.Л.2, МИРОШНИЧЕНКО Л.И.2, НАЗАРОВА М.Н.5, ПЕТРЕНКО И.Е.5, СУРОВА Г.М.2, ЯКОВЧУК О.С.2

Изв. РАН, Серия физическая Том: 79 Номер: 5 Год: **2015** Страницы: 627-630

Показано, что, несмотря на низкую солнечную активность на фазе роста и максимума цикла 24, число солнечных протонных событий (СПС) с энергией протонов E > 10 МэВ и E > 100 МэВ в этом цикле мало отличается от числа таких же событий в предшествующих циклах 21□23. При этом наблюдается дефицит наиболее мощных событий типа GLE, которые характеризуются высокими значениями потока протонов с E > 100 МэВ. Отношение числа СПС с E > 10 МэВ и E > 100 МэВ к числу солнечных пятен в цикле 24 выросло вдвое по сравнению с циклами 21□23, а относительное число GLE вдвое уменьшилось. Характеристики вспышек и выбросов корональной массы, ассоциированных с протонными событиями с E > 100 МэВ, в цикле 24 практически не отличаются от аналогичных параметров в цикле 23.

СОЛНЕЧНЫЕ ПРОТОННЫЕ СОБЫТИЯ В КОНЦЕ 23-ГО И НАЧАЛЕ 24-ГО СОЛНЕЧНЫХ ЦИКЛОВ, ЗАРЕГИСТРИРОВАННЫЕ В ЭКСПЕРИМЕНТЕ ПАМЕЛА

Базилевская Г.А., Майоров А.Г., Малахов В.В., Михайлов В.В., Адриани О., Барбарино Д.С., Белотти Р., Боецио М., Богомолов Э.А., Бонвичини В., Бонджи М., Бонеки Л., Борисов С.В., Боттаи С., Бруно А., Вакки А., Вануччини Е., Васильев Г.И., Воронов С.А., Ву Ю. и др.

Известия РАН, Серия физическая, том 77, № 5, с. 557–560, **2013**.

Магнитный спектрометр ПАМЕЛА был запущен на околоземную космическую орбиту на спутнике Ресурс-ДК1 в июне 2006 г. и в декабре 2006 г. зарегистрировал последнее сильное солнечное событие 23-го цикла. В дальнейшем из-за продолжительного минимума солнечной активности и слабого развития следующего, 24-го цикла наблюдался дефицит высокоэнергичных солнечных событий. В результате в период 2010–2012 годов было зарегистрировано всего несколько солнечных протонных событий, сопровождавшихся выбросом

протонов с энергией свыше 100 МэВ. В статье представлены предварительные результаты измерений потоков заряженных частиц в этих событиях спектрометром ПАМЕЛА. **Таблица**
http://elibrary.ru/item.asp?id=19051518
English paper: http://iopscience.iop.org/1742-6596/409/1/012188/pdf/1742-6596_409_1_012188.pdf

МЕТОД ГЛОБАЛЬНОЙ СЪЕМКИ ДЛЯ МИРОВОЙ СЕТИ НЕЙТРОННЫХ МОНИТОРОВ
А. В. **Белов***, Е. А. Ерошенко**, В. Г. Янке, В. А. Оленева, М. А. Абунина, А. А. Абунин
Г&А **2018**, том 58, № 3, с. 1–16 **File**
Приведено описание одного из вариантов метода глобальной съемки, который разработан и много лет применяется в ИЗМИРАН. С его помощью обработаны данные мировой сети нейтронных мониторов за каждый час с июля 1957 г. по настоящее время. Получен однородный непрерывный ряд ежечасных характеристик вариаций плотности и векторной анизотропии космических лучей с жесткостью 10 ГВ, на основе которых создана база данных Форбуш-эффектов в галактических космических лучах, обусловленных крупномасштабными возмущениями межпланетной среды за более чем полувековой период. Возможности базы данных позволяют проводить корреляционный анализ различных параметров космической среды (характеристики Солнца, солнечного ветра, межпланетного магнитного поля) с параметрами космических лучей и изучать их взаимосвязи в солнечно-земном пространстве. Рассмотрены особенности приемных коэффициентов для разных станций, позволяющих осуществлять переход от вариаций по наземным измерениям к вариациям первичных космических лучей. Оценены достоинства и недостатки данного варианта метода глобальной съемки и возможности его развития и улучшения. Разработанный метод позволяет свести к минимуму проблемы сети нейтронных мониторов и в значительной мере использовать ее преимущества.

ПРЕДЕЛЬНЫЕ НАЗЕМНЫЕ ВОЗРАСТАНИЯ ИНТЕНСИВНОСТИ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ
БЕЛОВ А.В.1, СТРУМИНСКИЙ А.Б.
ИЗВЕСТИЯ РОССИЙСКОЙ АКАДЕМИИ НАУК. СЕРИЯ ФИЗИЧЕСКАЯ
Том: 81 Номер: 2 Год: **2017** Страницы: 143-146
https://elibrary.ru/download/elibrary_28919137_88388497.pdf
Возможные величины наземных возрастаний (GLE) интенсивности солнечных космических лучей (СКЛ), которые могут быть зарегистрированы нейтронными мониторами (НМ), оценены двумя различными методами для предельных спектров солнечных протонов. Первый метод основан на использовании статистической зависимости между максимальными величинами интегрального потока протонов >100 МэВ и GLE, зарегистрированного НМ. Второй способ заключается в расчете ожидаемого эффекта для предельного спектра на конкретном НМ, при известных коэффициентах связи, глубине атмосферы и пороге геомагнитного обрезания. Оценка первым методом дает от 9600 до 160 000% для высокоширотных НМ, а вторым методом от 1200 до 750 000%. Полученные нижние пределы примерно соответствуют величинам GLE, уже наблюдавшимся в истории, а верхние пределы примерно на два порядка их выше. Необходимо дальнейшее изучение возможного влияния солнечных протонных событий со спектрами, близкими к предельным, на атмосферу, биосферу Земли.

Вспышки, выбросы, протонные события
А.В. **Белов**
Геомагн. и аэрономия Том: 57 Номер: 6 Год: **2017** Страницы: 783-793 **File**
https://www.elibrary.ru/download/elibrary_30645888_40282113.pdf

Проведен статистический анализ связи выбросов солнечного вещества (CME) и рентгеновских вспышек с наблюдаемыми у Земли потоками солнечных протонов с энергиями >10 и >100 МэВ. Основу анализа составили события 1976-2015 гг., для которых имеются надежные наблюдения рентгеновских вспышек на спутниках серии GOES и наблюдения CME на коронографах Soho/LASCO. Выявлена достаточно хорошая корреляция величины протонных возрастаний с мощностью и продолжительностью вспышек, а также с начальной скоростью CME. Статистика не дает явного преимущества ни CME, ни вспышкам в связи с протонными событиями, но характеристики вспышек и выбросов хорошо дополняют друг друга и их разумно использовать в прогностических моделях совместно. Получены численные зависимости, позволяющие оценивать ожидаемые у Земли протонные потоки по солнечным наблюдениям, обсуждаются возможности улучшения модели.
Таблица 1. Высокоскоростные CME без протонных возрастаний.
1999.07.25, 2001.04.11, 2003.05.29, 2003.11.11, 2005.02.16, 2012.03.10

НАЗЕМНЫЕ ВОЗРАСТАНИЯ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В ТРЁХ ПОСЛЕДНИХ ЦИКЛАХ СОЛНЕЧНОЙ АКТИВНОСТИ

А. В. **Белов**, Е. А. Ерошенко, О. Н. Крякунова, В. Г. Курт, В. Г. Янке

Геомагн. и аэрономия, **2010, Текст**

Geomagnetism and Aeronomy, Volume 50, Issue 1, pp.21-33, **2010 File**

https://elibrary.ru/download/elibrary_13066401_32317025.pdf

Представлен каталог наземных возрастаний солнечных космических лучей в 21-23 циклах солнечной активности. Исследованы основные свойства этих событий, их связь с солнечными источниками и протонными возрастаниями, наблюдаемыми на спутниках.

Таблица GLEs 1976-2006

А.В. **Белов**, Э. Гарсия, В.Г.Курт, Е. Мавромичалаки // Космические исследования. Т. 43. N.3 С.171 (**2005**).

УСКОРЕНИЕ ЧАСТИЦ И ГЕНЕРАЦИЯ АЛЬВЕНОВСКИХ ВОЛН МЕЖПЛАНЕТНОЙ УДАРНОЙ ВОЛНОЙ

БЕРЕЖКО Е. Г.1, ТАНЕЕВ С. Н

Письма в АЖ, Том: 42Номер: 2 Год: **2016** Страницы: 148

На основе события, зарегистрированного на аппарате ISEE 3 вблизи орбиты Земли в UT 5 апреля 1979 г., в рамках квазилинейного подхода исследован процесс регулярного (диффузионного) ускорения ионов и генерации альвеновских волн ускоренными частицами вблизи квазипродольных (квазипараллельных) участков фронтов межпланетных ударных волн. Показано, что при значительных углах отклонения межпланетного магнитного поля от нормали к ударному фронту теория дает сильно завышенный уровень генерации альвеновских волн ускоренными частицами. На орбите Земли альвеновские волны, произведенные ускоренными ионами, заключены в частотном диапазоне Гц со спектральным пиком, отвечающим частоте Гц, которому соответствуют амплитуды волн . Высокочастотная часть спектра волн (Гц) подвержена затуханию на тепловых протонах. Рассчитанные спектры ускоренных ионов и порождаемых ими альвеновских волн воспроизводят основные особенности, наблюдаемые в экспериментах.

УСКОРЕНИЕ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ УДАРНЫМИ ВОЛНАМИ

БЕРЕЖКО Е. Г.1, ТАНЕЕВ С. Н.

Письма в АЖ, Том: 39 Номер: 6 Год: **2013** Страницы: 443-455

Исследуется процесс ускорения солнечных космических лучей (СКЛ) ударными волнами, порождаемыми корональными выбросами вещества, с учетом генерации альвеновских волн ускоренными частицами. Выполнены детальные численные расчеты спектров СКЛ, формируемых при распространении ударных волн в короне Солнца, в рамках квазилинейного подхода с использованием реалистического набора физических параметров короны. Показано, что результирующий энергетический спектр СКЛ включает в себя степенной участок с показателем , заканчивающийся экспоненциальным хвостом. Максимальная энергия СКЛ лежит в пределах ГэВ в зависимости от величины скорости ударной волны км/с. Снижение величины альвеновского числа Маха ударной волны, обусловленное ростом альвеновской скорости с гелиоцентрическим расстоянием , приводит к тому, что эффективное ускорение СКЛ заканчивается при достижении ударной волной размера . При этом скорость диффузионного распространения СКЛ начинает превышать скорость ударной волны, вследствие чего частицы СКЛ интенсивно покидают окрестность ударной волны. Самосогласованная генерация альвеновских волн ускоренными частицами сопровождается смягчением спектра частиц и ростом их предельной энергии. Сопоставление результатов расчета потоков СКЛ, ожидаемых у орбиты Земли, с имеющимися экспериментальными данными показало, что теория объясняет основные наблюдаемые особенности.

Shock acceleration of solar cosmic rays

Berezhko E.G., Taneev S.N.

Astronomy Letters. 2013. Т. 39. № 6. С. 393-403.

2H- И 3HE-ИЗОТОПЫ В СОЛНЕЧНЫХ ВСПЫШКАХ ИЗ ДАННЫХ PAMELA 2006–2014 ГГ

Богомолов Э.А., Васильев Г.И., Менн В.

Известия РАН Том: 83Номер: 5 Год: **2019** Страницы: 582-585

В работе впервые представлены результаты наблюдений в орбитальном эксперименте PAMELA в 2006–2014 гг. изотопов 2H с энергией свыше ~50 МэВ/нукл. и 3He с энергией свыше ~90 МэВ/нукл. во время солнечных вспышек. Для селекции изотопов использован времяпролетный анализ ядер с известной из траекторных измерений жесткостью в сцинтилляционном телескопе магнитного спектрометра PAMELA и данные об их ионизационных потерях в стриповых детекторах трекера. Проведено GEANT4 моделирование генерации ядер 2H и 3He в солнечном веществе спектрами ядер 1H и 4He СКЛ для оценки пространственных масштабов области генерации изотопов. Вероятно обнаружено дополнительное ускорение ядер 2H и 3He во время вспышек.

СПЕКТРЫ СОЛНЕЧНЫХ НЕЙТРОНОВ С ЭНЕРГИЕЙ ~10–1000 МЭВ В ЭКСПЕРИМЕНТЕ PAMELA В ВСПЫШКАХ 2006–2015 ГГ

БОГОМОЛОВ Э.А.1, АДРИАНИ О.2,3, БАЗИЛЕВСКАЯ Г.А.4, ……

ИЗВЕСТИЯ РОССИЙСКОЙ АКАДЕМИИ НАУК. СЕРИЯ ФИЗИЧЕСКАЯ

Том: 81Номер: 2 Год: **2017** Страницы: 151-154

На основе анализа полетных данных международного космического эксперимента PAMELA впервые представлены предварительные результаты измерений спектров солнечных нейтронов с энергией ~10–1000 МэВ от вспышек на Солнце в 2006–2015 гг. Нейтронный детектор PAMELA на основе счетчиков 3He и замедлителя с площадью 0.18 м2 позволяет оценить потоки солнечных нейтронов во время солнечных вспышек. Солнечные нейтроны с энергией ~10–1000 МэВ вероятно обнаружены в 21 из 24 проанализированных вспышек 2006–2015 гг.

ПОТОКИ СОЛНЕЧНЫХ ЭНЕРГИЧНЫХ ПРОТОНОВ В ОКОЛОЗЕМНОМ ПРОСТРАНСТВЕ 13-23 МАРТА 2023 ГОДА

ВЛАСОВА Н.А.✉[1], **БАЗИЛЕВСКАЯ Г.А.**[2], **ГИНЗБУРГ Е.А.**[3], **ДАЙБОГ Е.И.**[1], **КАЛЕГАЕВ В.В.**[1,4], **КАПОРЦЕВА К.Б.**[1,4], **ЛОГАЧЕВ Ю.И.**[1], **МЯГКОВА И.Н.**[1]

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 62Номер: 2 Год: 2024 Страницы: 177-187

Представлены результаты исследования потоков солнечных протонов с энергией больше 5 МэВ в околоземном космическом пространстве 13-23.III.2023. Особенностями исследуемого периода являются отсутствие наблюдаемой солнечной вспышки, с которой можно ассоциировать начало события, нехарактерный временной профиль потоков протонов, а также большая длительность существования потоков солнечных протонов в околоземном пространстве. Предпринята попытка объяснить источники наблюдаемых вариаций потоков частиц и понять, что происходило на Солнце и в окружающем Землю пространстве. Источником солнечных протонов 13.III.2023 был взрывной процесс на обратной от Земли стороне Солнца, зарегистрированный как корональный выброс массы очень большой мощности. Причиной длительного и сложного временного профиля солнечных протонов был вклад процессов ускорения частиц на Солнце и в межпланетной среде, а также модуляция потоков частиц структурами межпланетного магнитного поля...

КАТАЛОГИ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ КАК ИНСТРУМЕНТ ИЗУЧЕНИЯ КОСМИЧЕСКОЙ ПОГОДЫ

Власова Н.А., Логачев Ю.И., Базилевская Г.А., Гинзбург Е.А., Дайбог Е.И., Ишков В.Н., Калегаев В.В., **Лазутин** Л.Л., Нгуен М.Д., Сурова Г.М., Яковчук О.С.

Косм. Том: 60Номер: 3 Год: **2022** 181-195

Описаны отличительные особенности серии каталогов солнечных протонных событий (СПС) 20–24 циклов солнечной активности. Представлены результаты сравнительного анализа 23 и 24 циклов солнечной активности, выполненного по данным серии каталогов СПС. Обсуждаются возможности, которые предоставляют каталоги СПС для исследований факторов космической погоды, таких как: динамика солнечной активности, структура и состояние межпланетной среды и магнитосферы Земли.

НЕКОТОРЫЕ ОСОБЕННОСТИ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ 7.III.2011 И 20.II.2014

ВЛАСОВА Н. А.*1, ТУЛУПОВ В. И.1, КАЛЕГАЕВ В. В.1

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 59 Номер: 4 Год: **2021** Страницы: 296-305

DOI: 10.31857/S0023420621040063

Представлены результаты исследования двух солнечных протонных событий 7.III.2011 и 20.II.2014, которые ассоциируются с солнечными вспышками, имеющими практически одинаковую мощность и находящимися на близких гелиодолготах, на западной стороне солнечного диска. Работа сделана на основе экспериментальных данных, полученных с КА ACE и ИСЗ GOES, расположенных в межпланетном пространстве в точке L1 и внутри магнитосферы Земли на геостационарной орбите, соответственно. Проведен сравнительный анализ особенностей временных профилей потоков солнечных энергичных протонов и вариаций параметров межпланетной среды: скорости и плотности солнечного ветра и величины и направления межпланетного магнитного поля. Показано, что основные различия временных профилей потоков протонов двух солнечных событий связаны с особенностями состояния межпланетной среды 7.III.2011 и 20.II.2014. Результаты сравнительного анализа временных вариаций потоков солнечных протонов с E > 10 МэВ и E > 30 МэВ и Bz- и Bx-компонент межпланетного магнитного поля 20.II.2014 свидетельствуют об определяющей роли структуры межпланетного магнитного поля на формирование особенностей временных профилей потоков частиц в данном событии.

ПАССИВНЫЕ ДОЛГОТЫ ИСТОЧНИКОВ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ

Гецелев И.В., Подзолко М.В., Охлопков В.П.

Известия РАН, Серия физическая, том 77, № 5, с. 567–569, **2013**

Рассмотрены солнечные протонные события в период с 1956 по 2012 годы. Рассчитаны флюенсы протонов различных энергий в этих событиях. На данном обширном материале подтверждена выявленная нами ранее неравномерность распределения их источников на Солнце по долготе Кэррингтона. Особое внимание обращено на выявленный нами интервал “пассивных долгот”, протяженный по долготе (90° 170°) и времени существования (весь указанный интервал наблюдений). Суммарный флюенс протонов в событиях, источники которых находились в данном интервале долгот Кэррингтона, существенно ниже, чем суммарные флюенсы протонов в других интервалах гелиодолгот. Из 60 наиболее мощных солнечных протонных событий за весь рассмотренный период наблюдений не более одного события произошло в указанном интервале “пассивных долгот”.

О КОРРЕЛЯЦИИ ОКОЛОЗЕМНЫХ ПРОТОННЫХ ВОЗРАСТАНИЙ >100 МЭВ С ПАРАМЕТРАМИ СОЛНЕЧНЫХ МИКРОВОЛНОВЫХ ВСПЛЕСКОВ

ГРЕЧНЕВ В.В.1, КИСЕЛЕВ В.И.1, МЕШАЛКИНА Н.С.1, ЧЕРТОК И.М.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том: 3Номер: 3 Год: **2017** Страницы: 3-14

Анализируются соотношения между различными комбинациями максимумов потоков и флюенсов солнечных микроволновых всплесков, записанных радиополяриметрами в Нобеяме на частоте 35 ГГц в 1990-2015 гг., и соответствующими параметрами протонных возрастаний с энергиями выше 100 МэВ, превышавших 0.1 pfu, зарегистрированных в околоземном пространстве мониторами GOES. Установлено, что наиболее высока корреляция между флюенсами протонов и микроволнового излучения. Этот факт отражает зависимость полного числа протонов от общей продолжительности процесса их ускорения. В событиях с мощными вспышками коэффициенты корреляции флюенсов протонов с флюенсами микроволнового и мягкого рентгеновского излучения выше, чем со скоростями КВМ. Результаты указывают на статистически больший вклад вспышечных процессов в ускорение высокоэнергичных протонов. Ускорение на ударных волнах оказывается менее значимым на высоких энергиях в событиях, связанных с мощными вспышками, хотя его вклад, вероятно, преобладает в более слабых событиях. Показано, что вероятность протонного возрастания прямо зависит от максимума потока и длительности микроволнового всплеска, что может быть использовано для диагностики протонных возрастаний по данным мониторинга микроволнового излучения.

ЭНЕРГЕТИЧЕСКИЙ СПЕКТР И ПОТОКИ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В ПЕРИОДЫ ИХ НАЗЕМНЫХ ВОЗРАСТАНИЙ

Григорьев В.Г., Стародубцев С.А., Евстафьева М.А.

Известия РАН, Серия физическая, том 77, № 5, с. 561–563, **2013**

По данным мировой сети станций нейтронных мониторов исследуются события наземных возрастаний релятивистских солнечных космических лучей. Методом эффективных энергий [1] проведена оценка показателя энергетического спектра и абсолютного потока солнечных космических лучей в 15 событиях, наблюдавшихся в 1977–2012 гг. Показано, что в исследуемых событиях наблюдается динамика изменения величины показателя степенного энергетического спектра в пределах от 3 до 7. Таблица

КОРОНАЛЬНОЕ РАСПРОСТРАНЕНИЕ СОЛНЕЧНЫХ ПРОТОНОВ ВО ВРЕМЯ И ПОСЛЕ ИХ СТОХАСТИЧЕСКОГО УСКОРЕНИЯ

ГРИГОРЬЕВА И. Ю.*[1], СТРУМИНСКИЙ А. Б.[2], ЛОГАЧЕВ Ю. И.[3], САДОВСКИЙ А. М.[2]

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 61Номер: 3 Год: 2023 Страницы: 230-241

В эруптивных вспышках солнечные протоны стохастически ускоряются в широком телесном угле, далее эффективно удерживаются за расширяющимся фронтом коронального выброса массы (КВМ), который может как приносить протоны на силовую линию, идущую к удаленному наблюдателю, так и уносить их от нее. **Рассматриваются 13 солнечных протонных событий 24-го цикла**, в которых были зарегистрированы протоны с энергией (E) > 100 МэВ и которые сопровождались регистрацией солнечного жесткого рентгеновского (HXR) излучения с E > 100 кэВ детектором ACS SPI и γ-излучения с E > 100 МэВ – телескопом FermiLAT, с источником на западной полусфере Солнца. Первый приход солнечных протонов на орбиту Земли определялся в каждом событии по значимому “протонному” превышению над фоном ACS SPI во время или после HXR всплеска. Все события рассматривались относительно выбранного нами нулевого времени (0 мин) родительских вспышек. “Ранний” приход протонов на орбиту Земли (<+20 мин), наблюдавшийся в 4 событиях, соответствует “быстрому” ускорению электронов (10 МэВ/с). “Поздний” приход протонов (>+20 мин) соответствует “медленному” ускорению электронов (1 МэВ/с) и наблюдался в шести событиях. В трех событиях наблюдался

"задержанный" приход протонов (>+30 мин), когда распространение КВМ ухудшало магнитное соединение источника с наблюдателем. Направление распространения КВМ характеризуется в каталоге (SOHO LASCO CME Catalog) позиционным углом (PA – Position Angle). Наблюдаемый угол PA систематизирует времена первого прихода протонов и темп роста их интенсивности. Параметр PA необходимо учитывать при анализе протонных событий.

ФОРМИРОВАНИЕ ИСТОЧНИКА СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В ЭРУПТИВНЫХ ВСПЫШКАХ X6.9 9 АВГУСТА 2011 ГОДА И M5.1 17 МАЯ 2012 ГОДА

Григорьева И.Ю., Струминский А.Б.

АЖ Том: 99Номер: 6 Год: **2022** Страницы: 486-495

Наличие корональных выбросов массы (КВМ) и солнечных протонных событий (СПС) в межпланетном пространстве (МП) после слабых вспышек в мягком рентгеновском диапазоне уже не является необычным фактом. Однако до сих пор оставалось непонятным, каким образом в таких случаях могут реализоваться близкие к предельным характеристики КВМ и СПС. В работе проведено сравнение результатов наблюдений событий на Солнце и в МП, связанных с длительной вспышкой M5.1 17 мая 2012 г. с невыраженной импульсной фазой (относительно слабым электромагнитным (ЭМ) излучением) и короткой мощной вспышкой X6.8 9 августа 2011 г. с ярко выраженной импульсной фазой (сильным ЭМ-излучением). Обе вспышки в МП сопровождались мощными потоками солнечных космических лучей (СКЛ): протонов >100 МэВ и электронов >1 МэВ; быстрыми КВМ со скоростями >1500 км/с. Из сравнения характеристик ЭМ-излучения вспышек, КВМ и СКЛ на масштабе времени от нескольких минут до нескольких часов (после начала наблюдения нетеплового излучения в M5.1 и X6.8) следует, что свойства КВМ и СКЛ определяла длительность вспышечных процессов, а не их наблюдаемая интенсивность. Более длительный и более интенсивный выход солнечных протонов в МП в событии M5.1, по сравнению с X6.8, был обусловлен развитием вспышки только в короне, без явного "хромосферного испарения" – изменений температуры $(dT/dt)_{M5.1} < (dT/dt)_{X6.8}$ и меры эмиссии $(dEM/dt)_{M5.1} < (dEM/dt)_{X6.8}$), движением КВМ с меньшей величиной ускорения ($a_{1705} < a_{0908}$) и, соответственно, с большей длительностью $t_{M5.1} = V_{\max M5.1}/a_{M5.1} > V_{\max X6.8}/a_{X6.8} = t_{X6.8}$ для достижения максимальной скорости. Более длительное ускорение КВМ предполагает и более длительные процессы энерговыделения (ускорения) на фазе спада вспышки. Эти процессы происходили в системе высоких послевспышечных петель при плотностях плазмы и величинах магнитного поля недостаточных для генерации жесткого рентгеновского и микроволнового излучения выше порога регистрации современных приборов. О том, что энерговыделение все же имело место, свидетельствовали только длительное γ-излучение, зарегистрированное FermiLAT, и продолжающиеся ускорение КВМ. **9 Avg 2011, 17 May 2012**

Микроволновые всплески и относительное содержание электронов и протонов во вспышечных солнечных космических лучах.

Дайбог Е.И., Столповский В.Г., Мельников В.Ф., Подстригач Т.С.

Письма в Астрон.ж., **1989**, Т.15, С.991-1000. **English File**

Надтепловые ионы в спокойное время на 1 а.е. в 23-м и 24-м циклах солнечной активности

М. А. **Зельдович**, Ю. И. Логачев, Г. М. Сурова, К. Кечкемети

Астрономический журнал, - **2014**, С. 474-480

Изучены относительное содержание ионов He, He, C, O и Fe в диапазоне надтепловых энергий (МэВ/нукл.) и энергетические спектры ионов He и Fe в околоземном космическом пространстве в течение спокойных периодов солнечной активности. Использованы измерения прибора ULEIS на космическом аппарате ACE в 23-м и 24-м солнечных циклах. Показано, что для выделенных спокойных периодов наблюдаются значительные различия в энергетических спектрах надтепловых ионов в 23-м и 24-м циклах. Сильное различие отмечено также и в зависимостях относительного содержания ионов от энергии. Возможное объяснение полученных результатов состоит в ускорении фоновых ионов до надтепловых энергий при различных условиях в солнечной короне в этих двух циклах.

ПРОГНОЗ СОЛНЕЧНЫХ ВСПЫШЕЧНЫХ ЯВЛЕНИЙ: СОЛНЕЧНЫЕ ПРОТОННЫЕ СОБЫТИЯ

ИШКОВ В. Н.[1]

Изв. РАН Том: 87Номер: 7 Год: 2023 Страницы: 1010-1013

С современных позиций рассматриваются вопросы прогноза солнечных вспышечных событий – единственного источника высокоэнергичных протонов, как от самого процесса энерговыделения, так и от сопровождающих его динамических явлений: ударных волн и корональных выбросов вещества, распространяющихся от места выделения энергии. Возможность прогноза самих вспышечных событий обеспечивает взаимодействие новых всплывающих магнитных потоков с магнитными полями активных областей и вне их, но всегда на линии раздела полярностей. Появление солнечных протонов во вспышечном событии определяется характеристиками во всем спектре его излучения, локализацией его на Солнце и параметрами его коронального выброса вещества.

СОВРЕМЕННОЕ ПРЕДСТАВЛЕНИЕ БАЗ ДАННЫХ НА ПРИМЕРЕ КАТАЛОГА СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ 23-ГО ЦИКЛА СОЛНЕЧНОЙ АКТИВНОСТИ

Ишков В.Н., Забаринская Л.П., Сергеева Н.А.

ГЕОМАГНЕТИЗМ И АЭРОНОМИЯ Том: 57Номер: 6 Год: **2017** Страницы: 736-743

Развитие исследований солнечных источников и их воздействий на состояние околоземного космического пространства потребовало систематизации соответствующей информации в виде баз данных и каталогов за все время наблюдений какого-либо геоэффективного явления, включающего в себя, по возможности на момент создания, все характеристики самих явлений и источников данных явлений на Солнце. Особое значение имеет однородное представление информации в виде серии однотипных каталогов, охватывающих продолжительные временные интервалы. Большой объем информации, собранный в таких каталогах, делает необходимым использование современных методов ее организации и оформления, обеспечивающих возможность перехода между отдельными частями каталога и быстрый поиск нужных событий и их характеристик, что и сделано в представляемом Каталоге солнечных протонных событий 23-го цикла солнечной активности из последовательности каталогов (6 отдельных выпусков), которые охватывают период с 1970 по 2009 гг. (20-23-й циклы солнечной активности).

Выход ускоренных протонов в солнечных эруптивных событиях

В.И. **Киселёв**, В.В. Гречнев, А.А. Кочанов, А. М. Уралов

2017 Доклад на байкальскую школу **File**

Задержка выхода ускоренных ионов у Солнца относительно вспышки считается подтверждением их ускорения головной ударной волной, возникающей перед корональным выбросом массы, превысившим альфвеновскую скорость. Возможно другое объяснение задержки выхода частиц. Часть ускоренных во вспышке электронов и ионов захватывается в расширяющемся магнитном жгуте. Его последующее пересоединение с открытыми корональными структурами открывает доступ в межпланетное пространство всем захваченным частицам. Для проверки этого сценария рассмотрены дека/гектометровые (ДГМ) всплески III типа, вызванные быстрыми электронами. Мы сравнили оценённые Д. Римсом [Reames 2009, ApJ, 693, 812] для 13 событий времена выхода тяжёлых частиц с началом ДГМ всплесков III типа. Для 11 событий разница не превысила пяти минут. Для двух событий оценённые времена выхода оказались нереалистично поздними, вероятно, из-за неучтённых эффектов распространения тяжелых частиц. Рассмотренный сценарий решает проблему выхода ускоренных протонов из области вспышки, а близость вероятных времён выхода энергичных частиц и ДГМ всплесков III типа подтверждает ускорение частиц вспышечными процессами. **2 мая 1998 г. (GLE56), 26 декабря 2001 г. (GLE63) и 29 октября 2003 г. (GLE66).**

УСЛОВИЯ ПРИХОДА СОЛНЕЧНЫХ ЭНЕРГИЧНЫХ ПРОТОНОВ НА ЗЕМЛЮ ПОСЛЕ МОЩНЫХ ВСПЫШЕК НА СОЛНЦЕ

Кичигин Г.Н., Кравцова М.В., Сдобнов В.Е.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том: 8Номер: 3 Год: **2022** Страницы: 24-28

https://elibrary.ru/download/elibrary_49522162_69964425.pdf

Проведен анализ процесса переноса от Солнца до Земли энергичных протонов, ускоренных в солнечных вспышках. Используется модель, в которой предполагается, протоны движутся к Земле в электромагнитном поле паркеровского представления. В рамках этой модели показано, что регистрация протонов на Земле происходит в том случае, когда протоны, движущиеся от вспышечной области Солнца, попадают в окрестность гелиосферного токового слоя, а Земля находится от нейтральной линии токового слоя на расстоянии, меньшем лармоовского радиуса протонов. Представлен анализ экспериментальных данных о солнечных вспышках в августе-сентябре 2011 г., из которого следует, что отсутствие регистрации энергичных протонов в окрестности Земли для некоторых мощных солнечных вспышек находит объяснение в рамках предложенной модели.

Таблца Солнечные события в августе– сентябре 2011 г

СПЕКТРЫ И АНИЗОТРОПИЯ КОСМИЧЕСКИХ ЛУЧЕЙ В ПЕРИОД GLE64
Ковалев И.И., Кравцова М.В., Олемской С.В., Сдобнов В.Е.
ГиА Том: 64Номер: 1 Год: 2024 Страницы: 55-59
По данным наземных наблюдений космических лучей методом спектрографической глобальной съемки проведено исследование наземного возрастания интенсивности космических лучей 24 августа 2002 г. Получены спектры вариаций первичных космических лучей и их анизотропия. По данным измерений космического аппарата GOES и мировой сети станций космических лучей рассчитаны дифференциальные жесткостные спектры ускоренных частиц в окрестности Солнца. Оценена максимальная жесткость, до которой произошло ускорение солнечных частиц.

ПРОГНОЗ ЭКСТРЕМАЛЬНЫХ СОБЫТИЙ КОСМИЧЕСКОЙ ПОГОДЫ ПО ФЛУКТУАЦИЯМ КОСМИЧЕСКИХ ЛУЧЕЙ
Козлов *В. И.*
Косм. Иссл. Том: 60Номер: 2 Год: **2022** Страницы: 105-115
В экстремальных событиях Космической погоды образуются и наибольшие по величине потоки “штормовых” частиц, предваряющих приход ударной волны на орбиту Земли. Именно они представляют наибольшую опасность для систем жизнеобеспечения в верхней атмосфере, в Космосе и на Земле. Проведена заверка результатов прогноза “штормовых” частиц ускоренных ударными волнами по вариациям космических лучей высоких энергий данными измерений на космическом аппарате *ACE*, США. Оценка достоверности прогноза $P \geq 80\%$.

ЗАГОРИЗОНТНОЕ ОБНАРУЖЕНИЕ МОЩНОГО ИСТОЧНИКА АКТИВНОСТИ НА СОЛНЦЕ ПО ЭФФЕКТУ “ГАЛО” В КОСМИЧЕСКИХ ЛУЧАХ

КОЗЛОВ В. И.*
КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 59Номер: 5 Год: 2021 Страницы: 361-372
DOI: 10.31857/S0023420621050071
В окрестности фронта ударной волны галактические космические лучи фокусируются в анизотропные “пучки” частиц. Подобные пучки коррелированных частиц – эффект “гало” в космических лучах, являются, по сути, предвестниками ударной волны. Наиболее ярко эффект “гало” в космических лучах проявляется при выявлении источника активности выходящего или заходящего за край солнечного диска. Задачу загоризонтного обнаружения в реальном времени мощного залимбового источника активности на Солнце мы решаем дистанционным методом диагностики околоземного космического пространства (http://www.forshock.ru/pred.html) посредством созданной роботизированной экспертной системы Cyber-FORSHOCK, на базе существующей мировой сети (высокоширотных) нейтронных мониторов (http://www.nmdb.eu). В данном случае, планета Земля, вместе с работающими на прием космической радиации высокоширотными станциями космических лучей (порядка ~10), представляет собой единый “прибор”.

АРИТМИЯ СОЛНЦА. В космических лучах **Book**
4-е издание, переработанное и дополненное
В. И. **Козлов**, В. В. Козлов
Институт космофизических исследований и аэрономии
им. Ю.Г. Шафера СО РАН **2019 File**
https://www.researchgate.net/profile/Valery_Kozlov/publication/336639864_ARRHYTHMIA_of_Sun_2019_Kozlov/links/5e998f0692851c2f52aa23a3/ARRHYTHMIA-of-Sun-2019-Kozlov.pdf?origin=publication_list
Монография посвящена изучению переходных режимов солнечного ветра различных масштабов по изучению «групповых» особенностей поведения космических лучей. Установлено, что фрактальные свойства замагниченной среды, проявляющиеся в коррелированности флуктуаций космических лучей в окрестности ударной волны, могут быть использованы для ее прогноза с заблаговременностью ~1 сутки, а на больших масштабах и… активной фазы солнечного цикла с заблаговременностью порядка ~1 оборота Солнца. Это обусловлено тем, что предвестник в космических лучах является индикатором начала перестройки магнитного поля на переходном режиме к активной фазе солнечного цикла. Более того, космические лучи могут дать ценную информацию и о возможном развитии 11-летнего цикла на несколько лет вперед: так в 2006 г., нами был сделан вывод о грядущем сбое 11-летней цикличности. Сейчас, это свершившийся факт.

С целью описания локальных и глобальных сбоев 11-летней цикличности с единой позиции, введен Инвариант с характерным масштабом длительности 22-летнего цикла, что предполагает консервативность системы в широком смысле, т.е. постоянство площади (энергоемкости) 22-летнего цикла. На основе чего дан предварительный прогноз восстановления 11-летней цикличности в 25 цикле (2020–2030 гг.).

Нарушение инварианта 22-летнего цикла (в случае невосстановления 11-летней цикличности в 25 цикле) явится указанием на нарушение консервативности системы: на относительно пониженный уровень светимости Солнца, как характеристики энергоемкости и, как следствие – на срыв режима регуляции энергии (автоколебаний) в конвективной зоне Солнца со всеми вытекающими отсюда последствиями. В частности: многолетнего повышения радиационного фона космических лучей высоких энергий и, соответственно – повышение облачности и последующей интенсификации ковективных процессв в атмосфере, сопровождающейся увеличением количества осадков и понижением температуры в планетарном масштабе.

Книга адресована как специалистам в области космических лучей, так и широкому кругу читателей интересующихся проблемами солнечно-земной физики и является русской версией (обновленной и дополненной) перевода ее на английский язык.

Статистическая связь между потоком солнечных энергичных протонов и флюенсом рентгеновского излучения во время солнечной вспышки

Коновалихин А.М., Власова Н.А., Калегаев В.В.

Ломоносовские чтения_**2024** НИИЯФ МГУ

НАЗЕМНОЕ ВОЗРАСТАНИЕ ИНТЕНСИВНОСТИ КОСМИЧЕСКИХ ЛУЧЕЙ 28 ОКТЯБРЯ 2003 Г.: СПЕКТРЫ И АНИЗОТРОПИЯ

Кравцова М.В., Сдобнов В.Е.

Известия РАН Том: 83Номер: 5 Год: **2019** Страницы: 586-589

По данным наземных и спутниковых наблюдений интенсивности космических лучей (КЛ) на мировой сети станций методом спектрографической глобальной съемки, разработанном в Институте солнечно-земной физики СО РАН, исследованы вариации жесткостного спектра и анизотропия КЛ в период наземного возрастания интенсивности КЛ (GLE) 28 октября 2003 г. Определены жесткостные спектры КЛ в отдельные периоды исследуемого события. Показано, что ускорение протонов в период этого GLE наблюдалось до жесткости ~10–14 ГВ, а дифференциальные жесткостные спектры КЛ во время рассматриваемого события не описываются ни степенной, ни экспоненциальной функцией от жесткости частиц. На основе проведенного анализа установлено, что в момент GLE Земля находилась в петлеобразной структуре межпланетного магнитного поля.

НАЗЕМНЫЕ ВОЗРАСТАНИЯ ИНТЕНСИВНОСТИ КОСМИЧЕСКИХ ЛУЧЕЙ В 24-ОМ ЦИКЛЕ СОЛНЕЧНОЙ АКТИВНОСТИ

КРАВЦОВА М.В.1, СДОБНОВ В.Е.1

ПАЖ Том: 43Номер: 7 Год: **2017** Страницы: 550-556

По данным наземных наблюдений космических лучей (КЛ) на мировой сети станций и космических аппаратов методом спектрографической глобальной съемки исследованы спектры протонов и анизотропия КЛ в период наземных возрастаний интенсивности КЛ **17.05.2012** г. (GLE71) и **06.01.2014** г. (GLE72), произошедших в 24-ом цикле солнечной активности. Приведены жесткостные спектры КЛ и относительные изменения интенсивности КЛ с жесткостью 2 ГВ в солнечно-эклиптической геоцентрической системе координат в отдельные периоды исследуемых событий. Показано, что ускорение протонов в периоды GLE71 и GLE72 произошло до жесткостей R ~ 2.3-2.5 ГВ, а дифференциальные жесткостные спектры солнечных КЛ не описываются ни степенной, ни экспоненциальной функцией от жесткости частиц. В моменты рассмотренных событий Земля находилась в петлеобразной структуре межпланетного магнитного поля.

ИССЛЕДОВАНИЕ ЭНЕРГЕТИЧЕСКОГО СПЕКТРА И АНИЗОТРОПИИ КОСМИЧЕСКИХ ЛУЧЕЙ В ПЕРИОДЫ СОЛНЕЧНО-ПРОТОННЫХ СОБЫТИЙ 11 И 15 ИЮНЯ 1991 Г

Кравцова М.В., Сдобнов В.Е.

ПАЖ Том: 41 Номер: 9 Год: **2015** Страницы: 573

По данным мировой сети нейтронных мониторов методом спектрографической глобальной съемки, исследованы энергетические спектры и анизотропия космических лучей (КЛ) во время возрастаний интенсивности КЛ, обусловленных событиями на Солнце 11 и 15 июня 1991 г. При совместном анализе данных наземных и спутниковых измерений в рамках модели модуляции КЛ регулярными электромагнитными полями гелиосферы определены параметры жесткостного спектра КЛ, отражающие электромагнитные характеристики полей гелиосферы за каждый час наблюдений. Приведены спектры КЛ, а также относительные изменения интенсивности КЛ в солнечно-эклиптической геоцентрической системе координат в отдельные моменты этих событий.

ЖЕСТКОСТНОЙ СПЕКТР И АНИЗОТРОПИЯ КОСМИЧЕСКИХ ЛУЧЕЙ В ПЕРИОД СПОРАДИЧЕСКИХ СОБЫТИЙ В ИЮЛЕ 2000 Г

Кравцова М.В., Сдобнов В.Е.
Известия РАН, Серия физическая, том 77, № 5, с. 602–606, **2013**.
По данным наземных наблюдений космических лучей (КЛ) на мировой сети станций и космических аппаратах методом спектрографической глобальной съемки в период GLE **14 июля 2000** г., а также во время сильной магнитной бури, связанной с корональным выбросом массы (CME), сопровождавшим солнечную вспышку, исследованы жесткостной спектр и анизотропия галактических КЛ. Показано, что в рассмотренный период жесткостной спектр КЛ в диапазоне от 1 до 20 ГВ не описывается одной степенной функцией от жесткости частиц, а распределение КЛ по направлениям прихода к Земле динамично во времени и зависит от их энергии.

ПРОЯВЛЕНИЯ В ГЕЛИОСФЕРЕ И В ИНТЕНСИВНОСТИ ГКЛ ДВУХ ВЕТВЕЙ СОЛНЕЧНОЙ АКТИВНОСТИ

Крайнев М.Б.
СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том 5 № 4 ,2019 С 12-25
https://naukaru.ru/ru/storage/viewWindow/43510
Дается представление о процессах в гелиосфере и модуляции галактических космических лучей (ГКЛ) в ней как результатах действия в этом слое Солнца двух ветвей солнечной активности, называемых по топологии солнечных магнитных полей внутри Солнца тороидальной ветвью (активные области, пятна, вспышки, корональные выбросы массы и т. д.) и полоидальной ветвью (высокоширотные магнитные поля, полярные корональные дыры, зональные униполярные магнитные области и т. д.). Формулируется основная причина различного проявления обеих ветвей на поверхности Солнца и в гелиосфере — наличие в основании гелиосферы слоя, в котором основным энергетическим фактором является магнитное поле. При этом преимущество при проникновении в гелиосферу получают более крупномасштабные, хотя и менее интенсивные солнечные магнитные поля полоидальной ветви. Показана связь с полоидальной ветвью солнечной активности гелиосферных характеристик (поле скорости солнечного ветра, размер гелиосферы, форма гелиосферного токового слоя, регулярное гелиосферное магнитное поле и его флуктуации), которые, согласно современным представлениям, определяют распространение в гелиосфере ГКЛ.

ОПРЕДЕЛЕНИЕ ВРЕМЕНИ НАЧАЛА УСКОРЕНИЯ РЕЛЯТИВИСТСКИХ ПРОТОНОВ В СОЛНЕЧНЫХ ВСПЫШКАХ

В.Г.**Курт**, Б.Ю.Юшков, К.Кудела
ИКИ-**2014**, Сессия: Солнце
http://plasma2014.cosmos.ru/presentations

Определение времени ускорения протонов, ответственных за начало возрастаний солнечных космических лучей.

Курт В. Г., Юшков Б. Ю., Белов А. В., Черток И. М., Гречнев В. В.
Известия РАН, Серия физическая, том 77, № 5, с. 546–549, **2013**.
Цель работы – определение времени ускорения на Солнце протонов, ответственных за начало наземных возрастаний солнечных космических лучей (СКЛ). По совокупности данных о временах максимальных значений производной мягкого рентгеновского излучения, интенсивностей жесткого рентгеновского и гамма-излучения, а также интенсивности радиовсплесков, измеренных в см/мм_диапазоне, был определен временной интервал максимального вспышечного энерговыделения для вспышек, связанных с 45 наземными возрастаниями СКЛ (№ 27–71). Для тех же событий было определено время начала наземных возрастаний. В 31 событии начало наземного возрастания запаздывало на 2–15 минут относительно измеренного максимума энерговыделения вспышки. Столь малые значения задержек могут означать, что эффективное ускорение протонов, ответственных по крайней мере за самое начало наземного возрастания, в большинстве событий происходило именно в интервале времени максимального энерговыделения вспышки. **Таблица**

Возрастания энергичных протонов СКЛ на Земле и их связь с источниками на Солнце.

Лазутин Л.Л.
СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том 6. **2020**. № 4. С. 46–50.
http://ru.iszf.irk.ru/images/6/69/836402_46-50.pdf
По данным каталога Логачева за 23-й цикл солнечной активности исследована зависимость измеренных возрастаний солнечных космических лучей (СКЛ) от возмущений на Солнце. Показано, что эффективность регистрации на Земле и в ее окрестностях возрастаний СКЛ, вызванных ускорением протонов в короне, зависит от мощности солнечной вспышки, создавшей ударную волну, и положения вспышки на солнечном

диске. По мере удаления потока частиц по гелиодолготе от родительской вспышки эффективность ускорения снижается, т. е. понижается максимальная энергия ускоренных частиц и, при равной энергии, интенсивность их потоков. В результате на определенном удалении по гелиодолготе от родительской вспышки поток солнечных протонов понижается до уровня галактического фона и возрастание СКЛ не регистрируется. **08 ноября 2000**

СРАВНЕНИЕ ПРОТОННОЙ АКТИВНОСТИ В 20–23-М СОЛНЕЧНЫХ ЦИКЛАХ
ЛОГАЧЁВ Ю.И.1, БАЗИЛЕВСКАЯ Г.А.2, ВАШЕНЮК Э.В.3, ДАЙБОГ Е.И.1, ИШКОВ В.Н.4, ЛАЗУТИН Л.Л.1, МИРОШНИЧЕНКО Л.И.1, НАЗАРОВА М.Н.5, ПЕТРЕНКО И.Е.5, СТУПИШИН А.Г.6, СУРОВА Г.М.1, ЯКОВЧУК О.С.1
ГиА Том: 55Номер: 3 Год: **2015** Страницы: 291-301
Разнообразие условий, сопровождающих СПС, приводит к большому разбросу параметров их потоков и энергетических спектров, различию временнх профилей. Корректное выявление закономерностей в распределении этих параметров за четыре цикла солнечной активности возможно только на базе статистического подхода, который используется в данной работе, при этом главным условием успешности сравнения является однородность анализируемых рядов данных. В статье описаны особенности протонной активности Солнца за весь период измерений СПС, начиная с 19-го солнечного цикла и по конец 23-го. Большое внимание уделено методикам привязки солнечных событий в частицах, регистрируемых вблизи Земли, к источникам на Солнце. На данном статистическом материале отмечено, что количество СПС по циклам и распределение их внутри солнечного цикла могут указывать на разный характер генерации СПС в солнечных циклах 20□21-м и в 22□23-м. х профилей.

КОМБИНИРОВАННЫЕ МЕХАНИЗМЫ УСКОРЕНИЯ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ
Лытова М.Ф., Остряков В.М.
Известия РАН, Серия физическая, том 77, № 5, с. 550–552, **2013**.
С использованием метода Монте-Карло в работе промоделированы спектры солнечных космических лучей на поверхности Солнца в области вспышки и у Земли. Одновременно приняты во внимание два важнейших механизма набора энергии частицами: регулярное ускорение ионов импульсным электрическим полем токового слоя и стохастическое ускорение альвеновской турбулентностью. Это приводит к существенным изменениям спектров частиц в области малых энергий.

СОЛНЕЧНАЯ АКТИВНОСТЬ И ВАРИАЦИИ КОСМИЧЕСКИХ ЛУЧЕЙ В СЕНТЯБРЕ 2017 Г
Махмутов В.С., Базилевская Г.А., Стожков Ю.И., Филиппов М.В., Калинин Е.В., Морзабаев А.К., Ерхов В.А., Гиниятова Ш.
Известия РАН Том: 83Номер: 5 Год: **2019** Страницы: 602-605
В работе представлены результаты анализа данных о солнечной активности и о вариациях космических лучей вблизи минимума 24-го цикла солнечной активности в сентябре 2017 г. В этот период зарегистрировано резкое увеличение солнечной вспышечной активности, сопровождавшееся геомагнитными возмущениями, форбуш-понижением интенсивности космических лучей и появлением значительных потоков солнечных космических лучей, зарегистрированных в околоземном космическом пространстве, в земной атмосфере и на наземных установках. Отдельные характеристики указанных событий представлены в данной работе.

Diagnostics of flares and prediction of solar proton event characteristics using the flare radioemission.-
Melnikov V.F.,Podstrigach T.S.,Daibog E.I.,Logachev Yu.I., Stolpovskii V.G.
In: Solar Terrestrial Predictions . US Depart. of Comm., NOAA,Boulder,Co.,**1990**, V.1, P.533-540.

Характер связи потоков электронов и протонов солнечных космических лучей с параметрами микроволновых всплесков.-
Мельников В.Ф., Подстригач Т.С., Дайбог Е.И., Столповский В.Г.
Космич. исслед., **1991**, Т.29, N1, С.95-103.

МАЛЫЕ НАЗЕМНЫЕ ВОЗРАСТАНИЯ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В 24-ОМ ЦИКЛЕ СОЛНЕЧНОЙ АКТИВНОСТИ
Мирошниченко Л.И., Ли Ч., Янке В.Г.

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 58Номер: 3 Год: **2020**, 191-198
https://doi.org/10.31857/S0023420620020090
Представлены первые (предварительные) результаты систематического поиска малых наземных возрастаний солнечных космических лучей (СКЛ) в 24-ом цикле солнечной активности. Поиск проводится по данным мировой сети нейтронных мониторов с учетом результатов прямых спутниковых измерений. Исходное предположение состоит в том, что такие возрастания указывают на возможное ускорение солнечных частиц на ударных волнах, которые генерируются выбросами коронального вещества. Решающим аргументом для проверки гипотезы может служить форма интегрального спектра ускоренных частиц по наблюдениям на нейтронных мониторах и измерениям на околоземных космических аппаратах. Изучение спектров свидетельствуют об информативности нашего подхода для лучшего понимания свойств источников СКЛ.

Солнечные космические лучи: 75 лет исследований. – **Review**
Л.И. **Мирошниченко**.
Успехи физических наук, **2018**, т.188, №4, с.345-376. DOI: 10.3367/UFNr.2017.03.038091.
https://ufn.ru/ru/articles/2018/4/a/
28 февраля 2017 г. исполнилось 75 лет с момента первой уверенной регистрации солнечных космических лучей (СКЛ), т.е. ускоренных солнечных частиц с энергией от 106 эВ до~ 1010—1011 эВ. Суммированы основные данные и обобщены результаты, накопленные за весь период наблюдений и теоретических исследований СКЛ. Кратко описаны история открытия, методы и аппаратура для регистрации СКЛ. Более подробно обсуждаются некоторые физические, методические и прикладные аспекты, связанные с генерацией СКЛ. Особое внимание уделено механизмам ускорения заряженных частиц на Солнце или вблизи него. Приведены современные представления о процессах взаимодействия СКЛ с атмосферой Солнца, особенностях их переноса в межпланетном магнитном поле, о движении в магнитосфере Земли и воздействии на земную атмосферу. Показано, что в этой области космофизики получены фундаментальные результаты, представляющие большой интерес для астрофизики, солнечно-земной физики, геофизики и практической космонавтики.

ЭКСТРЕМАЛЬНЫЕ СОЛНЕЧНЫЕ ВСПЫШКИ ПО АРХИВНЫМ ДАННЫМ О ПРОТОННЫХ СОБЫТИЯХ
Мирошниченко Л.И.
Астрономия-**2018** Том 2 Солнечно-земная физика – современное состояние и перспективы С.144
http://www.izmiran.ru/library/eaas2018/eaas-2018-2.pdf
One of serious challenges to the problem of radiation hazard in space is a lack of a clear, unambiguous relation between the fluxes (fluences) of relativistic SCR and non-relativistic SEPs.
Modern concept of Extreme Solar Event (ESE) is critically analyzed based on available direct/ proxy data on solar cosmic rays (SCR), or solar energetic particles (SEPs). Special attention is paid to recent debate on validity, origin and properties of the events AD1859 (Carrington event) identified by nitrate method and AD775, AD994 and 3372 BC by radionuclide data. In spite of existing uncertainties in proton fluences above 30 MeV, all of them are fitted well by a unique distribution function, at least, with present level of solar activity. Extremely large SEP fluxes (fluences) are shown to obey a probabilistic distribution with a sharp break in the range of large fluences (or low probabilities). The studies of this kind may be extended for the periods with different levels of solar activity in the past and/or in the future. Considering the confirmation of super-flares on Sun-like stars, this issue merits attention.

СОЛНЕЧНЫЕ КОСМИЧЕСКИЕ ЛУЧИ: 70 ЛЕТ НАЗЕМНЫХ НАБЛЮДЕНИЙ **Обзор**
Л. И. **Мирошниченко**1, 2, Э. В. Вашенюк3, Х. А. Перес%Переса4
*ГЕОМАГНЕТИЗМ И АЭРОНОМИЯ, **2013**, том 53, № 5, с. 579–600, **File***
*Geomagnetism and Aeronomy, **2013**, Vol. 53, No. 5, pp. 541–560. **File***
Суммированы основные данные и обобщены результаты, полученные по данным мировой сети станций за весь период наземных наблюдений солнечных космических лучей (СКЛ), начиная с момента их открытия 28 февраля 1942 г. Описаны методы и аппаратура для регистрации СКЛ, обсуждены физические, методические и прикладные аспекты, связанные с генерацией СКЛ, их взаимодействие с атмосферой Солнца, перенос в межпланетном магнитном поле, движение в магнитосфере Земли и воздействие на земную атмосферу. Показано, что в этой области космофизики за 70 лет исследований получены результаты, имеющие фундаментальное значение. Особое внимание уделено современным моделям и концепциям GLE (Ground Level Enhancement). Намечены наиболее перспективные направления развития и применения этого эффективного метода солнечно-земной физики.
Таблица

МОНИТОРИНГ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ НА ВЫСОТАХ ДО 1000 КМ - ДАННЫЕ РОССИЙСКИХ КОСМИЧЕСКИХ ЭКСПЕРИМЕНТОВ. ЭФФЕКТЫ СОЛНЕЧНЫХ ПРОТОНОВ В ОЗОНОСФЕРЕ ЗЕМЛИ

Мягкова И.Н., Криволуцкий А.А.

Геомагн. и аэроном. Том: 57Номер: 6 Год: **2017** Страницы: 724-735

В работе иллюстрируются возможности использования данных российских спутниковых экспериментов (серии КОРОНАС, "Университетский-Татьяна", серии "Метеор") по измерению потоков и спектров солнечных космических лучей на высотах 370-1000 км при моделировании состояния озо-носферы. Приведены результаты фотохимического моделирования и анализа данных наблюдений, показывающие воздействие на полярную озоносферу и нижнюю ионосферу солнечных протонов в периоды солнечных протонных событий (СПС) **4 ноября 2001 г., 28 октября 2003 и 16 января 2005** года. Показано, что воздействие солнечных протонов приводит к разрушению озона в мезо-сфере полярных областей. Наиболее сильное разрушение (до 70%) вызвано СПС 28.10.2003 г.

ЗАРЯДОВЫЕ СОСТОЯНИЯ ТЯЖЕЛЫХ ИОНОВ ПО ДАННЫМ ПАРАМЕТРОВ ЭНЕРГЕТИЧЕСКИХ СПЕКТРОВ СОБЫТИЙ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ

Ныммик Р.А.

Известия РАН, Серия физическая, том 77, № 5, с. 553–556, **2013**.

Определены зарядовые состояния ионов He, C, O и Fe в 51 постепенном событии солнечных космических лучей (СКЛ) 23-го цикла солнечной активности. Применялся метод, основанный на параметрах энергетических спектров частиц, состоящих из двух степенных участков разделенных так называемым коленом. Использовались экспериментальные данные спутников серии GOES (протоны) и приборов ULEIS (все частицы) и SIS (ионы He, C, O и Fe). Установлено, что зарядовые состояния тяжелых ионов не зависят от величины событий СКЛ и энергии частиц (в интервале 0.3–30 МэВ/нуклон).

ИСТОЧНИКИ ЭФФЕКТИВНОГО УСКОРЕНИЯ ЧАСТИЦ В СОЛНЕЧНЫХ ВСПЫШКАХ: НАБЛЮДАТЕЛЬНЫЙ АСПЕКТ

А. Р. Осокин, М. А. Лившиц, А. В. Белов

АСТРОНОМИЧЕСКИЙЖУРНАЛ, **2007**, том 84,№7, с. 642–654; File

Продолжен статистический анализ каталога протонных событий для солнечных космических лучей. Изучены спектры протонных возрастаний, отождествляемые с логарифмом отношения потоков частиц в диапазонах более 100 и 10 МэВ — величиной $\delta = \lg(F100/F10)$ — для 172 мощных событий с благоприятными условиями выхода из короны и распространения частиц в межпланетном пространстве. Распределение числа вспышек по величине δ является гауссовским со сравнительно небольшим разбросом по δ. Его максимум соответствует превышению максимального потока на 10 МэВ над потоком на 100 МэВ в 30 раз. Существование выделенного спектра свидетельствует о том, что как мягкие, так и более жесткие протоны эффективно ускоряются во взрывной фазе вспышки, скорее всего, единым механизмом. Небольшая высота области основного ускорения следует из проведенного изучения размера петель вспышек балла M2-X4, зарегистрированных прибором HXT Yohkoh в диапазоне более 50 кэВ. Существует некоторый избыток более “мягких” событий, выходящих за рамки распределения Гаусса. В этих событиях хорошо выражены постэруптивные явления. Для них величина δ коррелирует с введенной авторами полной длительностью вспышки. Таким образом, в солнечных вспышках существуют два источника ускорения частиц, действующие во взрывной и постэруптивной фазах на малых и больших высотах, соответственно. Во втором из них, непосредственно проявляющемся в некоторых длительных вспышках и явлениях типа выброса волокон, протоны ускоряются только до энергий 10–30 МэВ.

АНАЛИЗ ФАЗ КВАЗИДВУХЛЕТНИХ ВАРИАЦИЙ ПОТОКОВ КОСМИЧЕСКИХ ЛУЧЕЙ, ПАРАМЕТРОВ СОЛНЕЧНОЙ АКТИВНОСТИ И МЕЖПЛАНЕТНОЙ СРЕДЫ

Охлопков В. П.

Косм. Исслед. Том: 60Номер: 5 Год: **2022** 377-383

Исследованы фазы квазидвухлетних вариаций (КДВ) в потоках космических лучей, параметрах солнечной активности и межпланетной среды. Проведен спектральный анализ КДВ перечисленных данных. Для используемых данных выявлены спектральные составляющие с максимальной амплитудой (синусоидальная составляющая с периодом около 1.7 года (около 20.5

месяцев)). Проведено сравнение фаз КДВ с фазами этих синусоид в те временные интервалы, где КДВ однозначно выявлены достоверно. Показано, что по всем данным фазы квазидвухлетних вариаций сохраняются в течение многих десятилетий с незначительными отклонениями. Это свидетельствует о долготной стабильности областей на Солнце, ответственных за квазидвухлетнюю вариацию.

ИЗМЕНЕНИЕ ГЕЛИОДОЛГОТНОЙ ЗАВИСИМОСТИ ПИКОВЫХ ИНТЕНСИВНОСТЕЙ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ С СОЛНЕЧНЫМИ ЦИКЛАМИ

Очелков Ю.П.

Известия РАН   Том: 83Номер: 5 Год: **2019** Страницы: 590-593

На основе изучения двумерных распределений солнечных вспышек по пиковым интенсивностям мягких рентгеновских всплесков и солнечных протонных событий сделан вывод о том, что зависимость от гелиодолготы пиковой интенсивности солнечных протонных событий изменяется с солнечными циклами. Использованы данные КА GOES по рентгеновским всплескам в диапазоне длин волн 0.1–0.8 нм и данные по наблюдениям солнечных протонных событий с пороговыми энергиями 30 МэВ. Было обнаружено, что гелиодолготное ослабление пиковой интенсивности протонных событий в различных циклах может отличаться на порядок величины. В частности, ослабление пиковой интенсивности протонных событий от вспышек в интервале гелиололгот от 0○ до 30○ E относительно пиковых интенсивностей протонных событий от вспышек на западной половине диска равно 30 для 23 цикла солнечной активности и только 3 для 22 цикла. Изменение с циклами гелиодолготной зависимости пиковых интенсивностей солнечных протонных событий следует учитывать во всех статистических исследованиях.

ИНЖЕКЦИЯ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В СОБЫТИИ GLE 15.04.2001

ПЕТУХОВА А.С.1, ПЕТУХОВ И.С.1, ПЕТУХОВ С.И.1

ИЗВЕСТИЯ РОССИЙСКОЙ АКАДЕМИИ НАУК. СЕРИЯ ФИЗИЧЕСКАЯ

Том: 81Номер: 4 Год: **2017** Страницы: 568-570

Рассчитана инжекция СКЛ релятивистских энергий в межпланетное пространство в рамках разработанной модели ускорения частиц ударной волной в солнечной атмосфере. Из сопоставления результатов расчета с инжекцией частиц в событии GLE **15 апреля 2001** (Пасха) следует: 1) уровни турбулентности магнитного поля, образованной альвеновскими волнами, в солнечной атмосфере и межпланетном пространстве значительно различаются. Граница резкого перехода между ними расположена при шести радиусах Солнца; 2) уровни турбулентности за и перед ударным фронтом одинаковы.

ПРОТОННАЯ СОЛНЕЧНАЯ ВСПЫШКА НАД АКТИВНОЙ ОБЛА-СТЬЮ АО12673 НА ОБРАТНОЙ СТОРОНЕ СОЛНЦА

Подгорный1 И.М., Подгорный2 А.И.

Астрономия-**2018** Том 2 Солнечно-земная физика – современное состояние и перспективы С.144

http://www.izmiran.ru/library/eaas2018/eaas-2018-2.pdf

The active region AR12673 is appeared near the solar activity minimum and X8.2 flare on the back side of the Sun is produced. The energy for the flare is stored in the magnetic field of a current sheet and released in the corona above the active area. The flare is accompanied by a stream of solar cosmic rays that arrive to the Earth along the interplanetary magnetic lines with a delay equal to the time of free flight. Proton acceleration occurs in the flare current sheet. A similar mechanism seems to be responsible for galactic cosmic rays generation. **10 Sept 2017**

УСКОРЕНИЕ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ ВО ВСПЫШЕЧНОМ ТОКОВОМ СЛОЕ И ИХ РАСПРОСТРАНЕНИЕ В МЕЖПЛАНЕТНОМ ПРОСТРАНСТВЕ

ПОДГОРНЫЙ А.И.1, ПОДГОРНЫЙ И.М.

АЖ Том: 92Номер: 9 Год: **2015** Страницы: 767

Анализ данных космических аппаратов GOES показал, что быстрая компонента протонов высокой энергии приходит к Земле от вспышки, происшедшей на западной части солнечного диска, с пролетным временем, а запаздывающая компонента начинает регистрироваться через несколько часов. Ускорение всех протонов происходит во вспышке единым механизмом. Частицы быстрой компоненты распространяются вдоль магнитных линий спирали Архимеда, которые связывают вспышку с Землей. Быстрая компонента не регистрируется на Земле от вспышек, происшедших на восточной части солнечного диска. Частицы от таких вспышек не попадают на линию магнитного поля, связывающую вспышку с Землей. Эти частицы достигают Земли, перемещаясь поперек межпланетного магнитного поля. Захваченные магнитным полем частицы переносятся солнечным ветром благодаря вмороженности межпланетного магнитного поля в плазму и диффундируют поперек поля. Длительность запаздывающей компоненты достигает нескольких суток.

ХАРАКТЕРИСТИКИ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ В ПЕРИОДЫ ИНВЕРСИИ МАГНИТНОГО ПОЛЯ СОЛНЦА ЗА ПОСЛЕДНИЕ 6 СОЛНЕЧНЫХ ЦИКЛОВ

ПОДЗОЛКО М. В.[1], **КАЛЕГАЕВ В. В.**[1,2], **УСТИНОВ К. А.**[2]

Изв.РАН Том: 87Номер: 7 Год: **2023** Страницы: 1018-1022

Рассмотрены характеристики солнечных протонных событий в периоды инверсии магнитного поля Солнца в 19–24 циклах солнечной активности. В каждом из этих солнечных циклов найдены интервалы времени длительностью 8–12 месяцев, приходящиеся на время инверсии поля Солнца, во время которых число солнечных событий, суммарный и максимальный флюенс протонов ниже и энергетические спектры мягче, чем в равные по длительности периоды времени до и после этого. В большинстве рассмотренных циклов указанные периоды наступают после максимума цикла или во время локальных “минимумов Гневышева”.

РАСПРЕДЕЛЕНИЕ ФЛЮЕНСОВ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ, ЗАРЕГИСТРИРОВАННЫХ НА ОРБИТЕ ЗЕМЛИ, ПО ГЕЛИОДОЛГОТЕ ИСТОЧНИКОВ

Подзолко М.В.

Известия РАН Том: 83Номер: 5 Год: **2019** Страницы: 594-596

Рассмотрено распределение флюенсов солнечных протонных событий по гелиодолготе источников в 19–24 циклах солнечной активности. Показано, что наибольший вклад в суммарную величину флюенсов протонов с энергиями >30 МэВ, зарегистрированных на орбите Земли за весь период наблюдений, внесен событиями, источники которых находились вблизи центрального видимого меридиана Солнца.

АНАЛИЗ GLE 6 ЯНВАРЯ 2014 Г

СДОБНОВ В.Е.

ИЗВЕСТИЯ РОССИЙСКОЙ АКАДЕМИИ НАУК. СЕРИЯ ФИЗИЧЕСКАЯ

Том: 81Номер: 2 Год: **2017** Страницы: 140-142

По данным наземных наблюдений космических лучей (КЛ) на мировой сети станций и космических аппаратах методом спектрографической глобальной съемки исследованы вариации жесткостного спектра и анизотропии КЛ в период GLE 6 января 2014 г. Приведены жесткостной спектр КЛ, а также относительные изменения интенсивности КЛ с жесткостью 4 ГВ в солнечно-эклиптической геоцентрической системе координат в отдельные периоды исследуемого события. Показано, что ускорение протонов в период этого GLE произошло до жесткости частиц R ~ 2.4 ГВ, а дифференциальные жесткостные спектры КЛ во время рассматриваемого события в диапазоне жесткостей от ~0.3 до ~2.4 ГВ не описываются ни степенной, ни экспоненциальной функцией от жесткости частиц. В момент GLE Земля находилась в петлеобразной структуре ММП.

Анализ солнечных, космо- и геофизических событий в сентябре 2017 г. по комплексным наблюдениям ИКФИА СО РАН

Стародубцев С.А., Баишев Д.Г., Григорьев В.Г., Каримов Р.Р., Козлов В.И., Корсаков А.А., Макаров Г.А., Моисеев А.В.

Солнечно-земная физика Том 5 № 1 , **2019**, С. 17–38

https://naukaru.ru/upload/7fd3f86c299d8e1ce467f949bdfec858/files/c79f704a8899c493197f997a7f1f3fd1.pdf

Приводятся результаты мониторинга космических лучей и геомагнитного поля вдоль 210 магнитного меридиана на территории Якутии в первой половине сентября 2017 г. Сообщается об установлении энергетического спектра наземного возрастания космических лучей 10 сентября J=3027E–1.99exp(–E/729 МэВ). Приводятся результаты прогноза и комплексного анализа магнитной бури 7–9 сентября 2017 г. с Dst=–124 нТл. Заблаговременность прогноза составила около суток. Рассмотрено ее влияние на изменения электрического потенциала и распространение сигналов радиостанций радионавигационной системы РСДН-20 в ОНЧ-диапазоне. Во время магнитной бури 8 сентября 2017 г. с 12 до 20 UT в широком диапазоне периодов наблюдались иррегулярные пульсации от Pi3 до Pi1. При этом они сопровождались вариациями величин естественных потенциалов электротеллурического и геомагнитного полей с коэффициентом корреляции между ними ρ(E, H)=0.5÷0.9. Эффекты магнитной бури проявились в виде повышения затухания и уменьшения фазовой задержки ОНЧ-радиосигналов.

КРИТЕРИИ ДЛЯ ПРЕДСКАЗАНИЯ ПРОТОННЫХ СОБЫТИЙ ПО СОЛНЕЧНЫМ НАБЛЮДЕНИЯМ В РЕАЛЬНОМ ВРЕМЕНИ

Струминский А.Б., Садовский А.М., Григорьева И.Ю.

ГиА Том: 64Номер: 2 Год: 2024 Страницы: 163-174

Обсуждается последовательность преодоления пороговых значений ряда физических характеристик для предсказания протонных событий в реальном времени. Каждая характеристика добавляет новый физический смысл, который уточняет предсказание. Для учета всех характеристик необходимы следующие непрерывные патрульные наблюдения: 1) магнитного поля активной области (всплытие потока) и общего магнитного поля Солнца, которые могут предсказать начало вспышечной активности за несколько дней до основных событий; 2) мягкого рентгеновского излучения в двух каналах для вычисления температуры (T) и меры эмиссии плазмы, которые могут показать преднагрев до T > 10 МК, необходимый для начала ускорения протонов (первые минуты до начала жесткого рентгеновского излучения с энергиями >100 кэВ); 3) жесткого рентгеновского излучения >100 кэВ или микроволнового излучения (>3 ГГц), которые показывают интенсивность и длительность работы ускорителя электронов (единицы и десятки минут до прихода протонов с энергиями >100 МэВ); 4) радиоизлучения на плазменных частотах (<1000 МГц), показывающего развитие вспышечного процесса вверх в корону и ведущего к корональному выбросу массы за несколько минут до начала радиовсплесков II и IV типов (первые десятки минут до появления коронального выброса массы в поле зрения коронографа); 5) направление и скорость распространения корональных выбросов массы, которые определяют условия выхода ускоренных протонов в гелиосферу. Эти этапы солнечных протонных вспышек иллюстрируются наблюдениями протонных событий **2-9 августа 2011** г. Для количественного предсказания времени начала, максимума и величины протонного потока, а также его флюенса необходимо создание статистических регрессионных моделей, основанных на всех перечисленных характеристиках прошедших солнечных протонных событий.

ИСТОЧНИКИ СОЛНЕЧНЫХ ПРОТОНОВ В СОБЫТИЯХ 24-25 ФЕВРАЛЯ И 16-17 ИЮЛЯ 2023 ГОДА

СТРУМИНСКИЙ А.Б.[1], **САДОВСКИЙ А.М.**[1], **ГРИГОРЬЕВА И.Ю.**[2]

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 62Номер: 2 Год: 2024 Страницы: 188-200

С начала января 2021 г. по конец августа 2023 г. монитор радиационной обстановки космического аппарата Спектр-РГ зарегистрировал три возрастания темпа счета, которые превышают вариации фона в ходе цикла солнечной активности и имеют сопоставимую максимальную величину. Эти возрастания связаны с солнечными протонными событиями от вспышек X1.0 **28 октября 2021** г., M6.3 **25 февраля** и M5.7 **17 июля 2023** г. На примере этих событий, а также меньших солнечных протонных событий от вспышек M3.7 24 февраля и M4.0 **16 июля 2023** г. обсуждаются пороговые критерии «протонных» вспышек. В мощных солнечных протонных событиях вклад от солнечных протонов в радиационную дозу может превысить суммарный вклад от галактического космического излучения за достаточно длительный период, поэтому такие солнечные протонные события являются источниками повышенной радиационной опасности и нуждаются в прогнозировании по наблюдениям в реальном времени. Показано, что в этих пяти вспышках были преодолены пороги по трем критериям: температуре плазмы >12 МК (источник мягких рентгеновских лучей), длительности (>5 мин) микроволнового или жесткого рентгеновского излучения (ускорения электронов >100 кэВ), высоте развития вспышечного процесса >60 Мм (радиоизлучение на плазменных частотах <610 МГц). Приход первых солнечных протонов > 100 МэВ на орбиту Земли был ожидаем не ранее 10 мин относительно начала жесткого рентгеновского или микроволнового излучения, т.е. мог быть предсказан заблаговременно. Для исследования взаимосвязи солнечных вспышек и протонных событий использовались данные антисовпадательной защиты спектрометра на ИНТЕГРАЛе (ACS SPI), которая представляет собой эффективный, но не калиброванный детектор жесткого рентгеновского излучения >100 кэВ и протонов >100 МэВ, а также патрульные наблюдения радиоизлучения на фиксированных частотах (Radio Solar Telescope Network). Отмечается, что вспышка X2.2 (N25E64) **17 февраля 2023** г. удовлетворяла всем трем критериям «протонности» и могла стать источником мощного солнечного протонного события вблизи Земли при условии благоприятного расположения на Солнце. Во вспышке M8.6 (N27W29) **28 февраля 2023** г. не был выполнен третий критерий, и она ожидаемо не привела к солнечному протонному событию (развивалась в плазме с плотностью $>2.5\text{-}10^{10}$ $см^{-3}$, плазменная частота >1415 МГц).

СОЛНЕЧНЫЕ РЕЛЯТИВИСТСКИЕ ЭЛЕКТРОНЫ И ПРОТОНЫ 28 ОКТЯБРЯ 2021 ГОДА (GLE 73)

СТРУМИНСКИЙ А. Б.[1], **ГРИГОРЬЕВА И. Ю.**[2], **ЛОГАЧЕВ Ю. И.**[3], **САДОВСКИЙ А. М.**[1]

Изв. РАН Том: 87Номер: 7 Год: **2023** Страницы: 1023-1027

Рассматривается протонное событие **28 октября 2021** года, сопровождавшееся первым в текущем 25 цикле (73 в истории наблюдений) наземным возрастанием интенсивности космических лучей (GLE73). Период развития родительской вспышки с наибольшим энерговыделением длился более 10 мин, в процессе которого происходили: ускорение коронального выброса массы и, одновременно, ускорение заряженных частиц до релятивистских энергий. Подобие временных профилей интенсивности релятивистских электронов и протонов на орбите Земли, свидетельствует о стохастическом механизме их ускорения. Эруптивная вспышка X1.0 28 октября 2021 года в жестком рентгеновском излучении (>100 кэВ) по временным характеристикам подобна вспышке M5.1 **17 мая 2012** г. с координатами N11W76 (GLE71). Относительно позднее начало возрастания потоков релятивистских электронов и протонов на орбите Земли в событии GLE73 по сравнению с событием GLE71 объясняется расположением вспышки 28 октября 2021 г. (S26W05) и вылетом коронального выброса массы в южном направлении.

СОЛНЕЧНЫЕ ПРОТОННЫЕ СОБЫТИЯ 6 И 10 СЕНТЯБРЯ 2017 Г.: МОМЕНТ ПЕРВОГО ПРИХОДА ПРОТОНОВ И ЭЛЕКТРОНОВ

Струминский А.Б.

Известия РАН Том: 83Номер: 5 Год: **2019** Страницы: 597-601

Солнечные протонные события 6 и 10 сентября 2017 г. исследуются методами, разработанными автором ранее. Сравниваются результаты, полученные для событий **27 января и 17 мая 2012 г., 6 и 10 сентября 2017** г. Начало радиоизлучения на 15.4 ГГц в каждом событии принято за ноль времени. Относительно

нулевого момента времени рассматриваются временные профили интенсивности протонов GOES, электронов SOHO EPHIN и темпа счета антисовпадательной защиты спектрометра на ИНТЕГРАЛе (ACS SPI). Детектор ACS SPI используется как детектор жесткого рентгеновского излучения, так и релятивистских протонов. В событии 6 и 10 сентября 2017 г. были зарегистрированы электроны без протонов, ускоренные в импульсной (первой) фазе солнечной вспышки. Также во всех рассмотренных событиях протоны и электроны регистрировались практически одновременно; по всей видимости, они были ускорены во второй фазе солнечных вспышек и позднее.

ПРЕДЕЛЬНЫЙ СПЕКТР СОЛНЕЧНЫХ/ЗВЕЗДНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ

Струминский А.Б.

Пулково *«Солнечная и солнечно-земная физика – **2015**», с.343*

A physical approach is proposed to estimate an ultimate spectrum of solar/stellar cosmic rays (SCR) in a given point in the heliosphere (stellar sphere) basing on characteristic values of magnetic field intensity and dimensions of active region. An accelerator of given linear dimensions and magnetic field intensity may accelerate charge particles up to some maximal energy during a finite time. The spectrum proposed by Syrovatsky (1961) for relativistic and non-relativistic SCR is used as a source spectrum. The spectrum is normalized to the galactic CR intensity at the maximal SCR energy. Maximal fluxes of SCR propagating in the heliosphere are determined by pressure equilibrium of magnetic field and CR (Freier& Webber, 1963). Characteristic times of fluence accumulation for diffusive and convective propagation of SCR obtained from observations of most powerful solar proton events are used for estimates of ultimate SCR fluencies. The ultimate fluence of >30 MeV protons for a single event is in agreement with observational upper limits of ordinary events. In order to explain the 775 AD event a sequence of two single events are necessary. An application of the model to cases of stellar flares is discussed.

О СВЯЗИ СОЛНЕЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ С РАДИОВСПЛЕСКАМИ II ТИПА

Цап Ю.Т. 1 , Исаева Е.А.2

Сборник трудов XXVI Всероссийской ежегодной конференции по физике Солнца «Солнце и солнечно-земная физика – 2022» ГАО РАН.

http://www.gaoran.ru/russian/solphys/2022/book/conf2022.pdf

Based on the solar energetic particle intensities Ip with energy Ep>1 MeV obtained with the GOES satellites and the dynamic spectra of radio emission of type II radio bursts in the range of 25–180 MHz observed with Solar Radio Spectrograph, we analyze 112 proton events for the period from 24 November 2000 to 20 December 2014. The correlation between the intensity of Type II radio bursts Ii and Ip with the Pirson correlation coefficient of about 0.81 was revealed. The correlation coefficient between Ip and Ii reaches the maximum for protons with energy Ep = 30–100 MeV and it decreases at Ep >100 MeV. This supports the idea that the non-thermal electrons responsible for type II radio bursts and solar energetic particles are generated by the same shock. The energy of relativistic particles with Ep >100 MeV should be determined by acceleration processes in the region of flare energy release.

О СООТНОШЕНИИ СПЕКТРОВ МИКРОВОЛНОВЫХ ВСПЛЕСКОВ НА СОЛНЦЕ И ПОТОКОВ ПРОТОНОВ У ЗЕМЛИ

И. М. **Черток**1, В. В. Гречнев2, Н. С. Мешалкина2

*АСТРОНОМИЧЕСКИЙЖУРНАЛ, **2009**, том 86,№11, с. 1133–1144*

Анализ экстремального солнечного протонного события 20.01.2005 обострил дискуссию по давно обсуждаемой проблеме: ускоряются ли приходящие к Земле солнечные космические лучи во вспышке или в ударной волне перед быстро распространяющимся корональным выбросом? При этом одним из важных является вопрос о связи между энергетическим спектром солнечных космических лучей и параметрами, характеризующими частотный спектр вспышечных микроволновых всплесков. В ряде работ по материалам предшествующих циклов солнечной активности было показано, что такая связь существует, в частности, для протонов с энергией десятки МэВ. В данной работе представлены результаты анализа этой связи по данным 1987–2008 гг. Установлено, что для событий, связанных со вспышками на западной половине диска, имеет место существенная корреляция между индексом δ, эквивалентным показателю степенного интегрального энергетического спектра протонов, зарегистрированных у орбиты Земли в диапазоне 10–100 МэВ, и такими параметрами радиовсплесков, как отношение пиковых потоков S на двух частотах (например, 9 и 15 ГГц) и частота спектрального максимума *fm*. Микроволновым всплескам с жестким частотным спектром (у которых $S9/S15 \le 1$, $fm \ge 15$ ГГц) соответствуют потоки протонов с жестким (пологим) энергетическим спектром ($\delta \le 1.5$). Вспышки же с мягким радиоспектром ($S9/S15 \ge 1.5$, $fm \le 5$ ГГц) наоборот приводят к потокам протонов с мягким (крутым) энергетическим спектром ($\delta \ge 1.5-2$). Показано также, что мощные высокочастотные всплески с наиболее жестким радиоспектром ($fm \approx 30$ ГГц) могут служить информативным индикатором ускорения значительных потоков протонов во вспышках, происходящих в сильных магнитных полях. Эти результаты являются важным аргументом в пользу предположения, что частицы солнечных космических лучей (по крайней мере, их начального импульса) в основном ускоряются во вспышке в процессах импульсного и постэруптивного энерговыделения, а не в ударной волне на фронте коронального выброса.

See file **2016**: **Nunez** M. A preliminary assessment of the failed and successful predictions of proton spectral hardness using microwave emission

See also: However, this hypothesis was recently tested and its applicability is under debate.6 https://www.hesperia.astro.noa.gr/WP2/Hesperia_task_2-2.pdf.

Шаховская А.Н., Григорьева И.Ю. **Исследование событий, предшествующих вспышкам, связанным протонными событиями, 20.01.2005, 13.12.2006, 17.05.2012 и 10.09.2017**, в мягком рентгене и радиоизлучении …

Сборник трудов XXVI Всероссийской ежегодной конференции по физике Солнца «Солнце и солнечно-земная физика – 2022» ГАО РАН.

http://www.gaoran.ru/russian/solphys/2022/book/conf2022.pdf

ОБ ОСТАТОЧНОЙ МОДУЛЯЦИИ ГАЛАКТИЧЕСКИХ КОСМИЧЕСКИХ ЛУЧЕЙ В ГЕЛИОСФЕРЕ

Янке В.Г., Белов А.В., Гущина Р.Т., Кобелев П.Г., Трефилова Л.А.

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ Том: 61Номер: 1 Год: 2023 Страницы: 43-51

Исследована остаточная модуляция галактических космических лучей и ее энергетическая зависимость по данным трех типов наземных детекторов и по данным PAMELA, AMS-02 и Voyager 1/2. Получены количественные оценки остаточной модуляции в диапазоне жесткостей 4–41 ГВ. Показано, что остаточная модуляция примерно такая же по величине, как и модуляция, обусловленная циклом солнечной активности, что позволяет сделать некоторые выводы о модуляционных процессах в гелиосфере. Получен энергетический спектр остаточной модуляции. Проведено сравнение с результатами других авторов.