Hard X-rays and Gamma-rays

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Origin of High-Energy Protons Responsible for Late-Phase Pion-Decay Gamma-Ray Continuum from the Sun

ISEE, Nagoya University, Japan
October 16-20, 2023

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About **Solar Physics is open for submissions on a Topical Collection entitled "Sustained Gamma Ray Emission from the Sun."** see email on 10 Aug 2024

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**

Introduction is a good Review

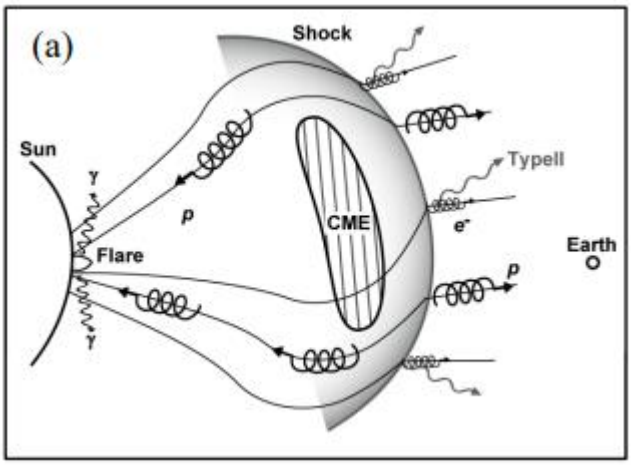
On the Shock Source of Sustained Gamma-Ray Emission from the Sun

N **Gopalswamy**, P. Makela, S. Yashiro, A. Lara, S. Akiyama, H. Xie

Journal of Physics: Conference Series, Volume 1332, Issue 1, article id. 012004 . **2019**

https://arxiv.org/ftp/arxiv/papers/1907/1907.13318.pdf **File**

https://iopscience.iop.org/article/10.1088/1742-6596/1332/1/012004/pdf



Ioffe Institute. Laboratory for Experimental Astrophysics

KW-Sun: Konus-Wind Solar Flare Database (1994-2017)

Solar Flare Database – All Data Are On-line Now

http://www.ioffe.ru/LEA/kwsun/

High-Energy Aspects of Solar Flares: A RHESSI-inspired monograph

Спец выпуск **Space Science Reviews**, Volume 159, Numbers 1-4, September **2011**
http://www.springerlink.com/content/0038-6308/159/1-4/

Overview of the Volume **A Review**
B. R. **Dennis**1, A. G. Emslie2, and H. S. Hudso
Space Sci. Rev., 159:3–17, **2011, File**

An Observational Overview of Solar Flares **A Review**
L. **Fletcher**1, B. R. Dennis2, H. S. Hudson3, S. Krucker3, K. Phillips4, A. Veronig5, M. Battaglia1, L. Bone4, A. Caspi3, Q. Chen7 , P. Gallagher8, P. T. Grigis9, · H. Ji10,11, W. Liu2,12, R. O. Milligan2, and M. Temmer5,13,14
Space Sci. Rev., 159:19–106, **2011, File**

Implications of X-ray Observations for Electron Acceleration and Propagation in Solar Flares
G.D. **Holman**1, M. J. Aschwanden2, H. Aurass3, M. Battaglia4, P. C. Grigis5, E. P. Kontar6, W. Liu1, P. Saint-Hilaire7, and V. V. Zharkova8
Space Sci. Rev., 159:107–166, **2011, File** A Review

Properties of Energetic Ions in the Solar Atmosphere from γ-Ray and Neutron Observations
N. **Vilmer**, A. L. MacKinnon and G. J. Hurford
Space Sci. Rev., 159:167– 224, **2011, File** A Review

The Relationship Between Solar Radio and Hard X-ray Emission **A Review**
S. M. **White**1,5, A. O. Benz2, S. Christe3, F. F´arn´ık4, M. R. Kundu5, G. Mann6, Z. Ning7, J.-P. Raulin8, A. V. R. Silva-V´alio8, P. Saint-Hilaire9, N. Vilmer10, and A.Warmuth6
Space Sci. Rev., 159:225–261, **2011, File**

Microflares and the Statistics of X-ray Flares **A Review**
I. G. **Hannah**, H. S. Hudson, M. Battaglia, S. Christe, J. Kašparová, S. Krucker, M. R. Kundu and A. Veronig
Space Sci Rev (**2011**) 159:263–300, **File**

Deducing Electron Properties from Hard X-ray Observations **A Review**
E. P. **Kontar**, J. C. Brown, A. G. Emslie, W. Hajdas, G. D. Holman, G. J. Hurford, J. Kašparová, P. C. V. Mallik, A. M. Massone and M. L. McConnell, et al.
Space Sci Rev (**2011**) 159:301–355, **File**

Recent Advances in Understanding Particle Acceleration Processes in Solar Flares
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**

Energy Release and Particle Acceleration in Flares: Summary and Future Prospects
R.P. **Lin**
Space Sci Rev (**2011**) 159:421–445, **File** **A Review**

Search for GeV Neutrino Emission During Intense Gamma-Ray Solar Flares with the IceCube Neutrino Observatory

R. **Abbasi**, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, ……..
2021
https://arxiv.org/pdf/2101.00610.pdf
Solar flares convert magnetic energy into thermal and non-thermal plasma energy, the latter implying particle acceleration of charged particles such as protons. Protons are injected out of the coronal acceleration region and can interact with dense plasma in the lower solar atmosphere, producing mesons that subsequently decay into gamma rays and neutrinos at O(MeV-GeV) energies. We present the results of the first search for GeV neutrinos emitted during solar flares carried out with the IceCube Neutrino Observatory. While the experiment was originally

designed to detect neutrinos with energies between 10 GeV and a few PeV, a new approach allowing for a O(GeV) energy threshold will be presented. The resulting limits allow us to constrain some of the theoretical estimates of the expected neutrino flux. **March 7th, 2012, February 25th, 2014, September 1st, 2014, September 6th, 2017, September 10th, 2017**

FERMI LARGE AREA TELESCOPE OBSERVATIONS OF TWO GAMMA-RAY EMISSION COMPONENTS FROM THE QUIESCENT SUN

A.A. **Abdo**1,50, M. Ackermann2, M. Ajello2, et al.
2011 ApJ 734 116
https://arxiv.org/pdf/1104.2093.pdf
http://sci-hub.tw/10.1088/0004-637X/734/2/116
We report the detection of high-energy γ-rays from the quiescent Sun with the Large Area Telescope on board the Fermi Gamma-Ray Space Telescope (Fermi) during the first 18 months of the mission. These observations correspond to the recent period of low solar activity when the emission induced by cosmic rays (CRs) is brightest. For the first time, the high statistical significance of the observations allows clear separation of the two components: the point-like emission from the solar disk due to CR cascades in the solar atmosphere and extended emission from the inverse Compton (IC) scattering of CR electrons on solar photons in the heliosphere. The observed integral flux (≥100 MeV) from the solar disk is (4.6 ± 0.2[statistical error]+1.0 – 0.8[systematic error]) × 10–7 cm–2 s–1, which is ~7 times higher than predicted by the "nominal" model of Seckel et al. In contrast, the observed integral flux (≥100 MeV) of the extended emission from a region of 20° radius centered on the Sun, but excluding the disk itself, (6.8 ± 0.7[stat.]+0.5 – 0.4[syst.]) × 10–7 cm–2 s–1, along with the observed spectrum and the angular profile, is in good agreement with the theoretical predictions for the IC emission.

Search for Solar Flare Neutrinos with the KamLAND detector

S. **Abe**, S. Asami, A. Gando, Y. Gando, T. Gima, A. Goto, ….
ApJ **2021**
https://arxiv.org/pdf/2105.02458.pdf
We report the result of a search for neutrinos in coincidence with solar flares from the GOES flare database. The search was performed on a 10.8 kton-year exposure of KamLAND collected from 2002 to 2019. We found no statistical excess of neutrinos and established 90\% confidence level upper limits of 8.4×107\,cm−2 (3.0×109\,cm−2) on electron anti-neutrino (electron neutrino) fluence at 20\,MeV normalized to the X12 flare, assuming that the neutrino fluence is proportional to the X-ray intensity. The 90\% C.L. upper limits from this work exclude the entire region of parameter space associated with the Homestake event excess for the large solar flare in 1991. **2004 Feb 26**

Fermi-LAT Observations of High-energy Behind-the-limb Solar Flares

M. **Ackermann**1, A. Allafort2, L. Baldini3, G. Barbiellini4,5, D. Bastieri6,7, R. Bellazzini8, E. Bissaldi9, R. Bonino10,11, E. Bottacini2, J. Bregeon12Show full author list
2017 ApJ 835 219
https://sci-hub.do/10.3847/1538-4357/835/2/219
https://arxiv.org/pdf/1702.00641v1.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/835/2/219/pdf
We report on the Fermi-LAT detection of high-energy emission from the behind-the-limb (BTL) solar flares that occurred on **2013 October 11, and 2014 January 6 and September 1**. The Fermi-LAT observations are associated with flares from active regions originating behind both the eastern and western limbs, as determined by STEREO. All three flares are associated with very fast coronal mass ejections (CMEs) and strong solar energetic particle events. We present updated localizations of the >100 MeV photon emission, hard X-ray (HXR) and EUV images, and broadband spectra from 10 keV to 10 GeV, as well as microwave spectra. We also provide a comparison of the BTL flares detected by Fermi-LAT with three on-disk flares and present a study of some of the significant quantities of these flares as an attempt to better understand the acceleration mechanisms at work during these occulted flares. We interpret the HXR emission to be due to electron bremsstrahlung from a coronal thin-target loop top with the accelerated electron spectra steepening at semirelativistic energies. The >100 MeV gamma-rays are best described by a pion-decay model resulting from the interaction of protons (and other ions) in a thick-target photospheric source. ***The protons are believed to have been accelerated (to energies >10 GeV) in the CME environment and precipitate down to the photosphere from the downstream side of the CME shock and landed on the front side of the Sun, away from the original flare site and the HXR emission.***

HIGH-ENERGY GAMMA-RAY EMISSION FROM SOLAR FLARES: SUMMARY OF FERMI LAT DETECTIONS AND ANALYSIS OF TWO M-CLASS FLARES

M. **Ackermann**2, M. Ajello3, A. Albert4, A. Allafort5,1, L. Baldini6, G. Barbiellini7,8, D. Bastieri et al.
Fermi-LAT collaboration
E-print, April **2013, File**; **2014** ApJ 787 15
https://iopscience.iop.org/article/10.1088/0004-637X/787/1/15/pdf
We present the detections of 19 solar flares detected in high-energy gamma rays (above 100 MeV) with the Fermi Large Area Telescope (LAT) during its first four years of operation. Interestingly, all flares are associated with fairly fast Coronal Mass Ejections (CMEs) and are not all powerful X-ray flares. We then describe the detailed temporal, spatial and spectral characteristics of the first two long-lasting events: the **2011 March 7** flare, a moderate (M3.7) impulsive flare followed by slowly varying gamma-ray emission over 13 hours, and the **2011 June 7** M2.5 flare, which was followed by gamma-ray emission lasting for 2 hours. We compare the Fermi-LAT data with X-ray and proton data measurements from GOES and RHESSI. We argue that a hadronic origin of the gamma rays is more likely than a leptonic origin and find that the energy spectrum of the proton distribution softens after the 2011 March 7 flare, favoring a scenario with continuous acceleration at the flare site. This work suggests that proton acceleration in solar flares is more common than previously thought, occurring for even modest X-ray flares, and for longer durations.

Fermi Detection of gamma-ray emission from the M2 Soft X-ray Flare on 2010 June 12

M. **Ackermann**2, M. Ajello3, A. Allafort3, W. B. Atwood4, L. Baldini5, G. Barbiellini
E-print, Dec 2011, File; ApJ, **2012**, 745..144A
The GOES M2-class solar flare, SOL2010-06-12T00:57, was modest in many respects yet exhibited remarkable acceleration of energetic particles. The flare produced an ~50 s impulsive burst of hard X- and gamma-ray emission up to at least 400 MeV observed by the Fermi GBM and LAT experiments. The remarkably similar hard X-ray and high-energy gamma-ray time profiles suggest that most of the particles were accelerated to energies greater or approximately equal to 300 MeV with a delay of ~10 s from mildly relativistic electrons, but some reached these energies in as little as ~3 s. The gamma-ray line fluence from this flare was about ten times higher than that typically observed from this modest GOES class of X-ray flare. There is no evidence for time-extended >100 MeV emission as has been found for other flares with high-energy gamma rays.
Erratum: 2012ApJ...748..151A http://sci-hub.tw/10.1088/0004-637X/748/2/151

Modelling of Shock-Accelerated Gamma-Ray Events **Review**

Alexandr **Afanasiev**, Angels Aran, Rami Vainio, Alexis Rouillard, Pietro Zucca, David Lario, Suvi Barcewicz, Robert Siipola, Jens Pomoell, Blai Sanahuja, and Olga E. Malandraki
In: O.E. Malandraki, N.B. Crosby (eds.), Solar Particle Radiation Storms Forecasting and Analysis
Chapter 9, **2018**, p. 157–177
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
Solar -ray events recently detected by the Fermi/LAT instrument at energies above 100 MeV have presented a puzzle for solar physicists as many of such events were observed lasting for many hours after the associated flare/coronal mass ejection (CME) eruption. Data analyses suggest the -ray emission originate from decay of pions produced mainly by interactions of high-energy protons deep in the chromosphere. Whether those protons are accelerated in the associated flare or in the CME-driven shock has been under active discussion. In this chapter, we present some modelling efforts aimed at testing the shock acceleration hypothesis **2012 January 23, 2012 May 17**

Comprehensive measurement of pp-chain solar neutrinos

Matteo **Agostini**, K. Altenmüller, S. Appel, Show all 108 authors, G. Zuzel
October **2018**, Nature 562(7728):505-510
DOI: 10.1038/s41586-018-0624-y
About 99 per cent of solar energy is produced through sequences of nuclear reactions that convert hydrogen into helium, starting from the fusion of two protons (the pp chain). The neutrinos emitted by five of these reactions represent a unique probe of the Sun's internal working and, at the same time, offer an intense natural neutrino beam for fundamental physics. Here we report a complete study of the pp chain. We measure the neutrino–electron elastic-scattering rates for neutrinos produced by four reactions of the chain: the initial proton–proton fusion, the electron-capture decay of beryllium-7, the three-body proton–electron–proton (pep) fusion, here measured with the highest precision so far achieved, and the boron-8 beta decay, measured with the lowest energy threshold. We also set a limit on the neutrino flux produced by the ^{3}He–proton fusion (hep). These measurements provide a direct determination of the relative intensity of the two primary terminations of the pp chain (pp-I and pp-II) and an indication that the temperature profile in the Sun is more compatible with solar models that assume high surface metallicity. We also determine the survival probability of solar electron neutrinos at different energies, thus probing

simultaneously and with high precision the neutrino flavour-conversion paradigm, both in vacuum and in matter-dominated regimes.

Improved measurement of 8B solar neutrinos with 1.5 kt y of Borexino exposure

The Borexino Collaboration: M. **Agostini**, K. Altenmueller, S. Appel, ….

2017

https://arxiv.org/pdf/1709.00756.pdf

We report on an improved measurement of the 8B solar neutrino interaction rate with the Borexino detector at the Laboratori Nazionali del Gran Sasso. Neutrinos are detected via their elastic scattering on electrons in a large, radio-pure liquid scintillator target. Novel analysis approaches exploiting most of the active volume of the detector have enabled the collection of data from 1.5 kt·y exposure between 2008 and 2016. The measured rate of solar neutrino-induced, scattered electrons above 3 MeV of energy is 0.220+0.015−0.016(stat)+0.006−0.006(syst)~cpd/100~t, which corresponds to an observed solar neutrino flux assuming no neutrino flavor conversion of 2.55+0.17−0.19(stat)+0.07−0.07(syst)×106~cm−2s−1. If one assumes the 8B solar neutrino flux predicted by the high metallicity Standard Solar Model, the average 8B solar ve survival probability is 0.36±0.08 at the mean visible energy of 7.9~MeV, in good agreement with the MSW-LMA

ON THE NEAR-EARTH OBSERVATION OF PROTONS AND ELECTRONS FROM THE DECAY OF LOW-ENERGY SOLAR FLARE NEUTRONS

Neus **Agueda**1,2, Säm Krucker1,3, Robert P. Lin1,4 and Linghua Wang

2011 ApJ 737 53

We investigate the near-Earth observation of interplanetary protons and electrons that result from the in-flight beta decay of low-energy (1-10 MeV) solar neutrons. We use in situ measurements throughout solar cycle 23 of 1-11 MeV protons and 50-400 keV electrons by the 3DP experiment on board the Wind spacecraft. We select a sample of isolated large (X-class) eastern hemisphere flares occurring during quiescent interplanetary conditions with the goal of discriminating neutron-decay particles from primary solar energetic particles. Unfortunately, all major flares of solar cycle 23 have to be excluded, with the largest flare in our sample being a X3.6 flare. For these relatively small event sizes, no in situ events due to the decay of solar flare neutrons are observed by Wind. From the one event with simultaneous γ-ray observations, we estimate the expected signal of neutron-decay protons in the Wind/3DP detectors. We use theoretical calculations of the spectrum of escaping neutrons at the Sun combined with an interplanetary propagation model to predict the neutron-decay proton spectrum expected near the Earth. We find that the expected spectrum is indeed well below the background intensities. However, using the estimates derived from the largest solar event of cycle 23 (**2003 October 28**) and assuming the flare would have occurred isolated in the eastern hemisphere, a clear signal above 5 MeV is expected to be seen.

Fermi Large Area Telescope Performance after 10 Years of Operation

M. **Ajello**1, W. B. Atwood2, M. Axelsson3,4, R. Bagagli75,5, M. Bagni75,5, L. Baldini5, D. Bastieri6,7, F. Bellardi75,5, R. Bellazzini8, E. Bissaldi9,10 Show full author list

2021 ApJS 256 12

https://doi.org/10.3847/1538-4365/ac0ceb

The Large Area Telescope (LAT), the primary instrument for the Fermi Gamma-ray Space Telescope (Fermi) mission, is an imaging, wide field-of-view, high-energy gamma-ray telescope, covering the energy range from 30 MeV to more than 300 GeV. We describe the performance of the instrument at the 10 yr milestone. LAT performance remains well within the specifications defined during the planning phase, validating the design choices and supporting the compelling case to extend the duration of the Fermi mission. The details provided here will be useful when designing the next generation of high-energy gamma-ray observatories.

First Fermi-LAT Solar are catalog Appendix

M. **Ajello**,1 L. Baldini,2 D. Bastieri,3, 4 R. Bellazzini,5 A. Berretta,6 E. Bissaldi,7, 8 et al.

To ApJSup. **252**, 13, **2021**

doi: 10.3847/1538-4365/abd32e

https://zenodo.org/record/4320856#.YTfQpC1h3UI **File**

We present the appendix of the first Fermi-Large Area Telescope (LAT) Solar are catalog covering the 24th Solar cycle. The catalog (published in ApJS) contains 45Fermi-LAT Solar ares (FLSFs) with emission in the -ray energy band (30 MeV - 10 GeV) detected with a significance >5_ over the years 2010-2018. A subsample containing 37 of these ares exhibit delayed emission beyond the prompt-impulsive hard X-ray phase with 21 ares showing delayed emission lasting more than two hours. No prompt-impulsive emission is detected in four of these ares. We also report the first time observations of GeV emission from 3 ares originating from Active Regions located behind the limb (BTL) of the visible Solar disk. We report the light curves, spectra, best proton index and localization (when

possible) for all the FLSFs and correlations with Solar multi-wavelength phenomena. The -ray spectra is consistent with the decay of pions produced by >300 MeV protons. The work presented in the First Fermi Solar Flare Catalog contains the largest sample of high-energy gamma-ray ares ever reported and provides the unique opportunity to perform population/correlation studies on the different phases of the are and thus allowing to open a new window in solar physics.

First Fermi-LAT Solar Flare Catalog

M. **Ajello**1, L. Baldini2, D. Bastieri3,4, R. Bellazzini5, A. Berretta6, E. Bissaldi7,8, R. D. Blandford9, R. Bonino10,11, P. Bruel12, S. Buson13Show full author list
2021 ApJS **252** 13
https://arxiv.org/pdf/2101.10010.pdf **File**
https://doi.org/10.3847/1538-4365/abd32e
https://iopscience.iop.org/article/10.3847/1538-4365/abd32e/pdf
We present the first Fermi-Large Area Telescope (LAT) solar flare catalog covering the 24th solar cycle. This catalog contains 45 Fermi-LAT solar flares (FLSFs) with emission in the γ-ray energy band (30 MeV–10 GeV) detected with a significance of ≥5σ over the years 2010–2018. A subsample containing 37 of these flares exhibits delayed emission beyond the prompt-impulsive hard X-ray phase, with 21 flares showing delayed emission lasting more than two hours. No prompt-impulsive emission is detected in four of these flares. We also present in this catalog observations of GeV emission from three flares originating from active regions located behind the limb of the visible solar disk. We report the lightcurves, spectra, best proton index, and localization (when possible) for all FLSFs. The γ-ray spectra are consistent with the decay of pions produced by >300 MeV protons. This work contains the largest sample of high-energy γ-ray flares ever reported and provides a unique opportunity to perform population studies on the different phases of the flare and thus allowing a new window in solar physics to be opened. **2011-09-06, 2012-03-07, 2012-03-09, 2013-05-15, 2013-10-28, 2014-02-25, 2014-09-01, 2017-09-10**
Table 1: FLSF catalog for flares detected with the Fermi-LAT SunMonitor and their likely GOES X-ray flare associations.
Table 2:: Maximum likelihood results for each SunMonitor observing time window associated with a solar flare detected by the Fermi-LAT. S
Table 3: LLE FLSF catalog results with associated GOES X-ray flare.
Table 4:: Multi-wavelength associations for all the FLSF in this work.
Table 5: List of FLSFs from similar Active Regions
Table 7: X-class GOES flares not associated with any γ-ray emission above 30 MeV.
Erratum: ApJS **256:**24, **2021** https://iopscience.iop.org/article/10.3847/1538-4365/ac2155/pdf
In the published article, several references were accidentally left out of the text. The papers that we would like to cite are the following:

IMPULSIVE AND LONG DURATION HIGH-ENERGY GAMMA-RAY EMISSION FROM THE VERY BRIGHT 2012 MARCH 7 SOLAR FLARES

M. **Ajello**1, A. Albert2, A. Allafort2, L. Baldini3, G. Barbiellini4,5, D. Bastieri6,7, R. et. al
Astrophysical Journal, 789:20 (15pp), **2014**
https://iopscience.iop.org/article/10.1088/0004-637X/789/1/20/pdf
The Fermi Large Area Telescope (LAT) detected gamma-rays up to 4 GeV from two bright X-class solar flares on **2012 March 7**, showing both an impulsive and temporally extended emission phases. The gamma-rays appear to originate from the same active region as the X-rays associated with these flares. The >100 MeV gamma-ray flux decreases monotonically during the first hour (impulsive phase) followed by a slower decrease for the next 20 hr. A power law with a high-energy exponential cutoff can adequately describe the photon spectrum. Assuming that the gamma rays result from the decay of pions produced by accelerated protons and ions with a power-law spectrum, we find that the index of that spectrum is ~3, with minor variations during the impulsive phase. During the extended phase the photon spectrum softens monotonically, requiring the proton index varying from ~4 to >5. The >30 MeV proton flux observed by the GOES satellites also shows a flux decrease and spectral softening, but with a harder spectrum (index ~2-3). Based on these observations, we explore the relative merits of prompt or continuous acceleration scenarios, hadronic or leptonic emission processes, and acceleration at the solar corona or by the fast coronal mass ejections. We conclude that the most likely scenario is continuous acceleration of protons in the solar corona that penetrate the lower solar atmosphere and produce pions that decay into gamma rays. However, acceleration in the downstream of the shock cannot be definitely ruled out.

Impulsive and Long Duration High-energy Gamma-Ray Emission from the Very Bright 2012 March 7 Solar Flares

M. **Ajello**1, A. Albert2, A. Allafort2,

E-print, April **2013, File**; **2014** ApJ 789 20
The Fermi Large Area Telescope (LAT) detected gamma-rays up to 4 GeV from two bright X-class solar flares on 2012 March 7, showing both an impulsive and temporally extended emission phases. The gamma-rays appear to originate from the same active region as the X-rays associated with these flares. The >100 MeV gamma-ray flux decreases monotonically during the first hour (impulsive phase) followed by a slower decrease for the next 20 hr. A power law with a high-energy exponential cutoff can adequately describe the photon spectrum. Assuming that the gamma rays result from the decay of pions produced by accelerated protons and ions with a power-law spectrum, we find that the index of that spectrum is ~3, with minor variations during the impulsive phase. During the extended phase the photon spectrum softens monotonically, requiring the proton index varying from ~4 to >5. The >30 MeV proton flux observed by the GOES satellites also shows a flux decrease and spectral softening, but with a harder spectrum (index ~2-3). Based on these observations, we explore the relative merits of prompt or continuous acceleration scenarios, hadronic or leptonic emission processes, and acceleration at the solar corona or by the fast coronal mass ejections. **We conclude that the most likely scenario is continuous acceleration of protons in the solar corona that penetrate the lower solar atmosphere and produce pions that decay into gamma rays. However, acceleration in the downstream of the shock cannot be definitely ruled out.**

Evidence for prolonged acceleration based on a detailed analysis of the long-duration solar gamma-ray flare of June 15, 1991

Akimov, V. V.; Ambrož, P.; Belov, A. V.; Berlicki, A.; Chertok, I. M.; Karlický, M.; Kurt, V. G.; Leikov, N. G.; Litvinenko, Yu. E.; Magun, A.; and 3 coauthors
Solar Physics, Volume 166, Issue 1, pp.107-134, **1996**
https://link.springer.com/content/pdf/10.1007%2FBF00179358.pdf
Gamma-ray emission extending to energies greater than 2 GeV and lasting at least for two hours as well as 0.8 8.1 MeV nuclear line emission lasting 40 min were observed with very sensitive telescopes aboard the GAMMA and CGRO satellites for the well-developed post-flare loop formation phase of the 3B/X12 flare on June 15, 1991. We undertook an analysis of optical, radio, cosmic-ray, and other data in order to identify the origin of the energetic particles producing these unusual gamma-ray emissions. The analysis yields evidence that the gamma-rays and other emissions, observed well after the impulsive phase of the flare, appear to be initiated by prolonged nonstationary particle acceleration directly during the late phase of the flare rather than by a long-term trapping of energetic electrons and protons accelerated at the onset of the flare. We argue that such an acceleration, including the acceleration of protons up to GeV energies, can be caused by a prolonged post-eruptive energy release following a coronal mass ejection (CME), when the magnetic field above the active region, strongly disturbed by the CME eruption, relaxes to its initial state through magnetic reconnection in the coronal vertical current sheet.

The High-Energy Gamma-Ray Flare of June, 15, 1991: Some Evidence of Prolonged Particle Acceleration at the Post-Eruption Phase

Akimov, V. V.; Belov, A. V.; Chertok, I. M.; Kurt, V. G.; Leikov, N. G.; Magun, A.; Melnikov, V. F.
Proceedings of Kofu Symposium, Kofu, Japan, Sept. 6-10, **1993**, p.371-374.
We compare the high-energy (up to 2 GeV) prolonged (at least 2 hours) gamma-ray emission, observed by the gamma-telescope GAMMA-1 in the June 15, 1991 flare, with microwave bursts and solar cosmic rays. The comparison testifies that the gamma-ray and radio emissions, observed well after the impulsive phase of the flare, appear to be initiated by prolonged nonstationary particle acceleration during the late phase of the flare rather than a long-term trapping of energetic electrons and protons accelerated at the onset of the flare. It is suggested that such an acceleration may be associated with a long post-eruption energy release following a coronal mass ejection.

Detection of high-energy gamma rays with the Gamma-1 telescope during the solar flares of March 26 and June 15, 1991

Akimov, V. V.; Afanasyev, V. G.; Belaousov, A. S.; Blokhintsev, I. D.; et al.
Soviet Astronomy Letters, Vol. 18, p. 69; Pis'ma v Astronomicheskii Zhurnal (ISSN 0320-0108), vol. 18, no. 2, Feb. **1992**, p. 167-172. In Russian.
Gamma radiation at energies up to about 2 GeV from the solar flares of March 26 and June 15, 1991 was detected by the Gamma-1 gamma telescope on board the Gamma astrophysical observatory. The values of the fluxes and energy spectra of the gamma rays are determined.

Observation of High Energy Gamma-Rays from the Sun with the GAMMA-1 Telescope (E > 30 MeV).

Akimov, V. V.; Afanassyey, V. G.; Belaousov, A. S.; Blokhintsev, I. D.; Kalinkin, L. F.; Leikov, N.G.; Nesterov, V. E.; Volsenskaya, V. A.; Galper, A. M.; Chesnokov, V. J.; Kirillov-Ugryumov, V. G.; Lutchkov, B. I.; Ozerov, Y. V.; Popov, A. V.; Rudko, V. A.; Runtso, M. F.; Voronov, S. A.; Zemskov, V.M.; Fradkin, M. I.; Kurnosova, L. V.; Rusakovitch, M. A.; Topchiev, N. P.; Chuikin, E. I.; Tugaenko,V. Y.; Tian, T. N.; Ishkov, V. N.; Gros, M.; Grenier, I.; Barouch, E.; Wallin, P.; Bazer-Bachi, A. R.; Lavigne, J.-M.; Olive, J.-F.; Juchniewicz, J.
ICRC **1991**, 3, 73.
https://articles.adsabs.harvard.edu/pdf/1991ICRC...22c..73A

Understanding breaks in solar flares x-ray spectra: Evaluation of a co-spatial return-current model

Meriem **Alaoui**, Gordon Holman
2017 *ApJ* **851** 78
https://arxiv.org/pdf/1706.03897.pdf
We investigate the possibility of explaining hard x-ray spectral breaks in terms of a 1D model with a co-spatial return current. We choose 19 flares observed by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) with strong spectral breaks at lower energies, around a few deka-keV, that cannot be explained by Compton back-scattering or non-uniform ionization alone. We identify these strong breaks at the HXR peak time, but we obtain 8 s cadence spectra of the entire impulsive phase. We then fit these spectra using a model in which electrons with an initially power-law distribution lose energy through return-current losses until they reach the thick-target chromosphere, where they lose all of their remaining energy through Coulomb collisions. Our main results are: (1) The return-current collisional thick-target model provides an acceptable fit for spectra with a strong flattening at lower energies; (2) the resistivity is found to be typically 2 orders of magnitude higher than Spitzer values (3) in the upper limit of the low-energy cutoff Ec, any runaway population of return-current electrons is negligible, and the anomalous Dreicer field is at least an order of magnitude higher than the return-current electric field. This also suggests that instability of the return current might not be responsible for the "enhanced" resistivity; (4) in the lower limit of Ec, a non-negligible runaway population can contribute to carrying the return current, but the background thermal electrons carry the return current in most cases; (5) in the upper limit of the cutoff energy, the drift velocity of the beam electrons is low enough to keep the return current stable to the generation of standard current-driven instabilities; (6) it is possible that the return current is carried by the beam electrons, which would require relaxing the 1D assumption, thus invalidating the anomalous resistivity result.
Table 1: Event list and spectral fit parameters at the time of peak emission.
19- and 20-Jan-2005

Discovery of Gamma Rays from the Quiescent Sun with HAWC

A. **Albert** et al. (HAWC Collaboration)
Phys. Rev. Lett. 131, 051201 –**2023**
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.051201
We report the first detection of a TeV γ-ray flux from the solar disk (6.3σ), based on 6.1 years of data from the High Altitude Water Cherenkov (HAWC) observatory. The 0.5–2.6 TeV spectrum is well fit by a power law, $dN/dE=A(E/1\ TeV)^{-\gamma}$, with $A=(1.6\pm0.3)\times10^{-12}\ TeV^{-1}\ cm^{-2}\ s^{-1}$ and $\gamma=3.62\pm0.14$. The flux shows a strong indication of anticorrelation with solar activity. These results extend the bright, hard GeV emission from the disk observed with Fermi-LAT, seemingly due to hadronic Galactic cosmic rays showering on nuclei in the solar atmosphere. However, current theoretical models are unable to explain the details of how solar magnetic fields shape these interactions. HAWC's TeV detection thus deepens the mysteries of the solar-disk emission.
RHESSI Nuggets, #454 2023
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/TeV_Gamma_rays_from_the_Quiescent_Sun

First HAWC Observations of the Sun Constrain Steady TeV Gamma-Ray Emission

A. **Albert**, R. Alfaro, C. Alvarez, R. Arceo, J.C. Arteaga-Velázquez, D. Avila Rojas, and many others
Physical Review D **2018**
https://arxiv.org/pdf/1808.05620.pdf
Steady gamma-ray emission up to at least 200 GeV has been detected from the solar disk in the Fermi-LAT data, with the brightest, hardest emission occurring during solar minimum. The likely cause is hadronic cosmic rays undergoing collisions in the Sun's atmosphere after being redirected from ingoing to outgoing in magnetic fields, though the exact mechanism is not understood. An important new test of the gamma-ray production mechanism will follow from observations at higher energies. Only the High Altitude Water Cherenkov (HAWC) Observatory has the required sensitivity to effectively probe the Sun in the TeV range. Using three years of HAWC data from November 2014 to December 2017, just prior to the solar minimum, we search for 1--100 TeV gamma rays from the solar disk.

No evidence of a signal is observed, and we set strong upper limits on the flux at a few 10−12 TeV−1 cm−2 s−1 at 1 TeV. Our limit, which is the most constraining result on TeV gamma rays from the Sun, is ∼10% of the theoretical maximum flux (based on a model where all incoming cosmic rays produce outgoing photons), which in turn is comparable to the Fermi-LAT data near 100 GeV. The prospects for a first TeV detection of the Sun by HAWC are especially high during solar minimum, which began in early 2018.

SATURATION OF NONTHERMAL HARD X-RAY EMISSION IN SOLAR FLARES
David **Alexander** and Antoun G. Daou
The Astrophysical Journal, 666:1268Y 1276, 2007
We consider a number of flares spanning a range of magnitudes over two decades in GOES soft X-ray luminosity and demonstrate an observational confirmation of the saturation of the nonthermal hard X-ray photon flux in large solar flares.
We argue that the saturation of the photon production sets in as a result of the transition from Coulomb collisions to return current ohmic dissipation dominating the energy losses as the flare magnitudes increase.

The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC
R. **Alfaro**, C. Alvarez, J.C. Arteaga-Velazquez, D. Avila Rojas, H.A. Ayala Solares, R. Babu, +++ **2022**
https://arxiv.org/pdf/2212.00815.pdf
We report the first detection of a TeV gamma-ray flux from the solar disk (6.3σ), based on 6.1 years of data from the High Altitude Water Cherenkov (HAWC) observatory. The 0.5--2.6 TeV spectrum is well fit by a power law, dN/dE = A(E/1 TeV)−γ,
with A=(1.6±0.3)×10−12 TeV−1 cm−2 s−1 and γ=−3.62±0.14. The flux shows a strong indication of anticorrelation with solar activity. These results extend the bright, hard GeV emission from the disk observed with Fermi-LAT, seemingly due to hadronic Galactic cosmic rays showering on nuclei in the solar atmosphere. However, current theoretical models are unable to explain the details of how solar magnetic fields shape these interactions. HAWC's TeV detection thus deepens the mysteries of the solar-disk emission.

HIGH-ENERGY GAMMA-RAY OBSERVATIONS OF SOLAR FLARES WITH THE FERMI LARGE AREA TELESCOPE **Thesis Catalog (2010-2017)**
Allafort, A. J.
(**2018**). PhD thesis, Stanford Univ. **File**
https://stacks.stanford.edu/file/druid:kp476kd8769/Allafort_Thesis_final_Dec13-augmented.pdf
Solar flares are the most energetic events in our Solar System. They consist of sudden energy release from reconfiguration of magnetic fields, leading to acceleration of particles to relativistic energies. The Fermi Large Area Telescope (LAT) gamma-ray observations of the Sun present a unique opportunity to explore the mechanisms of high-energy emission as well as particle acceleration and transport in solar flares. I will present the results of the first 9 years of observations of the active Sun by the Fermi-LAT, which represents the largest sample to date of detected solar flares with emission greater than 30 MeV. Some of the new detections confirm the standard models for solar flares based on observations from past missions in the 1980s and 90s, but new behaviors have also been identified: detections of delayed gamma-ray emission lasting up to 20 hours and the first detection of gamma-ray emission above 100 MeV from three solar flares originating from behind the visible part of the Sun. Considering all of the 45 flares detected by the Fermi-LAT, I will describe the characteristics of the first gamma-ray solar flare catalog covering Solar Cycle 24, exploring trends and correlations with the most relevant solar events: X-ray emission, coronal mass ejections, and direct detection of solar energetic particles. **2011-06-07, 2011-08-04, 2011-08-09, 2011-09-06, 2011-09-07, 2011-09-24, 2012-01-23, 2012-01-27, 2012-03-05, 7 Mar 2012, 2012-03-09, 2012-03-10, 2012-05-17, 2012-06-03, 2012-07-06, 2012-08-06, 2012-10-23, 2012-11-13, 2012-11-27, 2013-04-11, 2013-05-13, 2013-05-14, 2013-05-15, 2013-10-11, 2013-10-25, 2013-10-28, 2014-01-06, 2014- 01-07, 2014-02-25, 2014-06-10, 2014-06-11, 1 Sep 2014, 2014-09-10, 2015-06-21, 2015-06-25, 2017-09-06, 10 Sep 2017**

Allafort et al., in preparation, **2018**
A corollary of this scenario is that we would expect a similar spread of -ray emission over the solar disk for on-disk ares as well. In fact, the new PASS-8 analysis of the X5.4 are occurred on 2012 March 7 shows hints of migration of the centroid moving away from
its host AR over time

No correlation between Solar flares and the decay rate of several β-decaying isotopes

J.R. **Angevaare**, L. Baudis, P.A. Breur, A. Brown, A.P. Colijn, R.F. Lang, A. Massafferri, J.C.P.Y. Nobelen, R. Perci, C. Reuter, M. Schumann
Preprint submitted to Elsevier **2018**
https://arxiv.org/pdf/1806.03202.pdf
We report on finding no correlation between the two strongest observed Solar flares in September 2017 and the decay rates of 60Co, 44Ti and 137Cs sources, which are continuously measured by two independent NaI(Tl) detector setups. We test for variations in the number of observed counts with respect to the number of expected counts over multiple periods with timescales varying from 1 to 109 hours around the Solar flare. No excess or deficit exceeds the 2σ global significance. We set a conservative lower limit on the decay rate deviation over an 84-hour period around the two correlated Solar flares in September 2017 to 0.044% with 2σ confidence. A fractional change of 0.1% in the decay rate of 54Mn over a period of 84 hours was claimed with 7σ significance during multiple Solar flares in December 2006. We exclude such an effect at 4.7σ significance. **6 and 10 Sept 2017**

Improved measurement of solar neutrinos from the Carbon-Nitrogen-Oxygen cycle by Borexino and its implications for the Standard Solar Model

S. **Appel**, Z. Bagdasarian, D. Basilico, et al.
2022
https://arxiv.org/pdf/2205.15975.pdf
We present an improved measurement of the CNO solar neutrino interaction rate at Earth obtained with the complete Borexino Phase-III dataset. The measured rate RCNO = 6.7+2.0−0.8 counts/(day· 100 tonnes), allows us to exclude the absence of the CNO signal with about 7σ C.L. The correspondent CNO neutrino flux is 6.6+2.0−0.9×108 cm−2 s−1, taking into account the neutrino flavor conversion. We use the new CNO measurement to evaluate the C and N abundances in the Sun with respect to the H abundance for the first time with solar neutrinos. Our result of NCN = (5.78+1.86−1.00)×10−4 displays a ∼2σ tension with the "low metallicity" spectroscopic photospheric measurements. On the other hand, our result used together with the 7Be and 8B solar neutrino fluxes, also measured by Borexino, permits to disfavour at 3.1σ C.L. the "low metallicity" SSM B16-AGSS09met as an alternative to the "high metallicity" SSM B16-GS98.

Konus-W Gamma-ray burst experiment for the GGS Wind spacecraft

Aptekar, R.L., Frederiks, D.D., Golenetskii, S.V., et al.
Space Sci. Rev., **1995**, vol. 71, Issue 1-4, pp. 265–272.
https://link.springer.com/content/pdf/10.1007/BF00751332.pdf
The Konus-W experiment to be flown on board the GGS-Wind spacecraft is designed to observe gamma-ray bursts and solar flares with moderate spectral and high time resolution. Two large scintillators are used to provide omnidirectional sensitivity. The primary scientific objectives are the study of the continuum energy spectra and spectral features of these events in the energy range of 10 keV to 10 MeV, as well as their time histories in soft, medium, and hard energy bands, with a time resolution to 2 ms.

The emission in the region E>0.1MeV during disk and limb faint solar flares

Arkhangelskaja Irenea, Arkhangelskiy Andrewa, , Kotov Yurya, Glyanenko Alexandra, Kolchina Mariaa, Kirichenko Alexey
Advances in Space Research, Volume 51, Issue 11, 1 June **2013**, Pages 1996–2001
Hard X-ray and gamma-ray emission in energy band E>50E>50 keV was first observed by AVS-F apparatus onboard CORONAS-F satellite (detector SONG-D) during some solar flares with classes B and C by GOES classification. Such component registered in flares with duration less than 30 min. However γ-emission up to several tens of MeV was observed during some classes B and C events, which temporal profiles were not corresponded to Neupert effect. For example, during class B2.3 limb solar flare **January 7, 2005** maximum observed energy was Emax∼36 MeV and during class B4.6 disk solar event **January 12, 2005** maximum observed energy was Emax∼ 7 MeV. Properties of temporal profiles and energy spectra of faint solar flares, during which emission in the energy band of E>0.1E>0.1 MeV were registered are discussed in the presented work. There is not any strong correlation between presence or absence of hard X-ray and γ-ray emission and the intensity of soft X-ray emission during solar flares. The one of illustration of this fact is the absence of any observed statistically significant count rate exceed above background level during some class M flares in the energy band E>0.1E>0.1 MeV. The typical example of such flares is event **November 8, 2001** (class M4.2, lasts from 14:59 UT up to 16:00 UT, maximum of soft X-ray emission was at 15:35 UT on GOES data).

AVS-F observations of γ-ray emission during January 20, 2005 solar flare up to 140 MeV

I.V. **Arkhangelskaja**, A.I. Arkhangelsky[a], Yu.D. Kotov[a], P.A. Kalmykov[a] and A.S. Glyanenko
Advances in Space Research
Volume 43, Issue 4, 16 February **2009**, Pages 589-593
The solar flare of January 20, 2005 (X7.1, 06:36–07:26 UT, maximum at 07:01 UT by the GOES soft X-ray data) was the most powerful one in January 2005 series. The AVS-F apparatus onboard CORONAS-F registered γ-emission during soft X-ray rising phase of this flare in two energy ranges of 0.1–20 MeV and 2–140 MeV. The highest γ-ray energy registered during this flare was ~140 MeV. Six spectral features were registered in energy spectrum of this solar flare: annihilation + αα (0.4–0.6 MeV), ^{24}Mg + ^{20}Ne + ^{28}Si + neutron capture (1.7–2.3 MeV), ^{21}Ne + ^{22}Ne + ^{16}O + ^{12}C (3.2–5.0 MeV), ^{16}O (5.3–6.9 MeV), one from neutral pions decay (25–110 MeV) and one in energy band 15–21 MeV. Four of them contain typical for solar flares lines – annihilation, nuclear de-excitation and neutron capture at ^{1}H. Spectral feature caused by neutral pions decay was registered during several flares too. Some spectral peculiarities in the region of 15–21 MeV were first observed in solar flare energy spectrum.

Yet Another Sunshine Mystery: Unexpected Asymmetry in GeV Emission from the Solar Disk

Bruno **Arsioli**, Elena Orlando
ApJ **962** 52 **2024**
https://arxiv.org/pdf/2401.03466.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ad1bd2/pdf
The Sun is one of the most luminous gamma-ray sources in the sky and continues to challenge our understanding of its high-energy emission mechanisms. This study provides an in-depth investigation of the solar disk gamma-ray emission, using data from the Fermi Large Area Telescope (LAT) spanning August 2008 to January 2022. We focus on gamma-ray events with energies exceeding 5 GeV, originating from 0.5∘ angular aperture centered on the Sun, and implement stringent time cuts to minimize potential sample contaminants. We use a helioprojection method to resolve the gamma-ray events relative to the solar rotation axes, and combine statistical tests to investigate the distribution of events over the solar disk. We found that integrating observations over large time windows may overlook relevant asymmetrical features, which we reveal in this work through a refined time-dependent morphological analysis. We describe significant anisotropic trends and confirm compelling evidence of energy-dependent asymmetry in the solar disk gamma-ray emission. Intriguingly, the asymmetric signature coincides with the Sun's polar field flip during the cycle 24 solar maximum, around June 2014. Our findings suggest that the Sun's magnetic configuration plays a significant role in shaping the resulting gamma-ray signature, highlighting a potential link between the observed anisotropies, solar cycle, and the solar magnetic fields. These insights pose substantial challenges to established emission models, prompting fresh perspectives on high-energy solar astrophysics.
RHESSI Science Nuggets #466 **2024**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Unexpected_Asymmetry_in_GeV_Emission

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

A. **Artamonov**, G.L. Kovaltsov, A.L. Mishev, I.G. Usoskin
JGR 121, Issue 1 Pages 117–128 **2016**
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

Markus J. **Aschwanden** **Review**
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.**

See **2.5** Magnetic Topology of Acceleration Regions
(2) The magnetic field lines above the vertical current sheet of the main reconnection regions are likely ***to be open, which allows escape of accelerated particles*** into interplanetary space and along Earth-connected magnetic field lines;
2.6 Extended Particle Acceleration and Trapping **Extended γ -ray emission**

Two Classes of Gamma-Ray/Proton Flares: Impulsive and Gradual

Bai, T.
Astrophysical Journal v.308, p.912, **1986**
http://articles.adsabs.harvard.edu/pdf/1986ApJ...308..912B
Various observational properties of gamma-ray/proton (GR/P) flares are investigated. The question whether gamma ray line (GRL) flares are different from other flares is reevaluated, and flares with gradual hard X-ray time profiles are searched for and shown to share many common characteristics. Among the gradual flares, the only difference between those with observable nuclear gamma rays and those without is that hard X-ray burst spectrometer peak rates are greater than 4500 counts/s for the former, and less for the latter. It is proposed that GR/P flares be classified into impulsive and gradual flares. The differences between the two classes ofo GR/P flares are studied in phenomena occurring in the high corona and interplanetary medium. By examining the ratio of the number of interplanetary protons to the number of gamma-ray producing protons, it is found that it is small for impulsive GR/P flares but relatively large for gradual GR/P flares.

Band, D., Matteson, J., Ford, L., Schaefer, B., Palmer, D., Teegarden, B., Cline, T., Briggs, M., Paciesas, W., Pendleton, G., Fishman, G., Kouveliotou, C., Meegan, C., Wilson, R., Lestrade, P.: 1993, BATSE observations of gamma-ray burst spectra. I. Spectral diversity. *Astrophys. J.* **413**, 281. DOI. ADS.

Search for Gamma-Ray Emission from the Sun during Solar Minimum with the ARGO-YBJ Experiment

B. **Bartoli**1,2, P. Bernardini3,4, X. J. Bi5,6, Z. Cao5,6, S. Catalanotti1,2, S. Z. Chen5, T. L. Chen7, S. W. Cui8, B. Z. Dai9, A. D'Amone3,4Show full author list
2019 ApJ 872 143
https://doi.org/10.3847/1538-4357/aafe06
The hadronic interaction of cosmic rays with solar atmosphere can produce high energy gamma-rays. The gamma-ray luminosity is correlated both with the flux of primary cosmic rays and the intensity of the solar magnetic field. The gamma-rays below 200 GeV have been observed by Fermiwithout any evident energy cutoff. The bright gamma-ray flux above 100 GeV has been detected only during solar minimum. The only available data in the TeV range come from the HAWC observations, however, outside the solar minimum. The ARGO-YBJ data set has been used to search for sub-TeV/TeV gamma-rays from the Sun during the solar minimum from 2008 to 2010, the same time period covered by the Fermi data. A suitable model containing the Sun shadow, solar disk emission, and inverse-Compton emission has been developed, and the chi-square minimization method was used to quantitatively estimate the disk gamma-ray signal. The result shows that no significant gamma-ray signal is detected and upper limits to the gamma-ray flux at 0.3–7 TeV are set at the 95% confidence level. In the low energy range these limits are consistent with the extrapolation of the Fermi-LAT measurements taken during solar minimum and are compatible with a softening of the gamma-ray spectrum below 1 TeV. They also provide an experimental upper bound to any solar disk emission at TeV energies. Models of dark matter annihilation via long-lived mediators predicting gamma-ray fluxes >10−7 GeV cm−2 s−1 below 1 TeV are ruled out by the ARGO-YBJ limits.

Solar gamma rays powered by secluded dark matter

Batell, Brian; Pospelov, Maxim; Ritz, Adam; Shang, Yanwen
Physical Review D, vol. 81, Issue 7, id. 075004, **2010**
http://sci-hub.tw/10.1103/PhysRevD.81.075004

Secluded dark matter models, in which weakly interacting massive particles annihilate first into metastable mediators, can present novel indirect detection signatures in the form of gamma rays and fluxes of charged particles arriving from directions correlated with the centers of large astrophysical bodies within the Solar System, such as the Sun and larger planets. This naturally occurs if the mean free path of the mediator is in excess of the solar (or planetary) radius. We show that existing constraints from water Cerenkov detectors already provide a novel probe of the parameter space of these models, complementary to other sources, with significant scope for future improvement from high angular resolution gamma-ray telescopes such as Fermi-LAT. Fluxes of charged particles produced in mediator decays are also capable of contributing a significant solar system component to the spectrum of energetic electrons and positrons, a possibility which can be tested with the directional and timing information of PAMELA and Fermi.

On the proton precipitation sites in solar flares

Andrea Francesco **Battaglia**, Säm Krucker
A&A **2024**
https://arxiv.org/pdf/2412.11490
The Reuven Ramaty High Energy Solar Spectrocopy Imager (RHESSI) γ-ray observations of the extraordinary GOES X25 flare SOL2003-10-28T11:10 are revisited to investigate previously reported conclusions that flare-accelerated electrons and protons precipitate along spatially separated flare loops. In contrast to previous works which reconstructed 2.223 MeV images over extended time periods (∼20 minutes), we selected shorter integration times of the order of 2 to 3 minutes. Using simulations of the 2.223 MeV profile by Murphy et al. (2003) in combination with observations of the prompt γ-ray lines from the INTEGRAL mission, we obtain two separated integration time ranges representing the peak of the flare and the start of the decay, respectively. The resulting γ-ray images are then compared to GONG white-light (WL) observations to identify where along the flaring ribbons electrons and protons precipitation occurs. We point out that previously reported results comparing RHESSI hard X-ray (HXR) and γ-ray images only hold if the relative time evolution in the two energy ranges is the same. As the decay times for the **28 October 2003** is different at the considered two energy ranges (200-300 keV and around 2.223 MeV), the previously published conclusion that electrons and protons precipitate at different locations is an overstatement. Using shorter integration times reveals that the γ-ray and HXR sources spatially coincide with the WL flare ribbons. Our key conclusion is that electron and proton precipitation sites coincide with the flare ribbons, suggesting that the electron and proton precipitation sites are the same, at least within RHESSI's imaging capabilities. This result solves the twenty-years-long mystery around the previously reported different electron and proton precipitation sites.

Features of Solar Proton Events and Long-Duration Gamma-Ray Flares in the 24th Solar Cycle.

Bazilevskaya, G.A., Daibog, E.I., Logachev, Y.I. et al.
Bull. Russ. Acad. Sci. Phys. 85, 911–914 (**2021**).
https://link.springer.com/content/pdf/10.3103/S1062873821080037.pdf
https://doi.org/10.3103/S1062873821080037
Solar proton events are compared using the Catalogue of Solar Proton Events of the 24th Cycle of Solar Activity and solar events with long-duration high-energy gamma radiation based on measurements at the Fermi gamma-ray telescope. High-energy γ-quanta are mainly the product of the decay of πo-mesons during the interaction of high-energy protons on the Sun. Sources of gamma-ray flares not accompanied by solar protons are located in the eastern hemisphere of the Sun, and the associated coronal ejections do not move toward the Earth. Solar protons from such sources are not recorded by the terrestrial observer.

The motions of the hard X-ray sources in solar flares: images and statistics.

Bogachev, S., Somov, B. V., Kosugi, T., Sakao, T.
ApJ 620, 561-572, **2005**.

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The **Borexino** Collaboration
Nature volume 587, pages577–582(**2020**)
https://www.nature.com/articles/s41586-020-2934-0
For most of their existence, stars are fuelled by the fusion of hydrogen into helium. Fusion proceeds via two processes that are well understood theoretically: the proton–proton (pp) chain and the carbon–nitrogen–oxygen (CNO) cycle1,2. Neutrinos that are emitted along such fusion processes in the solar core are the only direct probe of the deep interior of the Sun. A complete spectroscopic study of neutrinos from the pp chain, which produces about 99 per cent of the solar energy, has been performed previously3; however, there has been no reported experimental evidence of the CNO cycle. Here we report the direct observation, with a high statistical significance, of neutrinos

produced in the CNO cycle in the Sun. This experimental evidence was obtained using the highly radiopure, large-volume, liquid-scintillator detector of Borexino, an experiment located at the underground Laboratori Nazionali del Gran Sasso in Italy. The main experimental challenge was to identify the excess signal—only a few counts per day above the background per 100 tonnes of target—that is attributed to interactions of the CNO neutrinos. Advances in the thermal stabilization of the detector over the last five years enabled us to develop a method to constrain the rate of bismuth-210 contaminating the scintillator. In the CNO cycle, the fusion of hydrogen is catalysed by carbon, nitrogen and oxygen, and so its rate—as well as the flux of emitted CNO neutrinos—depends directly on the abundance of these elements in the solar core. This result therefore paves the way towards a direct measurement of the solar metallicity using CNO neutrinos. Our findings quantify the relative contribution of CNO fusion in the Sun to be of the order of 1 per cent; however, in massive stars, this is the dominant process of energy production. This work provides experimental evidence of the primary mechanism for the stellar conversion of hydrogen into helium in the Universe.
See https://www.nature.com/articles/d41586-020-03238-9

Solar constraints on captured electrophilic dark matter

Debajit **Bose**, Tarak Nath Maity, Tirtha Sankar Ray
2021
https://arxiv.org/pdf/2112.08286.pdf
Dark matter captured by interaction with electrons inside the Sun may annihilate via long-lived mediator to produce observable gamma ray signals. We utilize the Fermi Large Area Telescope data to put bounds on the dark matter electron scattering cross-section which are three to four orders of magnitude stronger than the existing limits for dark matter masses ranging between GeV to TeV scale.

Solar neutrinos as indicators of the Sun's activity

O.M.**Boyarkin**, I.O.Boyarkina
International Journal of Modern Physics A, Vol. 35 (**2019**) 1950448
https://arxiv.org/pdf/2004.10056.pdf
Opportunity of the solar flares (SF's) prediction observing the solar neutrino fluxes is investigated. In three neutrino generations the evolution of the neutrino flux traveling the coupled sunspots (CS's) which are the SF source is considered. It is assumed that the neutrinos possess both the dipole magnetic moment and the anapole moment while the magnetic field above the CS's may reach the values 105−106 Gs, displays the twisting nature and has the nonpotential character. The possible resonance conversions of the solar neutrino flux are examined. Since the νeL→νμL resonance takes place before the convective zone, its existence can in no way be connected with the SF. However, when the solar neutrino flux moves through the CS's in the preflare period, then it may undergo the additional resonance conversions and, as a result, depleting the electron neutrinos flux may be observed.

RHESSI Results Time for a Rethink? **Review**

Brown, J. C.; Kontar, E. P.; Veronig, A. M.
The High Energy Solar Corona: Waves, Eruptions, Particles, Lecture Notes in Physics, Volume 725. ISBN 978-3-540-71569-6. Springer-Verlag Berlin Heidelberg, **2007**, p. 65
https://arxiv.org/pdf/astro-ph/0607440.pdf
Hard X-rays and γ-rays are the most direct signatures of energetic electrons and ions in the sun's atmosphere which is optically thin at these energies and their radiation involves no coherent processes. Being collisional they are complementary to gyro-radiation in probing atmospheric density as opposed to magnetic field and the electrons are primarily 10 100~keV in energy, complementing the (>100 keV) electrons likely responsible for microwave bursts. The pioneering results of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) are raising the first new major questions concerning solar energetic particles in many years. Some highlights of these results are discussed primarily around RHESSI topics on which the authors have had direct research involvement particularly when they are raising the need for re-thinking of entrenched ideas. Results and issues are broadly divided into discoveries in the spatial, temporal and spectral domains, with the main emphasis on flare hard X-rays/fast electrons but touching also on γ-rays/ions, non-flare emissions, and the relationship to radio bursts. **20 Feb 2002, 14 March 2002, 2002 April 14/15, July 23, 2002**

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 **953** 187 **2023**
https://arxiv.org/pdf/2306.14671.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ace24c/pdf **File**
Introduction is a good Review

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
.

Hard X-ray Emission During Flares and Photospheric Field Changes

O. **Burtseva**, J. C. Martínez-Oliveros, G. J. D. Petrie, A. A. Pevtsov
ApJ **2015**
http://arxiv.org/pdf/1505.00509v1.pdf
We study the correlation between abrupt permanent changes of magnetic field during X-class flares observed by the GONG and HMI instruments, and the hard X-ray (HXR) emission observed by RHESSI, to relate the photospheric field changes to the coronal restructuring and investigate the origin of the field changes. We find that spatially the early RHESSI emission corresponds well to locations of the strong field changes. The field changes occur predominantly in the regions of strong magnetic field near the polarity inversion line (PIL). The later RHESSI emission does not correspond to significant field changes as the flare footpoints are moving away from the PIL. Most of the field changes start before or around the start time of the detectable HXR signal, and they end at about the same time or later than the detectable HXR flare emission. Some of the field changes propagate with speed close to that of the HXR footpoint at a later phase of the flare. The propagation of the field changes often takes place after the strongest peak in the HXR signal when the footpoints start moving away from the PIL, i.e. the field changes follow the same trajectory as the HXR footpoint, but at an earlier time. Thus, the field changes and HXR emission are spatio-temporally related but not co-spatial nor simultaneous. We also find that in the strongest X-class flares the amplitudes of the field changes peak a few minutes earlier than the peak of the HXR signal. We briefly discuss this observed time delay in terms of the formation of current sheets during eruptions.

Stereoscopic measurements of X-ray anisotropy in solar flares with STIX and MiSolFA

Diego **Casadei**, Natasha L. S. Jeffrey, Eduard P. Kontar
A&A **2017**
https://arxiv.org/pdf/1702.08795.pdf
Context. During a solar flare, a large fraction of the magnetic energy released goes into the kinetic energy of non-thermal particles, with X-ray observations providing a direct diagnostic tool of keV flare-accelerated electrons. However, the electron angular distribution, a prime diagnostic tool of the acceleration mechanism and transport, is poorly known.
Aims. During the next solar maximum, two upcoming space-borne X-ray missions, STIX onboard Solar Orbiter and MiSolFA, will perform stereoscopic X-ray observations of solar flares at two di_erent locations: STIX at 0.28 AU (at perihelion) and up to inclinations of _ 25_, and MiSolFA at low-Earth orbit. The combined observations from these cross-calibrated detectors, will allow us to confidently detect the electron anisotropy of individual flares for the first time.
Methods. Both instrumental and physical effects are simulated for STIX and MiSolFA including thermal shielding, background and X-ray Compton backscattering (albedo effect) in the solar photosphere. We predict the expected number of observable flares and stereoscopic measurements during the next solar maximum. The range of useful spacecraft observation angles is estimated, for the challenging case of close-to-isotropic flare anisotropy.
Results. The simulated results show that STIX and MiSolFA will be capable of detecting low levels of flare anisotropy, even with a relatively small (_20–30_) angular separation of the spacecrafts, and will directly measure the flare electron anisotropy of about 40 M- and X-class solar flares during the next solar maximum.

Conclusions. Near-future stereoscopic observations with Solar Orbiter/STIX and MiSolFA will help distinguish between competing flare-acceleration mechanisms, and provide information regarding collisional and non-collisional transport processes occurring in the flaring atmosphere for individual solar flares.

A Spectroscopic Method Based on the Shapes of Nuclear Deexcitation γ-Ray Lines in Solar Flares

Wei **Chen** and W. Q. Gan
2020 ApJ 895 8
https://doi.org/10.3847/1538-4357/ab886c
The deexcitation γ-ray lines in solar flares result from energetic ions (e.g., protons, α-particles) interacting with the ambient nuclei in the solar atmosphere. The centroid and width of lines contain a wealth of information on the directionality, composition, and spectra of energetic ions as well as properties of the interaction sites. New calculations for the deexcitation γ-ray line shape analysis were done to study the properties of these ions. We calculate the shapes of the most intense deexcitation γ-ray lines in the solar flares, including the 12C 4.439 MeV, 16O 6.129 MeV, 24Mg 1.369 MeV, and 28Si 1.779 MeV lines, and explore the profiles of these line shapes as a function of the accelerated ion's energy spectra and composition, as well as the heliocentric angle of flare location. The merits of deexcitation γ-ray line shape analysis include (1) only a relatively small number of parameters being required in the fitting process and (2) the characteristics of accelerated ions with joint multi-line shape analysis being well constrained. We conclude that the measurement of the width and centroid of lines is an effective method for determining the properties of flare-accelerated ions.

Shapes of 20Ne de-excitation line in solar flare

Wei **Chen**, Wei Qun Gan
Astrophysics and Space Science September **2017**, 362:150
Since almost all de-excitation lines from nuclear states excited by flare-accelerated protons and αα-particles are emitted promptly after nuclear collisions, the emission photon's energy depends on the velocity of the recoiling nucleus. The energies and widths of γγ-ray lines provide a wealth of information on the directionality and spectra of ions in solar flares. In this paper, we use TALYS code to improve the cross sections of γγ-ray lines production, and calculate the shapes of the 1.634 MeV line from de-excitation of 20Ne as a function of ion's energy spectra and the heliocentric angle. Taking this line shape as an example, we try to develop a new method of line shape analysis to study the properties of accelerated ions in solar flares.

Double Coronal X-ray and Microwave Sources Associated With A Magnetic Breakout Solar Eruption

Yao **Chen**, Zhao Wu, Wei Liu, Richard A. Schwartz, Di Zhao, Bing Wang, Guohui Du
2017 *ApJ* **843** 8
https://arxiv.org/pdf/1705.06074.pdf
http://sci-hub.cc/10.3847/1538-4357/aa7462
Double coronal hard X-ray (HXR) sources are believed to be critical observational evidence of bi-directional energy release through magnetic reconnection in a large-scale current sheet in solar ares. Here we present a study on double coronal sources observed in both HXR and microwave regimes, revealing new characteristics distinct from earlier reports. This event is associated with a footpoint-occulted X1.3-class flare (**25 April 2014**, starting at 00:17 UT) and a coronal mass ejection that are likely triggered by the magnetic breakout process, with the lower source extending upward from the top of the partially-occulted flare loops and the upper source co-incident with rapidly squeezing-in side lobes (at a speed of ~250 km/s on both sides). The upper source can be identified at energies as high as 70-100 keV. The X-ray upper source is characterized by flux curves different from the lower source, a weak energy dependence of projected centroid altitude above 20 keV, a shorter duration and a HXR photon spectrum slightly-harder than those of the lower source. In addition, the microwave emission at 34 GHz also exhibits a similar double source structure and the microwave spectra at both sources are in line with gyro-synchrotron emission given by non- thermal energetic electrons. These observations, especially the co-incidence of the very-fast squeezing-in motion of side lobes and the upper source, indicate that the upper source is associated with (possibly caused by) this fast motion of arcades. This sheds new lights on the origin of the corona double-source structure observed in both HXRs and microwaves.

THE ROLE OF INVERSE COMPTON SCATTERING IN SOLAR CORONAL HARD X-RAY AND γ-RAY SOURCES

Bin **Chen**1 and T. S. Bastian
2012 ApJ 750 35
Coronal hard X-ray (HXR) and continuum γ-ray sources associated with the impulsive phase of solar flares have been the subject of renewed interest in recent years. They have been interpreted in terms of thin-target, non-thermal

bremsstrahlung emission. This interpretation has led to rather extreme physical requirements in some cases. For example, in one case, essentially all of the electrons in the source must be accelerated to non-thermal energies to account for the coronal HXR source. In other cases, the extremely hard photon spectra of the coronal continuum γ-ray emission suggest that the low-energy cutoff of the electron energy distribution lies in the MeV energy range. Here, we consider the role of inverse Compton scattering (ICS) as an alternate emission mechanism in both the ultra- and mildly relativistic regimes. It is known that relativistic electrons are produced during powerful flares; these are capable of upscattering soft photospheric photons to HXR and γ-ray energies. Previously overlooked is the fact that mildly relativistic electrons, generally produced in much greater numbers in flares of all sizes, can upscatter extreme-ultraviolet/soft X-ray photons to HXR energies. We also explore ICS on anisotropic electron distributions and show that the resulting emission can be significantly enhanced over an isotropic electron distribution for favorable viewing geometries. We briefly review results from bremsstrahlung emission and reconsider circumstances under which non-thermal bremsstrahlung or ICS would be favored. Finally, we consider a selection of coronal HXR and γ-ray events and find that in some cases the ICS is a viable alternative emission mechanism.

IMPULSIVE PHASE CORONAL HARD X-RAY SOURCES IN AN X3.9 CLASS SOLAR FLARE
Qingrong **Chen**1 and Vahé Petrosian
2012 ApJ 748 33, **File**
We present the analysis of a pair of unusually energetic coronal hard X-ray (HXR) sources detected by the Reuven Ramaty High Energy Solar Spectroscopic Imager during the impulsive phase of an X3.9 class solar flare on **2003 November 3**, which simultaneously shows two intense footpoint (FP) sources. A distinct loop top (LT) coronal source is detected up to ~150 keV and a second (upper) coronal source up to ~80 keV. These photon energies, which were not fully investigated in earlier analysis of this flare, are much higher than commonly observed in coronal sources and pose grave modeling challenges. The LT source in general appears higher in altitude with increasing energy and exhibits a more limited motion compared to the expansion of the thermal loop. The high-energy LT source shows an impulsive time profile and its nonthermal power-law spectrum exhibits soft-hard-soft evolution during the impulsive phase, similar to the FP sources. The upper coronal source exhibits an opposite spatial gradient and a similar spectral slope compared to the LT source. These properties are consistent with the model of stochastic acceleration of electrons by plasma waves or turbulence. However, the LT and FP spectral index difference (varying from ~0 to 1) is much smaller than commonly measured and than that expected from a simple stochastic acceleration model. Additional confinement or trapping mechanisms of high-energy electrons in the corona are required. Comprehensive modeling including both kinetic effects and the macroscopic flare structure may shed light on this behavior. These results highlight the importance of imaging spectroscopic observations of the LT and FP sources up to high energies in understanding electron acceleration in solar flares. Finally, we show that the electrons producing the upper coronal HXR source may very likely be responsible for the type III radio bursts at the decimetric/metric wavelength observed during the impulsive phase of this flare.

Scattered Light: Inverse Compton Scattering and Coronal Hard X-ray Sources
B. **Chen** and T. S. Bastian
RHESSI Nugget, No. 157, 17 July **2011**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Scattered_Light:_Inverse_Compton_Scattering_and_Coronal_Hard_X-ray_Sources
We conclude that for certain coronal HXR/γ-ray sources, ICS emission may be a viable alternative to thin-target bremsstrahlung emission, particularly if the responsible energetic electron distribution is anisotropic. If ICS indeed plays a role in the production of coronal HXR/γ−ray sources, it represents a new opportunity to diagnose the properties of energetic electrons.

High energy neutron and pion-decay gamma-ray emissions from solar flares **Review**
Chupp, Edward L.; Ryan, James M.
Research in Astron. Astrophys. Volume 9, Issue 1, pp. 11-40 (**2009**) **File**
http://www.raa-journal.org/raa/index.php/raa/article/view/50/36
https://iopscience.iop.org/article/10.1088/1674-4527/9/1/003/pdf
doi: 10.1088/1674-4527/9/1/003
Solar flare gamma-ray emissions from energetic ions and electrons have been detected and measured to GeV energies since 1980. In addition, neutrons produced in solar flares with 100 MeV to GeV energies have been observed at the Earth. These emissions are produced by the highest energy ions and electrons accelerated at the Sun and they provide our only direct (albeit secondary) knowledge about the properties of the accelerator(s) acting in a solar flare. The solar flares, which have direct evidence for pion-decay gamma-rays, are unique and are the focus of this paper. We review our current knowledge of the highest energy solar emissions, and how the characteristics of the acceleration process are deduced from the observations. Results from the RHESSI, INTEGRAL and CORONAS missions will also be covered. The review will also cover the solar flare capabilities of the new mission, FERMI GAMMA RAY SPACE TELESCOPE, launched on 2008 June 11. Finally, we discuss the requirements for future

missions to advance this vital area of solar flare physics. **1982 June 3, 1989 March 6, 1990 May 24, 1991 March 26, 1991 June 11, 1991 June 15, 2003 October 28, 2005 January 20**

Solar flare gamma-ray emission and energetic particles in space

Cliver, E. W.
AIP Conference Proceedings 374, 45 (**1996**);
https://sci-hub.si/10.1063/1.50980
We expand Reames' tabular summary of the two-class picture of solar energetic particle (SEP) events to include characteristics of the particles that interact at the Sun to produce gamma-ray emission. This addition underscores the contributions of gamma-ray observations to our current understanding. The broad picture that is emerging is remarkable for its simplicity: while SEP events come in two basic types depending on the duration of the associated flare, the interacting particles in impulsive and gradual flares appear to be indistinguishable and resemble the SEPs observed in space following impulsive flares. The expanded classification system includes hybrid events, i.e., flares in which the gradual/impulsive distinction is blurred and for which the SEP events contain a mixture of flare-accelerated and CME/shock-accelerated particles. We argue that SEP events associated with long duration flares can be expected to have a temporally and spatially confined ``core" of flare-accelerated particles surrounded by a ``halo" of CME/shock particles. Thus SEP composition should be checked in comparative studies of gamma-ray emission and particles in space to ensure that the SEPs are flare-accelerated. We discuss how recently-discovered types of gamma-ray flares (electron-dominated events, spatially and temporally extended gamma-ray events) may fit into the expanded classification scheme. We suggest that the acceleration process in the pion-rich phase of large flares (e.g., 1982 June 3) is similar to that occurring earlier in the flare, the main differences being the greater height of the acceleration region and the presence of previously accelerated seed particles.

On the Origin of Gamma-Ray Emission from the Behind-the-Limb Flare on 29 September 1989

Cliver, E. W.; Kahler, S. W.; Vestrand, W. T.
23rd International Cosmic Ray Conference, Vol. 3, held 19-30 July, 1993 at University of Calgary, Alberta, Canada. Edited by D.A. Leahy, R.B. Hicks, and D. Venkatesan. Invited, Rapporteur, and Highlight Papers. Singapore: World Scientific, **1993**., v. 3, p.91–94
https://ui.adsabs.harvard.edu/link_gateway/1993ICRC....3...91C/ADS_PDF
It was proposed by Cliver et al. (1993) that γ-ray events during solar events launched behind-the-limb are the consequence of particles acceleration by CME-driven coronal shocks in conjunction with their precipitation on the visible disk.
Although there were some scenarios put forth (Cliver et al. 1993), no convincing explanations were given for the acceleration and transport sites and mechanisms of particles responsible for these BTL observations.

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.
Astrophysical Journal v.343, p.953–970, **1989**
http://articles.adsabs.harvard.edu/pdf/1989ApJ...343..953C
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

Time delay between γ -ray lines and hard X-ray emissions during the 23 July 2002 solar flare interpreted by a trap plus precipitation model.

Dauphin C, Vilmer N
A&A 468:289–298, (**2007**), doi:10.1051/0004-6361:20066247

Context: The 23 July 2002 event was the first γ-ray flare observed by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Analysis of the time profiles of the hard X-ray and gamma-ray radiations of this flare shows a time delay between hard X-ray at 150 keV and gamma ray line emissions.
Aims: We aim to interpret this delay in terms of transport of the particles accelerated during the flare.
Methods: In this paper, we focus on the interpretation of this delay in the context of a trap plus precipitation model for energetic particles.
Results: The time profiles of hard-X-ray and prompt gamma-ray line fluxes can be reproduced given that electrons and ions are injected and partially trapped in different coronal loop systems with slightly different characteristics such as density and length, and that the energetic electron-to-ion ratio varies from peak to peak during the flare.
Conclusions: The results obtained from this analysis are discussed with respect to the constraints provided by the X-ray and gamma-ray images previously obtained, as well as with previously published analysis of the same event

Examining the Connection between Solar Energetic Particles and Long-Duration Gamma-ray Flares **Presentation**

G. A**. de Nolfo**1, A. Bruno2, E.R. Christian1, S. Dalla3, J. Giacalone4, I.G. Richardson5, J.M. Ryan6
Predentation at Fleishman's Webinar, **2020**
http://www.ioffe.ru/LEA/SF_AR/files/Webinar_LDGRF_2019_v2.pdf

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.
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. T

Comparing Long-Duration Gamma-Ray Flares and High-Energy Solar Energetic Particles

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.do/10.3847/1538-4357/ab258f
doi: 10.3847/1538-4357/ab258f
https://scholar.google.com/scholar_url?url=https://iopscience.iop.org/article/10.3847/1538-4357/ab258f/pdf
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**
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)

First search for GeV neutrinos from bright gamma-ray solar flares using the IceCube Neutrino Observatory

Gwenhaël **de Wasseige** (for the IceCube Collaboration)
the 36th International Cosmic Ray Conference (ICRC 2019). PoS-ICRC2019-1075 **2019**
PoS(**ICRC2019**)1075 pdf
https://arxiv.org/pdf/1908.08300.pdf
In response to a reported increase in the total neutrino flux in the Homestake experiment in coincidence with solar flares at the end of the eighties, solar neutrino detectors have searched for solar flare signals. Solar flares convert magnetic energy into thermal energy of plasma and kinetic energy of charged particles such as protons. As a consequence of magnetic reconnection, protons are injected downwards from the coronal acceleration region and can interact with dense plasma in the lower solar atmosphere, producing mesons that will subsequently decay into gamma rays and neutrinos at O(MeV-GeV) energies. The main motivation to search for solar flare neutrinos comes from their hadronic origin. As inherent products of high-energy proton collisions with the chromosphere, they are a direct probe of the proton accelerated towards the chromosphere. Using a multi-messenger approach, it is therefore possible to constrain the proton acceleration taking place in the solar flares, including the spectral index of the accelerated flux and its shape. We present the results of the first search for GeV neutrinos emitted during solar flares carried out with the IceCube Neutrino Observatory. We present a new approach which allows us to strongly lower the energy threshold of IceCube, originally designed to detect 10 GeV - PeV neutrinos. We compare the results with theoretical estimates of the corresponding flux. **Mar 7th, 2012, Feb 25th, 2014, Sep 1st, 2014, Sep 6th, 2017, Sep 10th, 2017**
See arXiv:1907.11699 for all IceCube contributions

Ramaty High Energy Solar Spectroscopic Imager (RHESSI) **Review**

Brian R. **Dennis**, Albert Y. Shih, Gordon J. Hurford, Pascal Saint-Hilaire
A chapter in the Handbook of X-ray and Gamma-ray Astrophysics **2022**
https://arxiv.org/abs/2206.00741
This paper describes the X-ray and gamma-ray imaging spectroscopy capabilities of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). It also outlines RHESSI's major scientific accomplishments during the 16 years of operations from 2002 to 2018. These include unique contributions to solar flare research and to other aspects of solar physics (oblateness), astrophysics (magnetars), and Earth sciences (terrestrial gamma-ray flashes).

Coronal hard X-ray sources revisited

Brian R. **Dennis**, Miguel A. Duval-Poo, Michele Piana, Andrew R. Inglis, A. Gordon Emslie, Jingnan Guo, Yan Xu
ApJ **867** 82 **2018**
https://arxiv.org/pdf/1809.04631.pdf
http://iopscience.iop.org/article/10.3847/1538-4357/aae0f5/pdf
This paper reports on the re-analysis of solar flares in which the hard X-rays (HXRs) come predominantly from the corona rather than from the more usual chromospheric footpoints. All of the 26 previously analyzed event time intervals, over 13 flares, are re-examined for consistency with a flare model in which electrons are accelerated near the top of a magnetic loop that has a sufficiently high density to stop most of the electrons by Coulomb collisions before they can reach the footpoints. Of particular importance in the previous analysis was the finding that the length of the coronal HXR source increased with energy in the 20 - 30 keV range. However, after allowing for the possibility that footpoint emission at the higher energies affects the inferred length of the coronal HXR source, and using analysis techniques that suppress the possible influence of such footpoint emission, we conclude that there is no longer evidence that the length of the HXR coronal sources increase with increasing energy. In fact, for the 6 flares and 12 time intervals that satisfied our selection criteria, the loop lengths decreased on average by 1.0 +/- 0.2 arcsec between 20 and 30 keV, with a standard deviation of 3.5 arcsec. We find strong evidence that the peak of the coronal HXR source increases in altitude with increasing energy. For the thermal component of the emission, this is consistent with the standard CHSKP flare model in which magnetic reconnection in a coronal current sheet results in new hot loops being formed at progressively higher altitudes. The explanation for the nonthermal emission is not so

clear. **12 April 2002, 14/15 April 2002, 17 April 2002, 17 June 2003, 10 July 2003, 02 December 2003, 21 May 2004, 31 August 2004, 01 June 2005, 23 August 2005, 13 February 2011, 03 August 2011, 25 September 2011, 15 May 2013**
Table 1. Dates, times, and locations for all 14 analyzed flares. (Apr 2002-May 2013)

Always a Farm Boy

Brian R. **Dennis**
Solar Phys. **2018**
https://arxiv.org/pdf/1805.03248.pdf
This is the **memoir** of Brian Dennis - his life story to date, and his involvement with high energy solar physics.

Analysis of the Impulsive Phase of Solar Flares with Pass 8 LAT data

R. **Desiante**, F. Longo, N. Omodei, M. Pesce-Rollins, V. Pelassa for the Fermi-LAT Collaboration
2014 Fermi Symposium proceedings - eConf C141020.1
http://arxiv.org/pdf/1502.04916v1.pdf
We show the results of analyses performed on high-energy gamma-ray emission during the impulsive phase of solar flares detected by the LAT using Pass 8 data. We compare results obtained with Pass 7 and Pass 8 data sets, using both LAT Low Energy and standard data classes. With a dedicated event selection, Pass 8 allows standard analysis during the impulsive phase: it has been designed to be less susceptible to pile-up in the LAT Anti-Coincidence Detector caused by the intense hard X-ray emission at early times. **2010-06-12, 2011-09-06, 2012-06-03**

First flight of the Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) instrument

Nicole **Duncan**, P. Saint-Hilaire, A. Y. Shih, G. J. Hurford, H. M. Bain, M. Amman, B. A. Mochizuki, J. Hoberman, J. Olson, B. A. Maruca, N. M. Godbole, D. M. Smith, J. Sample, N. A. Kelley, A. Zoglauer, A. Caspi, P. Kaufmann, S. Boggs, R. P. Lin
Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99052Q (July 18, 2016) **2016**
http://arxiv.org/pdf/1609.08558v1.pdf
The Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) is a balloon-borne telescope designed to study solar-flare particle acceleration and transport. We describe GRIPS's first Antarctic long-duration flight in Jan 2016 and report preliminary calibration and science results. Electron and ion dynamics, particle abundances and the ambient plasma conditions in solar flares can be understood by examining hard X-ray (HXR) and gamma-ray emission (20 keV to 10 MeV) with enhanced imaging, spectroscopy and polarimetry. GRIPS is specifically designed to answer questions including: What causes the spatial separation between energetic electrons producing HXRs and energetic ions producing gamma-ray lines? How anisotropic are the relativistic electrons, and why can they dominate in the corona? How do the compositions of accelerated and ambient material vary with space and time, and why? GRIPS's key technological improvements over the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) include 3D position-sensitive germanium detectors (3D-GeDs) and a single-grid, multi-pitch rotating modulator (MPRM) collimator. The 3D-GeDs have spectral FWHM resolution of a few hundred keV and spatial resolution <1 mm3. For photons that Compton scatter, usually ≳150 keV, the energy deposition sites can be tracked, providing polarization measurements as well as enhanced background reduction. The MPRM single-grid design provides twice the throughput of a bi-grid imaging system like RHESSI. The grid is composed of 2.5 cm thick W/Cu slats with 1-13 mm variable slit pitch, achieving quasi-continuous FWHM angular coverage over 12.5-162 arcsecs. This resolution is capable of imaging the separate magnetic loop footpoint emissions in a variety of flare sizes. In comparison, RHESSI's 35-arcsec resolution at similar energies makes the footpoints resolvable in only the largest flares.

Solar hard X-ray imaging by means of Compressed Sensing and Finite Isotropic Wavelet Transform

M. A. **Duval-Poo**, M. Piana, A. M. Massone
A&A **2017**
https://arxiv.org/pdf/1708.03877.pdf
This paper shows that compressed sensing realized by means of regularized deconvolution and the Finite Isotropic Wavelet Transform is effective and reliable in hard X-ray solar imaging. The method utilizes the Finite Isotropic Wavelet Transform with Meyer function as the mother wavelet. Further, compressed sensing is realized by optimizing a sparsity-promoting regularized objective function by means of the Fast Iterative Shrinkage-Thresholding Algorithm. Eventually, the regularization parameter is selected by means of the Miller criterion. The method is applied against both synthetic data mimicking the Spectrometer/Telescope Imaging X-rays (STIX) measurements and experimental observations provided by the Reuven Ramaty High Energy Solar Spectroscopic

Imager (RHESSI). The performances of the method are compared with the results provided by standard visibility-based reconstruction methods. The results show that the application of the sparsity constraint and the use of a continuous, isotropic framework for the wavelet transform provide a notable spatial accuracy and significantly reduce the ringing effects due to the instrument point spread functions.

A Catalog of Suzaku/WAM Hard X-Ray Solar Flares

A. **Endo**, T. Minoshima, K. Morigami, M. Suzuki, A. Shimamori, Y. Sato, Y. Terada, M. S. Tashiro, Y. Urata, E. Sonoda, K. Yamaoka, S. Sugita, and K. Watanabe
Publ. Astron. Soc. Japan 62, pp.1341-1349 **(2010)**
We developed a catalog of solar flares in the hard X-ray band observed with the Wide-band All-sky Monitor (WAM) onboard the Suzaku satellite between 2005 July and 2009 November. During this period, 105 solar flares (GOES class X: 13, M: 29, C: 47, B: 16) were detected with WAM, including 10% of GOES-class C events reported during the same period. The observed photon flux ranged between 9 10 and 9 10photons scmkeV at 100 keV. The averaged hard X-ray spectrum for each solar flare was evaluated for 70 of the 105 events, and 43 of them were well fitted with a single power-law model with a photon index ranging between 7 and 3. We observed a weak trend where events with longer durations exhibited harder spectral slopes.

Solar neutrino flare, megaton neutrino detectors and human space journey

Danile **Fargion**, Pietro Oliva, Silvia Pietroni, Fabio La Monaca, Paolo Paggi, Emanuele Habib, Maxim Khlopov
WSPC Proceedings **2018**
https://arxiv.org/pdf/1809.02004.pdf
The largest solar flare have been recorded in gamma flash and hard spectra up to tens GeV energy. The present building and upgrade of Hyper- Kamiokande (HK) in Japan and Korea, (as well as Deep Core, PINGU) Megatons neutrino detectors do offer a novel way to detectable trace of solar flares: their sudden anti-neutrino (or neutrino) imprint made by proton scattering and pion decays via Delta resonance production on solar corona foot-point. These signals might be observable at largest flare by HK via soft spectra up to tens-hundred MeV energy and by IceCube-PINGU at higher, GeVs energies. We show the expected rate of signals for the most powerful solar flare occurred in recent decades extrapolated for future Megaton detectors. The neutrino solar flare detection with its prompt alarm system may alert astronauts on space journey allowing them to hide themselves into inner rocket container surrounded by fuel or water supply. These container walls are able to defend astronauts from the main lethal (the dominant soft component) radiation wind due to such largest solar flares. **20 Jan 2005, 4-17 March 2012, 6 Sept 2017**

Probing Lorentz Invariance Violation with Absorption of Astrophysical Gamma-rays by Solar Photons

Justin D. **Finke**, Parshad Patel
ApJ **2024**
https://arxiv.org/pdf/2403.07063.pdf
We compute in detail the absorption optical depth for astrophysical γ-ray photons interacting with solar photons to produce electron positron pairs. This effect is greatest for γ-ray sources at small angular distances from the Sun, reaching optical depths as high as $\tau_{\gamma\gamma} \sim 10-2$. We also calculate this effect including modifications to the absorption cross section threshold from subluminal Lorentz invariance violation (LIV). We show for the first time that subluminal LIV can lead to increases or decreases in $\tau_{\gamma\gamma}$ compared to the non-LIV case. We show that, at least in principle, LIV can be probed with this effect with observations of γ-ray sources near the Sun at $\gtrsim$20 TeV by HAWC or LHAASO, although a measurement will be extremely difficult due to the small size of the effect.

Neutral Pion Production in Solar Flares

Forrest, D. J.; Vestrand, W. T.; Chupp, E. L.; Rieger, E.; Cooper, J. F.; Share, G. H.
Proceedings from the 19th International Cosmic Ray Conference, Volume 4 (SH Sessions), p.146, **1985**
The Gamma-Ray Spectrometer (GRS) on SMM has detected more than 130 flares with emission approx 300 keV. More than 10 of these flares were detected at photon energies 10 MeV. Although the majority of the emission at 10 MeV must be from electron bremsstrahlung, at least two of the flares have spectral properties 40 MeV that require gamma rays from the decay of neutral pions. It is found that pion production can occur early in the impulsive phase as defined by hard X-rays near 100 keV. It is also found in one of these flares that a significant portion of this high-energy emission is produced well after the impulsive phase. This extended production phase, most clearly observed at high energies, may be a signature of the acceleration process which produces solar energetic particles (SEP's) in space.

Evidence from Hard X-Rays for Two-Stage Particle Acceleration in a Solar Flare

Frost, K. J.; Dennis, B. R.

Astrophysical Journal, vol. 165, p.655, **1971**

http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1971ApJ...165..655F&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetyp
f

A solar X-ray burst which evolves in time through two nonthermal phases is presented
The burst is considered to be bremsstrahlung from electrons accelerated in two stages in the solar atmosphere
In the first stage, acceleration effectively to 100 keV occurs, perhaps by an induced electric field; in the second stage, the acceleration to higher energies could occur by a Fermi mechanism operating in a shock front
1969 March 30

On the motions of RHESSI flare footpoints –

W. Q. **Gan**, Y. P. Li, L. I. Miroshnichenko, E-print, Oct 2006, File

Advances in Space Research, Volume 41, Issue 6, *Pages 908-913,* **2008**

The footpoint motions of flare hard X-ray (HXR) sources are directly related to the reconnection scenario of a solar flare. In this work, we tried to extract the information of footpoint motions for a number of flares observed with RHESSI. We found that the RHESSI flare results of the footpoint motions strongly support the classification proposed from the observations of YOHKOH/HXT. Furthermore, it is found that a flare can consist of two types of footpoint motions. We discussed the connections of the footpoint motions with the two-dimensional reconnection models.

Everything Under the Sun: A Review of Solar Neutrino

G. D. Orebi **Gann**

2015

http://arxiv.org/pdf/1504.02154v1.pdf

Solar neutrinos offer a unique opportunity to study the interaction of neutrinos with matter, a sensitive search for potential new physics effects, and a probe of solar structure and solar system formation. This paper describes the broad physics program addressed by solar neutrino studies, presents the current suite of experiments programs, and describes several potential future detectors that could address the open questions in this field. This paper is a summary of a talk presented at the Neutrino 2014 conference in Boston.

EOVSA Coverage of a Recent Gamma-ray Flare

Dale **Gary** and Gregory Fleishman.

RHESSI Science Nugget No. 252, May **2015**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/EOVSA_Coverage_of_a_Recent_Gamma-Ray_Flare

Expanded Owens Valley Solar Array (EOVSA) Imaging spectroscopy in the microwave range from the new Owens Valley instrument. **2015-05-05**

SOL2015-05-05 flare was quite remarkable due to the fact that its X-ray emission extends well into the gamma-ray range. This nugget gives an overview of the flare and shows the correspondence between the microwave and hard X-ray emissions.

The recent X2.7 flare of SOL2015-05-05 was unusually energetic in its non-thermal properties, and merits further study. The unique microwave data provided EOVSA give the opportunity to study the time behavior of the pulsations more closely, and to relate them to the magnetic field in the source region due to the microwave spectral dependence of peak frequency on magnetic field strength.

Sun CubE OnE: A Multi-wavelength Synoptic Solar Micro Satellite

L. **Giovannelli**, F. Berrilli, M. Casolino, F. Curti, D. Del Moro, D. Calchetti, M. Cantoresi, A. D'Ambrosio, G. Francisco, P. Giobbi, L. Marcelli, P. Mazzotta, R. Mugatwala, G. Pucacco, R. Reda, S. K Dhara, F. Tombesi, D. Blandino, N. Benigno, M. Cilia, A. Di Salvo, V. Di Tana, F. Ingiosi, S. Loddo, M. Marmonti, M. Musazzi, S. Simonetti, G. Truscelli

Adv. Space Res. **2022**

https://arxiv.org/pdf/2209.12251.pdf

The Sun cubE onE (SEE) is a 12U CubeSat mission proposed for a phase A/B study to the Italian Space Agency that will investigate Gamma and X-ray fluxes and ultraviolet (UV) solar emission to support studies in Sun-Earth interaction and Space Weather from LEO. More in detail, SEE's primary goals are to measure the flares emission from soft-X to Gamma ray energy range and to monitor the solar activity in the Fraunhofer Mg II doublet at 280 nm,

taking advantage of a full disk imager payload. The Gamma and X-ray fluxes will be studied with unprecedented temporal resolution and with a multi-wavelength approach thanks to the combined use of silicon photodiode and silicon photomultiplier (SiPM) -based detectors. The flare spectrum will be explored from the keV to the MeV range of energies by the same payload, and with a cadence up to 10 kHz and with single-photon detection capabilities to unveil the sources of the solar flares. The energy range covers the same bands used by GOES satellites, which are the standard bands for flare magnitude definition. At the same time SiPM detectors combined with scintillators allow to cover the non-thermal bremsstrahlung emission in the gamma energy range. Given its UV imaging capabilities, SEE will be a key space asset to support detailed studies on solar activity, especially in relation to ultraviolet radiation which strongly interacts with the upper layers of the Earth's atmosphere, and in relation to space safety, included in the field of human space exploration. The main goal for the UV payload is to study the evolution of the solar UV emission in the Mg II band at two different time scales: yearly variations along the solar cycle and transient variations during flare events.

Status of Direct Determination of Solar Neutrino Fluxes after Borexino

M. C. **Gonzalez-Garcia**, Michele Maltoni, João Paulo Pinheiro, Aldo M. Serenelli
Journal of High Energy Physics (JHEP) **2023**
https://arxiv.org/pdf/2311.16226.pdf
We determine the solar neutrino fluxes from the global analysis of the most up-to-date terrestrial and solar neutrino data including the final results of the three phases of Borexino. The analysis are performed in the framework of three-neutrino mixing with and without accounting for the solar luminosity constraint. We discuss the independence of the results on the input from the Gallium experiments. The determined fluxes are then compared with the predictions provided by the latest Standard Solar Models. We quantify the dependence of the model comparison with the assumptions about the normalization of the solar neutrino fluxes produced in the CNO-cycle as well as on the particular set of fluxes employed for the model testing.

RE-EVALUATION OF THE NEUTRON EMISSION FROM THE SOLAR FLARE OF 2005 SEPTEMBER 7, DETECTED BY THE SOLAR NEUTRON TELESCOPE AT SIERRA NEGRA

L. X. **González**1, J. F. Valdés-Galicia2, F. Sánchez3, Y. Muraki4, T. Sako4, K. Watanabe5, Y. Matsubara4,Y. Nagai4, S. Shibata6, T. Sakai7Show full author list
2015 ApJ 814 136
The X17.0 solar flare of **2005 September 7** released high-energy neutrons that were detected by the Solar Neutron Telescope (SNT) at Sierra Negra, Mexico. In three separate and independent studies of this solar neutron event, several of its unique characteristics were studied; in particular, a power-law energy spectra was estimated. In this paper, we present an alternative analysis, based on improved numerical simulations of the detector using GEANT4, and a different technique for processing the SNT data. The results indicate that the spectral index that best fits the neutron flux is around 3, in agreement with previous works. Based on the numerically calculated neutron energy deposition on the SNT, we confirm that the detected neutrons might have reached an energy of 1 GeV, which implies that 10 GeV protons were probably produced; these could not be observed at Earth, as their parent flare was an east limb event.

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**

Particle Acceleration and Transport at the Sun Inferred from Fermi/LAT Observations of >100 MeV Gamma-rays

Nat **Gopalswamy**, Pertti Mäkelä, Seiji Yashiro
AOGS2021 Conference Proceedings for the 18th Annual Meeting **2021**
https://arxiv.org/ftp/arxiv/papers/2108/2108.11286.pdf **File**

The sustained gamma-ray emission (SGRE) events from the Sun are associated with an ultrafast (2000 km/s or greater) halo coronal mass ejection (CME) and a type II radio burst in the decameter-hectometric (DH) wavelengths. The SGRE duration is linearly related to the type II burst duration indicating that >300 MeV protons required for SGREs are accelerated by the same shock that accelerates tens of keV electrons that produce type II bursts. When magnetically well connected, the associated solar energetic particle (SEP) event has a hard spectrum, indicating copious acceleration of high-energy protons. In one of the SGRE events observed on **2014 January 7** by Fermi/LAT, the SEP event detected by GOES has a very soft spectrum with not many particles beyond 100 MeV. This contradicts the presence of the SGRE, implying the presence of significant number of >300 MeV protons. Furthermore, the durations of the type II burst and the SGRE agree with the known linear relationship between them (Gopalswamy et al. 2018, ApJ 868, L19). We show that the soft spectrum is due to poor magnetic connectivity of the shock nose to an Earth observer. Even though the location of the eruption (S15W11) is close to the disk center, the CME propagated non-radially making the CME flank crossing the ecliptic rather than the nose. High-energy particles are accelerated near the nose, so they do not reach GOES but they do precipitate to the vicinity of the eruption region to produce SGRE. This study provides further evidence that SGRE is caused by protons accelerated in shocks and propagating sunward to interact with the atmospheric ions.

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 Volume 915, Issue 2, id.82, **2021**
https://arxiv.org/ftp/arxiv/papers/2105/2105.01206.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac004f/pdf **File**
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

A Weak Fermi Gamma-ray Event Associated with a Halo CME and a Type II Radio Burst

N. Gopalswamy, P. Mäkelä, S. Yashiro
Proceedings URSI GASS 2020 **2021**
https://arxiv.org/ftp/arxiv/papers/2105/2105.01212.pdf

We report on the **2015 June 25** sustained gamma-ray emission (SGRE) event associated with a halo coronal mass ejection and a type II radio burst in the decameter-hectometric (DH) wavelengths. The duration and ending frequency of the type II burst are linearly related to the SGRE duration as found in previous works involving intense gamma-ray events. This study confirms that the SGRE event is due to protons accelerated in the shock that produced the DH type II burst.
Table 1. The five halo CMEs from AR 12371 (18 Jun- 01 Jul)

Interplanetary shocks as a source of sustained gamma-ray emission from the Sun

Nat **Gopalswamy** & Pertti Mäkelä
EGU2020 May **2020**
Presentation #21334 **File**

- The lack of correlation between SEP protons and those inferred from SGRE is explained.
- High-energy particles from CME nose at large ecliptic distances is not well observed at Earth → underestimate of high-energy proton number

- Since SGRE sources are spatially extended, gamma-ray flux is underestimated, so are the inferred proton number
- Well connected events are reasonably correlated; accounting for the above effects move the data points close to the well-connected group
- Shock source is consistent with the SGRE properties

Positron Processes in the Sun **Review**

Nat **Gopalswamy**

Atoms **2020**

https://arxiv.org/ftp/arxiv/papers/2004/2004.04280.pdf **File**

Positrons play a major role in the emission of solar gamma-rays at energies from a few hundred keV to >1 GeV. Although the processes leading to positron production in the solar atmosphere are well known, the origin of the energetic particles that interact with the ambient particles is poorly understood. With the aim of understanding the full gamma-ray spectrum of the Sun, I review the key emission mechanisms that contribute to the observed gamma-ray spectrum, focusing on the ones involving positrons. In particular, I review the processes involved in the 0.511 MeV positron annihilation line and the positronium continuum emissions at low energies, and the pion continuum emission at high energies in solar eruptions. It is thought that particles accelerated at the flare reconnection and at the shock driven by coronal mass ejections are responsible for the observed gamma-ray features. Based on some recent developments I suggest that energetic particles from both mechanisms may contribute to the observed gamma-ray spectrum. **2003 October 28, 2014 Sep 1**

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**, No. 2, 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.

CESRA #370 Feb **2020**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/The_Temporal_and_Spatial_Extension_of_Gamma-ray_Emission_from_the_Sun

Fermi, Wind, and SOHO Observations of Sustained Gamma-Ray Emission from the Sun

N. **Gopalswamy**(1), P. Mäkelä(1,2), S. Yashiro(1,2), A. Lara(1,2,3), H. Xie(1,2), S. Akiyama(1,2), R. J. MacDowall(1)

URSI AP-RASC 2019, New Delhi, India, 09 - 15 March **2019** **File**

https://sci-hub.ru/10.23919/URSIAP-RASC.2019.8738168

https://arxiv.org/ftp/arxiv/papers/1810/1810.08958.pdf

We report on the linear relationship between the durations of two types of electromagnetic emissions associated with shocks driven by coronal mass ejections: sustained gammaray emission (SGRE) and interplanetary type II radio bursts. The relationship implies that shocks accelerate ~10 keV electrons (for type II bursts) and >300 MeV protons (for SGRE) roughly over the same duration. The SGRE events are from the Large Area Telescope (LAT) on board the Fermi satellite, while the type II bursts are from the Radio and Plasma Wave Experiment (WAVES) on board the Wind spacecraft. Here we consider five SGRE events that were not included in a previous study of events with longer duration (>5 hours). The five events are selected by relaxing the minimum duration to 3 hours. We found that some SGRE events had a tail that seems to last until the end of the associated type II burst. We pay special

attention to the **2011 June 2** SGRE event that did not have a large solar energetic particle event at Earth or at the STEREO spacecraft that was well connected to the eruption. We suggest that the preceding CME acted as a magnetic barrier that mirrored protons back to Sun. **2011 June 7, 2012 January 27, 2012 May 17, 2013 May 13**

On the Shock Source of Sustained Gamma-Ray Emission from the Sun

N **Gopalswamy**, P. Makela, S. Yashiro, A. Lara, S. Akiyama, H. Xie

Journal of Physics: Conference Series, Volume 1332, Issue 1, article id. 012004 . **2019**

https://arxiv.org/ftp/arxiv/papers/1907/1907.13318.pdf **File**

https://iopscience.iop.org/article/10.1088/1742-6596/1332/1/012004/pdf

It has recently been shown that the spatially and temporally extended gamma-ray emission in solar eruptions are caused by greater than 300 MeV protons precipitating on the Sun from shocks driven by coronal mass ejections (CMEs). The gamma-rays result from the decay of neutral pions produced in the proton-proton interaction when the greater than 300 MeV protons collide with those in the chromosphere. The evidence comes from the close correlation between the durations of the sustained gamma-ray emission (SGRE) and the associated interplanetary (IP) type II radio bursts. In this paper, we provide further evidence that support the idea that protons accelerated in IP shocks driven by CMEs propagate toward the Sun, precipitate in the chromosphere to produce the observed SGRE. We present the statistical properties of the SGRE events and the associated CMEs, flares, and type II radio bursts. It is found that the SGRE CMEs are similar to those associated with ground level enhancement events. The CME speed is well correlated with the SGRE fluence. High CME speed is an important requirement for the occurrence of SGRE, while the flare size is not. Based on these results, we present a schematic model illustrating the spatially and temporally extended nature of SGRE related to the CME flux rope-shock structure. **2011 March 07, 11/06/2 , 11/06/7 , 2012 January 23, 12/01/27 , 12/03/05 , 12/03/07, 12/03/09, 12/03/10, 12/05/17 , 13/05/13 , 13/05/14, 13/05/15, 2014 February 25, 14/09/01 , 2015 June 21, 17/09/06, 17/09/10**

Table 1. List of SGRE events with the associated CMEs, flares, and type II bursts

Interplanetary Type II Radio Bursts from Wind/WAVES and Sustained Gamma-Ray Emission from Fermi/LAT: Evidence for Shock Source

Nat **Gopalswamy**1, Pertti Mäkelä1,2, Seiji Yashiro1,2, Alejandro Lara1,2, Hong Xie1,2, Sachiko Akiyama1,2, and Robert J. MacDowall1

2018 ApJL 868 L19

http://iopscience.iop.org/article/10.3847/2041-8213/aaef36/pdf **File**

We present quantitative evidence that interplanetary type II radio bursts and sustained gamma-ray emission (SGRE) events from the Sun are closely related. Out of about 30 SGRE events reported in Share et al. we consider 13 events that had a duration exceeding ~5 hr to exclude any flare-impulsive phase gamma-rays. The SGRE duration also has a linear relation with the ending frequency of the bursts. The synchronism between the ending times of SGRE and the type II emission strongly supports the idea that the same shock accelerates electrons to produce type II bursts and protons (>300 MeV) that propagate from the shock to the solar surface to produce SGRE via pion decay. The acceleration of high-energy particles is confirmed by the associated solar energetic particle (SEP) events detected at Earth and/or at the Solar Terrestrial Relations Observatory spacecraft. Furthermore, the presence of >300 MeV protons is corroborated by the fact that the underlying coronal mass ejections (CMEs) had properties identical to those associated with ground-level enhancement events: they had speeds of >2000 km s−1 and all were full-halo CMEs. Many SEP events did not have detectable flux at Earth in the >300 MeV energy channels, presumably because of poor magnetic connectivity. **1991 June 11 , 2011 Mar 7, 2012 Jan 23 , 2012 Mar 5, 2012 Mar 7, 2012 Mar 9, 2012 Mar 10, 2013 May 13, 2013 May 14, 2013 May 15, 2014 Feb 25, 2015 Jun 21, September 6 2017, 2017 Sep 10**

Table 1 Properties of SGREs and the Associated CMEs, Type II Bursts, and SEP Events

Fermi, Wind, and SOHO Observations of Sustained Gamma-Ray Emission from the Sun

N. **Gopalswamy**, P. Makela, S. Yashiro, A. Lara, H. Xie, S. Akiyama, R. J. MacDowall

Submitted to 2019 URSI Asia Pacific Radio Science Conference **2018**

https://arxiv.org/ftp/arxiv/papers/1810/1810.08958.pdf

We report on the linear relationship between the durations of two types of electromagnetic emissions associated with shocks driven by coronal mass ejections: sustained gamma-ray emission (SGRE) and interplanetary type II radio bursts. The relationship implies that shocks accelerate about 10 keV electrons (for type II bursts) and greater than 300 MeV protons (for SGRE) roughly over the same duration. The SGRE events are from the Large Area Telescope (LAT) on board the Fermi satellite, while the type II bursts are from the Radio and Plasma Wave Experiment (WAVES) on board the Wind spacecraft. Here we consider five SGRE events that were not included in a previous study of events with longer duration (greater than 5 hours). The five events are selected by relaxing the minimum duration to 3 hours. We found that some SGRE events had a tail that seems to last until the end of the associated type II burst. We pay special attention to the 2011 June 2 SGRE event that did not have a large solar energetic

particle event at Earth or at the STEREO spacecraft that was well connected to the eruption. We suggest that the preceding CME acted as a magnetic barrier that mirrored protons back to Sun. **2-3 June 2011, 2011 June 7, 27-28 Jan 2012, 2012 May 17, 13 May 2013**

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.

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.

Direct Observation of Two-Step Magnetic Reconnection in a Solar Flare

Tingyu **Gou**, Astrid M. Veronig, Ewan Dickson, Aaron Hernandez-Perez, Rui Liu
ApJL, 845: L1 (**2017**)
http://sci-hub.cc/10.3847/2041-8213/aa813d
https://arxiv.org/pdf/1707.06198.pdf
We report observations of an eruptive X2.8 flare on **2013 May 13**, which shows two distinct episodes of energy release in the impulsive phase. The first episode is characterized by the eruption of a magnetic flux rope, similar to the energy-release process in most standard eruptive flares. While the second episode, which is stronger than the first normal one and shows enhanced high-energy X-ray and even γ-ray emissions, is closely associated with magnetic reconnection of a large-scale loop in the aftermath of the eruption. The reconnection inflow of the loop leg is observed in the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) 304 \r{A} passband and accelerates towards the reconnection region to a speed as high as ∼130 km/s. Simultaneously the corresponding outflow jets are observed in the AIA hot passbands with a speed of ∼740 km/s and mean temperature of ∼14 MK. RHESSI observations show a strong burst of hard X-ray (HXR) and γ-ray emissions with hard electron spectra of δ≈3, exhibiting a soft-hard-harder behavior. A distinct altitude decrease of the HXR loop-top source coincides with the inward swing of the loop leg observed in the AIA 304 \r{A} passband, which is suggested to be related to the coronal implosion. This fast inflow of magnetic flux contained in the loop leg greatly enhances the reconnection rate and results in very efficient particle acceleration in the second-step reconnection, which also helps to achieve a second higher temperature peak up to T ≈ 30 MK.

Eruptive Flare, CME, and Shock Wave in the 25 August 2001 High-Energy Solar Event

V. V. **Grechnev**, A. A. Kochanov & A. M. Uralov
Solar Physics volume 298, Article number: 49 (**2023**)
https://doi.org/10.1007/s11207-023-02144-3
The major SOL**2001-08-25** event produced a fast coronal mass ejection (CME: 1430 km s−1), strong flare emissions in hard X-rays and γ-rays extending to high energies, and neutrons detected both on spacecraft and by a low-latitude neutron monitor. To supplement the probable picture of this outstanding event, we reconstruct kinematic plots of the eruption and the shock-wave history. The hard X-ray and γ-ray emissions exhibited soft-hard-soft evolution. The emissions were strongest and hardest during a two-minute interval soon after the highest change rate of the magnetic flux within the flare ribbons of 2.6×10^{19} Mx s−1, which was simultaneous with the reconstructed acceleration of the erupting flux rope. We reveal an indication of accelerated electrons injected into the erupting flux rope that then precipitated far from the main flare site, producing a hard X-ray source that moved along the footprint of a

stretching flux-rope leg. These results suggest that the particle acceleration was governed by magnetic reconnection during the eruption. As in a typical situation, a piston shock was excited early in the impulsive phase and gradually transformed into a bow shock later. The frequency drift of a Type-II burst is shown to be proportional to a power of frequency f, $df/dt \propto -f^{\epsilon}$, with a typical range of ϵ being between 5/3 and 2. Overall, the SOL**2011-08-25** event was a typical eruptive two-ribbon flare. Its strength was determined mainly by the intensity of the reconnection processes.

Radio, Hard X-Ray, and Gamma-Ray Emissions Associated with a Far-Side Solar Event

V.V. **Grechnev** (1), V.I. Kiselev (1), L.K. Kashapova (1, 2), A.A. Kochanov (1, 2), I.V. Zimovets (3, 4, 5), A.M. Uralov (1), B.A. Nizamov (6, 7), I.Yu. Grigorieva(8), D.V. Golovin (3), M.L. Litvak (3), I.G. Mitrofanov (3), A.B. Sanin

Solar Phys. **293**, Article number: 133 **2018**

https://arxiv.org/pdf/1808.10103.pdf **File**

https://link.springer.com/content/pdf/10.1007/s11207-018-1352-z.pdf

The SOL**2014-09-01** far-side solar eruptive event produced hard electromagnetic and radio emissions observed with detectors at near-Earth vantage points. Especially challenging was a long-duration >100 MeV γ-ray burst probably produced by accelerated protons exceeding 300 MeV. This observation raised a question of how high-energy protons could reach the Earth-facing solar surface. Some preceding studies discussed a scenario in which protons accelerated by a CME-driven shock high in the corona return to the solar surface. We continue with the analysis of this challenging event, involving radio images from the Nan\c{c}ay Radioheliograph and hard X-ray data from the High Energy Neutron Detector (HEND) of the Gamma-Ray Spectrometer onboard the Mars Odyssey space observatory located near Mars. HEND recorded unocculted flare emission. The results indicate that the emissions observed from the Earth's direction were generated by flare-accelerated electrons and protons trapped in static long coronal loops. Their reacceleration is possible in these loops by a shock wave, which was excited by the eruption, being initially not CME-driven. The results highlight the ways to address remaining questions.

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.

Spectral Hardening of Large Solar Flares

Paolo C. **Grigis** & Arnold O. Benz

E-print, August 2007, Astrophysical Journal, 683:1180–1191, **2008**

http://www.journals.uchicago.edu/toc/apj/2008/683/2

The evidence we find points toward a single acceleration mechanism acting in the two phases, rather than two different separated mechanisms, because the impulsive and gradual phases are closely interconnected in time and space.

Spectral Hardening in Large Solar Flares

P. C. **Grigis** and A. O. Benz

A&A, 2007, File
In particular, we investigate whether two different acceleration mechanisms are responsible for the impulsive and gradual phases. The temporal evolution of the spectra is compared with the configuration and motion of the hard X-ray sources in RHESSI images.
Both soft-hard-soft (impulsive) phases and hardening (gradual) phases are observed during the events and are well described by piecewise linear dependence of the spectral index on the logarithm of the flux. The transition between the impulsive and gradual phases is smooth and progressive rather than abrupt, both in spectra and images. Comparison with a pure trapping model in the late phase leads to good agreement with the observation for the spectral index vs. flux relation, but poor predictions for the spectral curvature.
Conclusions. The evidence we find points toward a single acceleration mechanism acting in the two phases, rather than two different separated mechanisms, because the impulsive and gradual phases are closely interconnected in time and space.
7-NOV-2004 16:05 X2.0 F
10-NOV-2004 02:13 X2.6 A
17-JAN-2005 09:52 X3.9 B
19-JAN-2005 08:23 X1.4 C & D
20-JAN-2005 07:01 X7.1 E

Observations and Models of the Dynamical Evolution of Solar Flares

-- Paolo C. **Grigis**, Thesis, E-print, Nov **2006**
http://solar.physics.montana.edu/cgi-bin/eprint/index.pl?entry=2095
In this thesis, novel **RHESSI hard X-ray observations** of solar flares are compared with quantitative predictions from modern theoretical models of stochastic acceleration of electrons.

The evolution of reconnection along an arcade of magnetic loops.

Grigis, P. C., Benz, A. O. ApJ 625, L143-L146, **2005**, file .
We study quantitatively the hard X-ray spectral evolution of large solar flares featuring hardening trends. In particular, we investigate whether two different acceleration mechanisms are responsible for the impulsive and gradual phases.
The evidence we find points toward a single acceleration mechanism acting in the two phases, rather than two different separated mechanisms, because the impulsive and gradual phases are closely interconnected in time and space.

Quasi-Periodic Pulsations: Fermi/GBM Results

D. **Gruber** and Pawel Lachowicz
RHESSI Science Nuggets, No. 161, Oct **2011**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Quasi-Periodic_Pulsations:_Fermi/GBM_Results
Here, we present time series and periodogram analyses of four solar flares which were observed by the Fermi Gamma-Ray Burst Monitor (GBM) and display compelling quasi-periodic behavior in their light curves. A more comprehensive analysis on this subject can be found here, and a general review of coronal waves and oscillations here.

Quasi-periodic pulsations in solar flares: new clues from the Fermi Gamma-Ray Burst Monitor

D. **Gruber**1, P. Lachowicz2, E. Bissaldi3, M. S. Briggs4, V. Connaughton4, J. Greiner1, A. J. van der Horst4, G. Kanbach1, A. Rau1, P. N. Bhat4, R. Diehl1, A. von Kienlin1, R. M. Kippen5, C. A. Meegan6, W. S. Paciesas4, R. D. Preece4 and C. Wilson-Hodge
A&A 533, A61 (**2011**)
Aims. In the past four decades, it has been observed that solar flares display quasi-periodic pulsations (QPPs) from the lowest, i.e. radio, to the highest, i.e. gamma-ray, frequencies in the electromagnetic spectrum. It remains unclear which mechanism creates these QPPs. In this paper, we analyze four bright solar flares that display compelling signatures of quasi-periodic behavior and were observed with the Gamma-Ray Burst Monitor (GBM) onboard the Fermi satellite. Because GBM covers over three decades in energy (8 keV to 40 MeV), it is regarded as a key instrument in our attempt to understand the physical processes that drive solar flares.
Methods. We tested for periodicity in the time series of the solar flares observed by GBM by applying a classical periodogram analysis. However, in contrast to previous authors, we did not detrend the raw light curve before creating the power spectral density (PSD) spectrum. To assess the significance of the frequencies, we used a method that is commonly applied to X-ray binaries and Seyfert galaxies. This technique takes into account the underlying continuum of the PSD, which for all of these sources has a $P(f) \sim f^{-\alpha}$ dependence and is typically labeled red-noise.
Results. We checked the reliability of this technique by applying it to observations of a solar flare that had been observed by the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). These data contain, besides any potential periodicity from the Sun, a 4 s rotational period caused by the rotation of the spacecraft about its axis. We were unable to identify any intrinsic solar quasi-periodic pulsation but we did manage to reproduce the instrumental periodicity. Moreover, with the method adopted here, we do not detect significant QPPs in the four

bright solar flares observed by GBM. We stress that for this kind of analyses it is of utmost importance to account appropriately for the red-noise component in the PSD of these astrophysical sources.

A Basic Introduction to the Physics of Solar Neutrinos Review

Mike **Guidry**, Jay Billings
2018
https://arxiv.org/pdf/1812.00035.pdf
A comprehensive introduction to the theory of the solar neutrino problem is given that is aimed at instructors who are not experts in quantum field theory but would like to incorporate these ideas into instruction of advanced undergraduate or beginning graduate students in courses like astrophysics or quantum mechanics, it is also aimed at the inquisitive student who would like to learn this topic on their own. The presentation assumes as theoretical preparation only that the reader is familiar with the basics of quantum mechanics in Dirac notation and elementary differential equations and matrices.

The Solar Disk at High Energies

Miguel **Gutiérrez**1, Manuel Masip1, and Sergio Muñoz1
2022 ApJ 941 86
https://iopscience.iop.org/article/10.3847/1538-4357/aca020/pdf
High energy cosmic rays illuminate the Sun and produce an image that could be observed in up to five different channels: a cosmic-ray shadow (whose energy dependence has been studied by HAWC); a gamma-ray flux (observed at $E \leq 200$ GeV by Fermi-LAT); a muon shadow (detected by ANTARES and IceCube); a neutron flux (undetected, as there are no hadronic calorimeters in space); a flux of high energy neutrinos. Since these signals are correlated, the ones already observed can be used to reduce the uncertainty in the still undetected ones. Here we define a simple setup that uses the Fermi-LAT and HAWC observations to imply very definite fluxes of neutrons and neutrinos from the solar disk. In particular, we provide a fit of the neutrino flux at 10 GeV–10 TeV that includes its dependence on the zenith angle and on the period of the solar cycle. This flux represents a neutrino floor in indirect dark matter searches. We show that in some benchmark models the current bounds on the dark matter–nucleon cross section push the solar signal below this neutrino floor.

Implications of X-ray Observations for Electron Acceleration and Propagation in Solar Flares

G.D. **Holman**1, M. J. Aschwanden2, H. Aurass3, M. Battaglia4, P. C. Grigis5, E. P. Kontar6, W. Liu1, P. Saint-Hilaire7, and V. V. Zharkova8
Space Sci. Rev., **2011, File** **A Review**
High-energy X-rays and g-rays from solar flares were discovered just over fifty years ago. Since that time, the standard for the interpretation of spatially integrated flare X-ray spectra at energies above several tens of keV has been the collisional thick-target model. After the launch of the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) in early 2002, X-ray spectra and images have been of sufficient quality to allow a greater focus on the energetic electrons responsible for the X-ray emission, including their origin and their interactions with the flare plasma and magnetic field. The result has been new insights into the flaring process, as well as more quantitative models for both electron acceleration and propagation, and for the flare environment with which the electrons interact. In this article we review our current understanding of electron acceleration, energy loss, and propagation in flares. Implications of these new results for the collisional thick-target model, for general flare models, and for future flare studies are discussed.

Constraining Neutrino Lifetimes and Magnetic Moments via Solar Neutrinos in the Large Xenon Detectors

Guo-yuan **Huang**, Shun Zhou
2018
https://arxiv.org/pdf/1810.03877.pdf
The multi-ton-scale liquid xenon detectors, with an excellent energy resolution of a few keV, will be constructed to probe the dark-matter particles. In this paper, we show that precision measurements of the low-energy solar neutrinos via the elastic neutrino-electron scattering in this kind of detectors are able to improve the present limits on neutrino lifetimes and neutrino magnetic moments by about one order of magnitude. We carefully study the impact of the unknown neutrino mass spectrum on the ultimate limits in the case of non-radiative visible neutrino decays. In the case of invisible neutrino decays, the lower bounds $\tau_1/m_1 \gtrsim 3\times10^{-2}$ s/eV and $\tau_2/m_2 \gtrsim 8\times10^{-3}$ s/eV at

the 2σ level can be obtained for a total exposure of 70 ton·year. Furthermore, a restrictive constraint on the effective magnetic moment of neutrinos μeff≲2.6×10−12 μB, with μB being the Bohr magneton, can be achieved. This is among the best results that will be available in the laboratory experiments in the near future.

Cosmic-Ray Interactions in the Solar Atmosphere

Hugh S. **Hudson**1,2 , Alec MacKinnon1 , Mikolaj Szydlarski3 , and Mats Carlsson3
MNRAS **2020** 491. Issue 4, 4852-4856 H
https://arxiv.org/pdf/1910.0 1186.pdf
https://sci-hub.si/10.1093/mnras/stz3373
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

Chapter 9 - High-Energy Solar Physics Review

H.S. **Hudson** and A.L. MacKinnon
In: ***The Sun as a Guide to Stellar Physics*** ***Book***
Eds. Oddbjørn Engvold, Jean-Claude Vial, and Andrew Skumanich
Elsevier , November **2018**
https://www.sciencedirect.com/book/9780128143346/the-sun-as-a-guide-to-stellar-physics
This chapter deals generally with the high-energy astrophysics of the Sun, specifically with solar flares and coronal mass ejections (CMEs), but it also touches on the whole range of nonthermality or departures from Maxwellian distributions in solar plasmas. Radio, x-ray, and γ-ray observations provide primary remote-sensing observations of these departures, but such signatures can be hidden by brighter thermal emissions that may not be as fundamental in physics events. The solar paradigm for flare/CME development appears to match many of the new stellar observations of similar phenomena, but the limitations of observational sensitivity mean that we have few direct observations of the expected hard x-rays and none at all of the γ-rays that could confirm this.

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, pp. 49-53 **2017 File (2018)**
https://doi.org/10.1017/S1743921317009681
https://arxiv.org/pdf/1711.05583.pdf
sci-hub.ru/10.1017/S1743921317009681
https://www.cambridge.org/core/journals/proceedings-of-the-international-astronomical-union/article/relationship-between-longduration-gammaray-flares-and-solar-cosmic-rays/AA110058A9A4D2D8F8AB885CD9D86A28
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**

A Lasso Model for Solar Gamma-Ray Events

Hugh **Hudson**

RHESSI Science Nuggets, No. 300, May **2017**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/A_Lasso_Model_for_Solar_Gamma-ray_Events
Retracting large-scale coronal magnetic fields can trap SEP particles to support a long-duration gamma-ray event. A toy model hoping to explain the SEP/LAT relationship. **2011-06-07, 2012-03-07**

High Energies in the Inner Heliosphere

Hugh **Hudson**
RHESSI Science Nuggets, No. 258, Aug **2015**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/High_Energies_in_the_Inner_Heliosphere
How bright is the hard X-ray Sun at solar minimum? We do not know, since even RHESSI has only established upper limits at present (Ref. [1]). Why should it emit any hard X-rays at all? This is easy to answer, at least partially, and there are observations by Fermi at much higher photon energies (Ref. [2]) - indeed, Fermi observes not only the disk of the Sun, but also a diffuse source centered on it. Both of these components originate in galactic cosmic rays with energies high enough to penetrate into the inner heliosphere, and even to strike and interact in the photosphere itself. This would be the solar equivalent, not much explored yet, of the celebrated Størmer problem of cosmic-ray transport around the Earth.

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**

"Impulse Response Flares" and Gamma Rays

Hugh **Hudson** and Stephen White
RHESSI Nugget, No. 188, Nov **2012**
We've speculated in this Nugget that we can identify two distinct radiation signatures with the same process: the prompt acceleration of primary protons to energies above 100 MeV in regions of intense magnetic fields. The impulse-response time profile of this process may reveal a somewhat different paradigm for flare energetics, one that has a characteristic temporal signature on a time scale of about 20 s. If this is so, we may expect to see more such events with Fermi and at even shorter radio wavelengths with the new ALMA facility. RHESSI may also have signatures of this process that have not yet been disentangled from other features it detects at its highest energies.
mm-wave radio observations recorded at 86 GHz at the Hat Creek Observatory SOL2010-06-12

Dimmings and Sustained Gamma-Ray Events

Hugh **Hudson** and Nicola Omodei.
RHESSI Nugget, No. 179, July **2012**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Dimmings_and_Sustained_Gamma-Ray_Events
Coronal disruptions reveal themselves as depletions and gamma-ray emissions
SOL2012-03-07

The Alfven Speed above a Sunspot, and Gamma-rays

H. **Hudson**, L. Fletcher
RHESSI Science Nugget, 12 Apr **2011**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/The_Alfven_Speed_above_a_Sunspot,_and_Gamma-rays
It is common for powerful flares to occur actually within sunspots, with their H-alpha ribbons blithely crossing over these regions of very strong magnetic field. What does this association mean for flare theory, and what does it mean for the interesting differences RHESSI has discovered between flares with and without gamma-rays? We discuss these issues in the context of the X-class flare of **February 15, 2011**. This was only the second X-class flare of this solar maximum; it was not a gamma-ray event but it was the source of a clear sunquake.

Coronal Radiation Belts

Hudson, H. S.; MacKinnon, A. L.; De Rosa, M. L.; Frewen, S. F. N.
Astrophysical Journal Letters, Volume 698, Issue 2, pp. L86-L89 (**2009**)
https://arxiv.org/pdf/0905.3824.pdf
The magnetic field of the solar corona has a large-scale dipole character, which maps into the bipolar field in the solar wind. Using standard representations of the coronal field, we show that high-energy ions can be trapped stably in these large-scale closed fields. The drift shells that describe the conservation of the third adiabatic invariant may have complicated geometries. Particles trapped in these zones would resemble the Van Allen belts and could have detectable consequences. We discuss potential sources of trapped particles.

Ion energy storage for post-flare loops

Hudson, H. S
In NASA. Goddard Space Flight Center 19th Intern. Cosmic Ray Conf., Vol. 4 p 58-61 , **1985**
Low-energy non-thermal protons may have long lifetimes in coronal loops with low density and high temperature. If energy were stored in such protons in the initial phases of a solar flare, it could be released slowly during the later phases. Within the present observational limits for post-flare loops, this mechanism should be considered in addition to a field-line reconnection theory of the Kopp and Pneuman type. The thin-target gamma ray emission from the trapped protons is below present limits, but more sensitive observations can test the hypothesis.

Second-stage acceleration in a limb-occulted flare

Hudson, H. S.; Lin, R. P.; Stewart, R. T.
Solar Physics, vol. 75, Jan. **1982**, p. 245-261.
From radio observations it is known that two distinct groups of phenomena occur in large solar flares. The phenomena are related to an impulsive phase of approximately 100 s duration in the early stage of a flare and a following second phase lasting for tens of minutes. A study is presented of the limb-occulted flare event of July 22, 1972, giving particular attention to the second stage particle acceleration. The study takes into account hard X-ray, energetic particle, and radio observations. The conducted analysis shows that second stage acceleration is physically distinct from the impulsive phase, and is characterized by continuous and widespread electron acceleration to high energies, most likely by the type II burst shock wave.

A purely coronal hard X-ray event

Hudson, H. S.
Astrophysical Journal, Part 1, vol. 224, Aug. 15, **1978**, p. 235-240.
OSO 7 observations of a hard X-ray event of coronal origin are described. This event had a duration of more than 42 min as well as an abnormally large hard/soft ratio and apparently occurred after the disappearance of a bright coronal streamer. This gradual hard X-ray event is tentatively associated with open field lines extending well above the closed loop structures that participated in the originating flare. It is noted that a gradual hardening of the hard X-ray spectral distribution occurred during the event. Physical conditions in the source are considered, and the results are compared with observations of other hard X-ray events associated with flares.

Energetic Proton Back-Precipitation onto the Solar Atmosphere in Relation to Long-Duration Gamma-Ray Flares

Adam **Hutchinson**, Silvia Dalla, Timo Laitinen, Georgia A. de Nolfo, Alessandro Bruno, James M. Ryan
ApJ 658, A23 **2022**
https://www.aanda.org/articles/aa/pdf/2022/02/aa42002-21.pdf **File**
https://doi.org/10.1051/0004-6361/202142002
Context. Gamma-ray emission during long-duration gamma-ray flare (LDGRF) events is thought to be caused mainly by > 300 MeV protons interacting with the ambient plasma at or near the photosphere. Prolonged periods of the gamma-ray emission have prompted the suggestion that the source of the energetic protons is acceleration at a coronal mass ejection (CME)-driven shock, followed by particle back-precipitation onto the solar atmosphere over extended times.
Aims. We study the latter hypothesis using test particle simulations, which allow us to investigate whether scattering associated with turbulence aids particles in overcoming the effect of magnetic mirroring, which impedes back-precipitation by reflecting particles as they travel sunwards.

Methods. The instantaneous precipitation fraction, P, the proportion of protons that successfully precipitate for injection at a fixed height, ri, is studied as a function of scattering mean free path, λ and ri. Upper limits to the total precipitation fraction, $\overline{P}$, were calculated for eight LDGRF events for moderate scattering conditions (λ = 0.1 AU). Results. We find that the presence of scattering helps back-precipitation compared to the scatter-free case, although at very low λ values outward convection with the solar wind ultimately dominates. For eight LDGRF events, due to strong mirroring, $\overline{P}$ is very small, between 0.56 and 0.93% even in the presence of scattering.
Conclusions. Time-extended acceleration and large total precipitation fractions, as seen in the observations, cannot be reconciled for a moving shock source according to our simulations. Therefore, it is not possible to obtain both long duration γ ray emission and efficient precipitation within this scenario. These results challenge the CME shock source scenario as the main mechanism for γ ray production in LDGRFs. **2011-03-07, 2012-01-23, 2012-03-05, 2012-03-07, 2012-03-09, 2013-05-13, 2013-05-14, 2014-02-25**

Energetic Proton Back-Precipitation onto the Solar Atmosphere in Relation to Long-Duration Gamma-Ray Flares

Adam **Hutchinson**, Silvia Dalla, Timo Laitinen, Georgia A. de Nolfo, Alessandro Bruno, James M. Ryan
ApJ **2020**
https://arxiv.org/pdf/2012.05146.pdf **File**
Gamma-ray emission during Long-Duration Gamma-Ray Flare (LDGRF) events is thought to be caused mainly by > 300 MeV protons interacting with the ambient plasma at or near the photosphere. Prolonged durations of the gamma-ray emission have prompted the suggestion that the source of the energetic protons is acceleration at a CME-driven shock, followed by particle back-precipitation onto the solar atmosphere over extended times. We study the latter phenomenon by means of test particle simulations, which allow us to investigate the effect of magnetic mirroring, which impedes back-precipitation by reflecting particles as they travel sunwards, and of scattering associated with turbulence in the magnetic field. The precipitation fraction, P, the proportion of protons that successfully precipitate for injection at a fixed height, ri, is studied as a function of ri and scattering mean free path, λ. We characterise how P decreases with increasing radial distance, obtaining a dependence of r−1.78i for λ=0.1 AU, and we find that the presence of moderate scattering helps back-precipitation compared to the scatter-free case. We determine the total precipitation fraction for eight LDGRF events, finding that it is very small, between 0.23 and 1.99\%. ***Time-extended acceleration and large total precipitation fractions, as seen in the observations, cannot be reconciled for a moving shock source according to our simulations. These results challenge the CME-shock source scenario as the main mechanism for γ-ray production in LDGRFs.*** **2011-03-07, 2012-01-23, 2012-03-05, 2012-03-07, 2012-03-09, 2013-05-13, 2013-05-14, 2014-02-25**
Table 2. Total precipitation fractions over the full duration of the eight LDGRF events

ESTIMATING THE PROPERTIES OF HARD X-RAY SOLAR FLARES BY CONSTRAINING MODEL PARAMETERS

J. **Ireland**1, A. K. Tolbert2, R. A. Schwartz2, G. D. Holman3, and B. R. Dennis
2013 ApJ 769 89
We wish to better constrain the properties of solar flares by exploring how parameterized models of solar flares interact with uncertainty estimation methods. We compare four different methods of calculating uncertainty estimates in fitting parameterized models to Ramaty High Energy Solar Spectroscopic Imager X-ray spectra, considering only statistical sources of error. Three of the four methods are based on estimating the scale-size of the minimum in a hypersurface formed by the weighted sum of the squares of the differences between the model fit and the data as a function of the fit parameters, and are implemented as commonly practiced. The fourth method is also based on the difference between the data and the model, but instead uses Bayesian data analysis and Markov chain Monte Carlo (MCMC) techniques to calculate an uncertainty estimate. Two flare spectra are modeled: one from the Geostationary Operational Environmental Satellite X1.3 class flare of **2005 January 19**, and the other from the X4.8 flare of **2002 July 23**. We find that the four methods give approximately the same uncertainty estimates for the 2005 January 19 spectral fit parameters, but lead to very different uncertainty estimates for the 2002 July 23 spectral fit. This is because each method implements different analyses of the hypersurface, yielding method-dependent results that can differ greatly depending on the shape of the hypersurface. The hypersurface arising from the 2005 January 19 analysis is consistent with a normal distribution; therefore, the assumptions behind the three non-Bayesian uncertainty estimation methods are satisfied and similar estimates are found. The 2002 July 23 analysis shows that the hypersurface is not consistent with a normal distribution, indicating that the assumptions behind the three non-Bayesian uncertainty estimation methods are not satisfied, leading to differing estimates of the uncertainty. We find that the shape of the hypersurface is crucial in understanding the output from each uncertainty estimation technique, and that a crucial factor determining the shape of hypersurface is the location of the low-energy cutoff relative to energies where the thermal emission dominates. The Bayesian/MCMC approach also allows us to provide detailed information on probable values of the low-energy cutoff, Ec , a crucial parameter in

defining the energy content of the flare-accelerated electrons. We show that for the 2002 July 23 flare data, there is a 95% probability that Ec lies below approximately 40 keV, and a 68% probability that it lies in the range 7-36 keV. Further, the low-energy cutoff is more likely to be in the range 25-35 keV than in any other 10 keV wide energy range. The low-energy cutoff for the 2005 January 19 flare is more tightly constrained to 107 ± 4 keV with 68% probability. Using the Bayesian/MCMC approach, we also estimate for the first time probability density functions for the total number of flare-accelerated electrons and the energy they carry for each flare studied. For the 2002 July 23 event, these probability density functions are asymmetric with long tails orders of magnitude higher than the most probable value, caused by the poorly constrained value of the low-energy cutoff. The most probable electron power is estimated at 1028.1 erg s–1, with a 68% credible interval estimated at 1028.1-1029.0 erg s–1, and a 95% credible interval estimated at 1028.0-1030.2 erg s–1. For the 2005 January 19 flare spectrum, the probability density functions for the total number of flare-accelerated electrons and their energy are much more symmetric and narrow: the most probable electron power is estimated at 1027.66 ± 0.01 erg s–1 (68% credible intervals). However, in this case the uncertainty due to systematic sources of error is estimated to dominate the uncertainty due to statistical sources of error.

Constraining hot plasma in a non-flaring solar active region with FOXSI hard X-ray observations

Ishikawa, Shin-nosuke; Glesener, Lindsay; Christe, Steven; Ishibashi, Kazunori; Brooks, David H.; Williams, David R.; Shimojo, Masumi; Sako, Nobuharu; Krucker, S
PASJ (**2014**) 66 (SP1), S15 (1–7)
http://pasj.oxfordjournals.org/content/66/SP1/S15.full.pdf+html
We present new constraints on the high-temperature emission measure of a non-flaring solar active region using observations from the recently flown Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket payload. FOXSI has performed the first focused hard X-ray (HXR) observation of the Sun in its first successful flight on **2012 November 2**. Focusing optics, combined with small strip detectors, enable high-sensitivity observations with respect to previous indirect imagers. This capability, along with the sensitivity of the HXR regime to high-temperature emission, offers the potential to better characterize high-temperature plasma in the corona as predicted by nanoflare heating models. We present a joint analysis of the differential emission measure (DEM) of active region 11602 using coordinated observations by FOXSI, Hinode/XRT, and Hinode/EIS. The Hinode-derived DEM predicts significant emission measure between 1 MK and 3 MK, with a peak in the DEM predicted at 2.0-2.5 MK. The combined XRT and EIS DEM also shows emission from a smaller population of plasma above 8 MK. This is contradicted by FOXSI observations that significantly constrain emission above 8 MK. This suggests that the Hinode DEM analysis has larger uncertainties at higher temperatures and that > 8 MK plasma above an emission measure of 3 ? 1044 cm-3 is excluded in this active region.

SUZAKU/WAM AND RHESSI OBSERVATIONS OF NON-THERMAL ELECTRONS IN SOLAR MICROFLARES

Shin-nosuke **Ishikawa**1,2, Säm Krucker2,3, Masanori Ohno4, and Robert P. Lin
2013 ApJ 765 143
We report on hard X-ray spectroscopy of solar microflares observed by the Wide-band All-sky Monitor (WAM), on board the Suzaku satellite, and by RHESSI. WAM transient data provide wide energy band (50 keV-5 MeV) spectra over a large field of view (~2π sr) with a time resolution of 1 s. WAM is attractive as a hard X-ray solar flare monitor due to its large effective area (~800 cm2 at 100 keV, ~13 times larger than that of RHESSI). In particular, this makes it possible to search for high energy emission in microflares that is well below the RHESSI background. The WAM solar flare list contains six GOES B-class microflares that were simultaneously observed by RHESSI between the launch of Suzaku in 2005 July and 2010 March. At **100 keV**, the detected WAM fluxes are more than ~20 times below the typical RHESSI instrumental background count rates. The RHESSI and WAM non-thermal spectra are in good agreement with a single power law with photon spectral indices between 3.3 and 4.5. In a second step, we also searched the RHESSI microflare list for events that should be detectable by WAM, assuming that the non-thermal power-law emission seen by RHESSI extends to >50 keV. From the **12 detectable events** between 2005 July and 2007 February, 11 were indeed seen by WAM. This shows that microflares, similar to regular flares, can accelerate electrons to energies up to at least 100 keV.

RHESSI IMAGING SURVEY OF γ -RAY BREMSSTRAHLUNG EMISSION IN SOLAR FLARES

S. **Ishikawa**1,2, S¨am Krucker3,4, T. Takahashi1,2, and R. P. Lin
Astrophysical Journal, 728:22 (7pp), **2011** February

We present a high-energy (>150 keV) imaging survey of all solar γ -ray flares observed by the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) to study bremsstrahlung emission from relativistic electrons. Using *RHESSI* rear segment data, images in the energy range from 150 to 450 keV integrated over the total duration of the impulsive phase of the flare are derived. Out of the 29 γ -ray peaks in 26 *RHESSI* flares, we successfully obtained images for 21 γ -ray peaks in 20 flares. The remaining eight peaks have >150 keV fluences of less than a few hundred photons per cm2 and counting statistics are too poor for detailed imaging. The flux ratio of the footpoint sources is found to be similar at 50 keV and above 150 keV, indicating that relativistic electrons are present in both footpoints of the flare loop. No correlation between the footpoint separation and the fluence ratio of the 2.2 MeV line and the >300 keV photons is found. This indicates that the relative efficiency of proton to electron acceleration does not depend on loop length, as could have been expected from stochastic acceleration models. As previously reported, the three flares with the best counting statistics show not only footpoint emission, but also a coronal γ -ray bremsstrahlung source. For events with lower counting statistics, no coronal source could be identified. However, instrumental limitation could easily hide a coronal source for events with lower statistics, suggesting that coronal γ -ray bremsstrahlung sources are nevertheless a general feature of γ -ray flares.
Table

Small electron acceleration episodes in the solar corona

Tomin **James**, Prasad Subramanian, Eduard P Kontar
MNRAS **2017**
https://arxiv.org/pdf/1706.04031.pdf
We study the energetics of nonthermal electrons produced in small acceleration episodes in the solar corona. We carried out an extensive survey spanning 2004--2015 and shortlisted 6 impulsive electron events detected at 1 AU that was not associated with large solar flares(GOES soft X-ray class > C1) or with coronal mass ejections. Each of these events had weak, but detectable hard Xray (HXR) emission near the west limb, and were associated with interplanetary type III bursts. In some respects, these events seem like weak counterparts of "cold/tenuous" flares. The energy carried by the HXR producing electron population was ≈1023 -- 1025 erg, while that in the corresponding population detected at 1 AU was ≈1024--1025 erg. The number of electrons that escape the coronal acceleration site and reach 1 AU constitute 6 % to 148 % of those that precipitate downwards to produce thick target HXR emission. **28-02-2004, 16-03-2004, 26-06-2004, 27-06-2004, 25-12-24**
Table 1. Impulsive electron events detected in-situ at 1 AU: first shortlist
Table 2. Final shortlist and spectral parameters

The spatial, spectral and polarization properties of solar flare X-ray sources

Natasha L. S. **Jeffrey**
Ph.D. **Thesis**, **2014**
http://arxiv.org/pdf/1412.8163v1.pdf
X-rays are a valuable diagnostic tool for the study of high energy accelerated electrons. Bremsstrahlung X-rays produced by, and directly related to, high energy electrons accelerated during a flare, provide a powerful diagnostic tool for determining both the properties of the accelerated electron distribution, and of the flaring coronal and chromospheric plasmas. This thesis is specifically concerned with the study of spatial, spectral and polarization properties of solar flare X-ray sources via both modelling and X-ray observations using the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Firstly, a new model is presented, accounting for finite temperature, pitch angle scattering and initial pitch angle injection. This is developed to accurately infer the properties of the acceleration region from the observations of dense coronal X-ray sources. Moreover, examining how the spatial properties of dense coronal X-ray sources change in time, interesting trends in length, width, position, number density and thermal pressure are found and the possible causes for such changes are discussed. Further analysis of data in combination with the modelling of X-ray transport in the photosphere, allows changes in X-ray source positions and sizes due to the X-ray albedo effect to be deduced. Finally, it is shown, for the first time, how the presence of a photospheric X-ray albedo component produces a spatially resolvable polarization pattern across a hard X-ray (HXR) source. It is demonstrated how changes in the degree and direction of polarization across a single HXR source can be used to determine the anisotropy of the radiating electron distribution. **13 January 1992, 14-15 Apr 2002, 23 July 2002, 20 September 2002, 21 May 2004, 10 Nov 2004, 23 Aug 2005**

A Hard X-Ray Sigmoidal Structure During the Initial Phase of the 2003 October 29 X10 Flare

Haisheng **Ji**, Haimin Wang, Chang Liu and Brian R. Dennis
BBSO, #1356, 2008
http://solar.njit.edu/preprints/Ji1356.pdf
The Astrophysical Journal, Vol. 680, No. 1: 734-739, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/587138
We find a hard X-ray (HXR) sigmoidal (S-shaped) structure observed by *RHESSI* between 6 and 150 keV during the initial phase of the X10 flare of 2003 October 29.

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**

Probing the Puzzle of Behind-the-limb γ-Ray Flares: Data-driven Simulations of Magnetic Connectivity and CME-driven Shock Evolution

Meng **Jin**1,2, Vahe Petrosian3,4, Wei Liu1,5, Nariaki V. Nitta1, Nicola Omodei3, Fatima Rubio da Costa3, Frederic Effenberger5,6, Gang Li7, Melissa Pesce-Rollins8, Alice Allafort3.....
2018 ApJ 867 122
sci-hub.tw/10.3847/1538-4357/aae1fd **File**
https://iopscience.iop.org/article/10.3847/1538-4357/aae1fd/pdf
Recent detections of high-energy γ-rays from behind-the-limb (BTL) solar flares by the Fermi Gamma-ray Space Telescope pose a puzzle and challenge on the particle acceleration and transport mechanisms. In such events, the γ-ray emission region is located away from the BTL flare site by up to tens of degrees in heliographic longitude. It is thus hypothesized that particles are accelerated at the shock driven by the coronal mass ejection (CME) and then travel from the shock downstream back to the front side of the Sun to produce the observed γ-rays. To test this scenario, we performed data-driven, global magnetohydrodynamics simulations of the CME associated with a well-observed BTL flare on **2014 September 1**. We found that part of the CME-driven shock develops magnetic connectivity with the γ-ray emission region, facilitating transport of particles back to the Sun. Moreover, the observed increase in γ-ray flux is temporally correlated with (1) the increase of the shock compression ratio and (2) the presence of a quasi-perpendicular shock over the area that is magnetically connected to the γ-ray emitting region, both conditions favoring the diffusive shock acceleration (DSA) of particles. These results support the above hypothesis and can help resolve another puzzle, i.e., long-duration (up to 20 hr) γ-rays flares. We suggest that, in addition to DSA, stochastic acceleration by plasma turbulence may also play a role, especially in the shock downstream region and during the early stage when the shock Alfvén Mach number is small.

Data-driven Simulations of Magnetic Connectivity in Behind-the-Limb γ-ray Flares and Associated Coronal Mass Ejections

Meng **Jin**, Vahe Petrosian, Wei Liu, Nariaki V. Nitta, Nicola Omodei, Fatima Rubio da Costa, Frederic Effenberger, Gang Li, Melissa Pesce-Rollins, Alice Allafort, Ward Manchester IV
ApJ 867, 122, **2018**
doi: 10.3847/1538-4357/aae1fd
https://arxiv.org/pdf/1807.01427.pdf **File**
https://iopscience.iop.org/article/10.3847/1538-4357/aae1fd/pdf
Recent detections of high-energy γ-rays by \emph{Fermi} from behind-the-limb (BTL) solar flares pose a puzzle on the particle acceleration/transport mechanisms in such events. Due to the large separation between the flare site and the location of γ-ray emission, it is suggested that the associated coronal mass ejections (CMEs) play an important role in accelerating and subsequently transporting particles back to the Sun to produce the observed γ-rays. We explore this scenario by simulating the CME associated with a BTL flare that occurred on **2014 September 1** about 40$\arcdeg$ behind the east solar limb. The flare was well observed by {\it Fermi}, {\it RHESSI}, {\it SDO}, and {\it STEREO}. \emph{Fermi}/LAT detected a substantial flux of >100 MeV γ-rays for more than an hour with an emission centroid located near the east limb but about 300$\arcsec$ north of the centroid of the \emph{RHESSI}

HXR source. We utilize a data-driven global magnetohydrodynamics model (AWSoM: Alfv\'{e}n-wave Solar Model) and initiate the CME by the Gibson-Low flux rope to track the dynamic evolution of the global magnetic field during the event and investigate the magnetic connectivity between the CME/CME-driven shock and the \emph{Fermi}/LAT emission region. Moreover, we derive the time-varying shock parameters over the area that becomes magnetically connected to \emph{Fermi} γ-ray emission region on the visible solar disk. Our simulations show that the CME/CME-driven shock develops connections both to the flare region and the visible solar disk during the eruption, indicating that the CME's interaction with the global solar corona is critical for \emph{Fermi} BTL events and the associated long duration γ-ray emission.

Spatial Distribution of Magnetic Reconnection in the 2006 December 13 Solar Flare As Observed by Hinode

Ju **Jing**1;2, Jongchul Chae3, and Haimin Wang1;2
Preprint BBSO #1352, 2007, File; The Astrophysical Journal Letters, Vol. 672, No. 1: L73-L76.
http://www.journals.uchicago.edu/doi/abs/10.1086/526339

A massive two-ribbon flare and its source magnetic field region were well captured by the Solar Optical Telescope (SOT) on board *Hinode* in the Ca II H spectral line and by the Spectro-Polarimeter of SOT, respectively. Using the high-resolution *Hinode* data sets, we compare the spatial distribution of the local magnetic reconnection rate and the energy release rate along the ribbons with that of G-band kernels that serve as a proxy for the primary energy release. The G-band kernels spatially coincide with the maximum of both modeled quantities, which gives strong support for the reconnection model. We also investigate the magnitude scaling correlation between the ribbon separation speed V_r and magnetic field strength B_n at four 2 minute time bins around the maximum phase of the flare. It is found that V_r is weakly and negatively correlated with B_n. An empirical relation of $V_r \propto B_n^{-0.15}$ is obtained at the flare peak time with an correlation coefficient $\sim$−0.33. The correlation is weaker at other time bins.

Correlation and asymmetry between solar flare hard X-ray footpoints: a statistical study:

M. **Jin** and M. D. Ding
A&A 471 (2007) 705-709
Our analysis indicates that the asymmetry between hard X-ray footpoints is a ubiquitous feature in solar flares. However, in most asymmetric cases, the correlations between the light curves of the two footpoints remain high. In particular, the correlation coefficients between the slowly-varying components are significantly higher than those between the fast-varying components. We discuss the causes and implications of the asymmetries and correlations between hard X-ray footpoints.

Hard X-Ray Intensity Distribution Along Hα Ribbons

Ju **Jing**, Jeongwoo Lee, Chang Liu, Dale E. Gary and Haimin Wang
BBSO, Number: 1342, 2007, File
Abstract: Unusual ribbon-like hard X-ray sources were found with the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (RHESSI) observation of a 2B/M8.0 are on **2005 May 13**. We use this unique observation to investigate the spatial distribution of the hard X-ray intensity along the ribbons and compare it with the local magnetic reconnection rate and energy release rate predicted by the standard magnetic reconnection model for two ribbon flares. In the early phase of the flare, the hard X-ray sources appear to be concentrated in strong field regions within the Hα ribbons, which is explicable by the model. At and after the are maximum phase, the hard X-ray sources become spatially extended to resemble Hα ribbons in morphology, during which the spatial distribution of hard X-ray intensity lacks a correlation with that of the local magnetic reconnection rate and energy release rate predicted by the model. We argue that the magnetic reconnection during this event may involve the rearrangement of magnetic field along the magnetic arcade axis which is inevitably overlooked by the two-dimensional model and suggest that this type of three-dimensional reconnection will be best seen in so-called sigmoid-to-arcade transformations.

Energetic Gamma-Ray Emission from Solar Flares

Ervin **Kafexhiu**1, Carlo Romoli1,2, Andrew M. Taylor3, and Felix Aharonian
2018 ApJ 864 148
https://sci-hub.tw/10.3847/1538-4357/aad801
Recent advances in the γ-ray observations of solar flares by the Fermi satellite demand revisions in the hadronic γ-ray flux computation below 1 GeV. In this work, we utilize recently updated pion production cross sections, along with an accurate description of low-energy nuclear interactions. Applying these new interaction descriptions to model the Fermi Large Area Telescope solar flare data, we infer primary particle spectral parameters. Application of this new cross section description leads to significantly different spectral parameters compared to those obtained

previously. Furthermore, the inclusion of nuclei in these calculations leads to a primary spectrum that is generally harder than that required from proton-only considerations. Finally, the flare data at lower MeV energies, detected by the Fermi Gamma-ray Burst Monitor, are shown to provide additional low-energy spectral information.
1991 Jun 15, 2011 June 7, 2012 March 7, 2013 Oct 11, 2014 Sep 1
Table 2 The MCMC Results for the Primary Spectrum Power-law Index α for the Published Solar Flare Data that We Have Considered Here

Magnetic Flux Reconnection in Flaring Active Regions with Sustained Gamma-Ray Emission

S. W. **Kahler**1, E. W. Cliver2, and M. Kazachenko3
2018 ApJ 868 81
https://iopscience.iop.org/article/10.3847/1538-4357/aae9d8/pdf
Characteristics of sustained >100 MeV γ-ray emission (SGRE) events observed by the Large Area Telescope on Fermi were recently reported by Share et al. Their spectra are consistent with the decay of pions produced by >300 MeV protons and appear spectrally and spatially distinct from preceding associated flares. The source(s) of the sustained production of the >300 MeV protons is uncertain, but acceleration in coronal/interplanetary shock waves driven by coronal mass ejections, followed by a return of the protons back to the Sun, is favored. This scenario requires proton transport through converging magnetic fields behind the shock, which might result in considerable reflection of the protons back into space, and 1 au observations of the associated solar energetic proton (SEP) events do not always include a population of E > 300 MeV protons. Alternative source candidates that involve trapping or continued acceleration of SEPs in coronal loops have been considered. The energy release rates from magnetic reconnection in flaring active regions (ARs) have been measured with a new technique, and in this work we compare those measured flux reconnection rates with emission profiles in 11 SGRE events. In general, the magnetic reconnection event is nearly or completely finished before the bulk of the γ-ray emission, which argues against scenarios of continued proton acceleration in the flaring ARs. **20110602, 20110804, 20110906, 20110907, 20120123, 20120307, 20120309, 20130411, 20131028, 20150621**

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.

REMOTE SENSING OF GAMMA-RAY EMISSION FROM SOLAR ENERGETIC PROTON INTERACTIONS WITH THE SOLAR WIND

S. W. **Kahler** and B. R. Ragot1,
The Astrophysical Journal, 675:846Y852, **2008** March 1
http://www.journals.uchicago.edu/doi/pdf/10.1086/526416?cookieSet=1
The properties of solar energetic particles (SEPs) in solar flares are studied through remote imaging in the radio, hard X-ray, and _-ray energy ranges. However, the heliospheric SEP populations are observed only in situ by satellite measurements, which drastically limits our understanding of their spatial and temporal variations. Can those SEP populations be remotely imaged, as are the solar SEPs?We consider two possibilities for detecting faint _-ray emission from SEP interactionswith solar wind (SW) ions. First, the 6.13 and 4.44 MeV _-ray lines of $_{16}$Oand $_{12}$C, respectively, produced by the interactions of the SEPs froma large low-energy (E < 30MeV) gradual event are calculated and found to be far below a detectable level. Then the expected $_0$-decay _-ray emission is calculated for the intense ground-level event (GLE) of 2005 January 20 and compared with (1) the observed Galactic and extragalactic background and (2) the expected near-solar emission from inverse-Compton scattering of solar photons by cosmic-ray electrons and from Galactic cosmic-ray collisions with the solar atmosphere. It appears feasible to detect the $_0$-decay emission from that event with a detector of the size of the Large Area Telescope on GLAST.

Earlier 1982 and 1991 flare observations of long-duration (hours) _0-decays were attributed to E >300 MeV protons captured in strong coronal loops, but we suggest that the observed emission was due to SEP-SW collisions following shock acceleration on open field lines.

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**.

The Fourth Fermi-GBM Gamma-Ray Burst Catalog: A Decade of Data

A. von **Kienlin**1, C. A. Meegan2, W. S. Paciesas3

2020 ApJ 893 46

sci-hub.si/10.3847/1538-4357/ab7a18

We present the fourth in a series of catalogs of gamma-ray bursts (GRBs) observed with Fermi's Gamma-ray Burst Monitor (Fermi-GBM). It extends the six year catalog by four more years, now covering the 10 year time period from trigger enabling on **2008 July 12 to 2018 July 11**. During this time period GBM triggered almost twice a day on transient events, 2356 of which we identified as cosmic GRBs. Additional trigger events were due to **solar flare** events, magnetar burst activities, and terrestrial gamma-ray flashes. The intention of the GBM GRB catalog series is to provide updated information to the community on the most important observables of the GBM-detected GRBs. For each GRB the location and main characteristics of the prompt emission, the duration, peak flux, and fluence are derived. The latter two quantities are calculated for the 50–300 keV energy band, where the maximum energy release of GRBs in the instrument reference system is observed and also for a broader energy band from 10–1000 keV, exploiting the full energy range of GBM's low-energy detectors. Furthermore, information is given on the settings of the triggering criteria and exceptional operational conditions during years 7 to 10 in the mission. This fourth catalog is an official product of the Fermi-GBM science team, and the data files containing the complete results are available from the High-Energy Astrophysics Science Archive Research Center.

Fermi-GBM burst catalog at HEASARC: https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

Modeling Hadronic Gamma-ray Emissions from Solar Flares and Prospects for Detecting Non-thermal Signatures from Protostars

Shigeo S. **Kimura**, Shinsuke Takasao, Kengo Tomida

2023 ApJ 944 192

https://arxiv.org/pdf/2211.13891.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/acb649/pdf

We investigate gamma-ray emission in the impulsive phase of solar flares and the detectability of non-thermal signatures from protostellar flares. Energetic solar flares emit high-energy gamma rays of GeV energies, but their production mechanism and emission site are still unknown. Young stellar objects, including protostars, also exhibit luminous X-ray flares, but the triggering mechanism of the flaring activity is still unclear due to the strong obscuration. Non-thermal signatures in mm/sub-mm and gamma-ray bands are useful to probe protostellar flares owing to their strong penetration power. We develop a non-thermal emission model of the impulsive phase of solar flares, where cosmic-ray protons accelerated at the termination shock produce high-energy gamma rays via hadronuclear interaction with the evaporation plasma. This model can reproduce gamma-ray data in the impulsive phase of a solar flare. We apply our model to protostellar flares and show that Cherenkov Telescope Array will be able to detect gamma rays of TeV energies if particle acceleration in protostellar flares is efficient. Non-thermal electrons accelerated together with protons can emit strong mm and sub-mm signals via synchrotron radiation, whose power is consistent with the energetic mm/sub-mm transients observed from young stars. Future gamma-ray and mm/sub-mm observations from protostars, coordinated with a hard X-ray observation, will unravel the triggering mechanism of non-thermal particle production in protostellar flares.

Хорошее описание импульсной и постепенной (ПЭ) фаз вспышки

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, 133–155, **2018**
https://link.springer.com/content/pdf/10.1007%2F978-3-319-60051-2.pdf
File Malandraki_Crosby_SEPs_Forecasting and Analysis_Book.pdf
doi: 10.1007/978-3-319-60051-2_8
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**

Subsecond Spikes in Fermi GBM X-ray Flux as a Probe for Solar Flare Particle Acceleration

Trevor **Knuth**, Lindsay Glesener
ApJ **903** 63 **2020**
https://arxiv.org/pdf/2003.05007.pdf
https://doi.org/10.3847/1538-4357/abb779
Solar flares are known to release a large amount of energy into accelerating electrons. Studying small timescale (≤ 2s) fluctuations in nonthermal X-ray flux offers the opportunity to probe the nature of those acceleration mechanisms. By comparing the durations, differences in timing between energy bands, and the periodicity of these spikes against the relevant timescales called for by various acceleration mechanisms, a test for each mechanism's validity can be made. This work details the analysis of fast fluctuations in Fermi Gamma-ray Burst Monitor (Fermi GBM) data from 2 M9.3 class solar flares that occurred on **SOL2011-07-30 and SOL2011-08-04**. This study shows the usefulness of Fermi GBM data as a means of examining these small timescale spikes and presents a rigorous method of identifying, counting, and measuring the temporal properties of these subsecond X-ray spikes. In the 2 flares examined we found spikes to primarily occur in spans of 60-100 seconds in the impulsive phase. The relative spike intensity ranged from 5% to 46% of the total counts, depending on the energy band the spike was measured in. The average spike durations were 0.96 and 0.66 seconds and the median durations were 0.79 and 0.32 seconds for the 2 flares. The spike duration distribution for the SOL2011-08-04 flare was found to follow a power law with a -1.8 ± 0.5 index. Of the 3 spiking intervals identified, only 1 was found to have a periodicity, showing significant power at the 1.7 ± 0.1 Hz frequency.
RHESSI Nuggets #407 April **2021**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Subsecond_Spikes_in_Solar_Flare_X-ray_Flux_as_Seen_by_Fermi_GBM

Localization of the Gamma-Ray Emission Region in the 1 September 2014 Behind-the-Limb Solar Flare According to the Fermi/LAT Data.

Kochanov, A.A., Kiselev, V.I., Grechnev, V.V., & A. M. Uralov
Sol Phys 299, 18 (**2024**).
https://doi.org/10.1007/s11207-024-02264-4
https://link.springer.com/content/pdf/10.1007/s11207-024-02264-4.pdf **File**
Since the launch of the Fermi mission in 2008, it has become possible to study high-energy solar γ -rays with an unprecedented imaging capability. In particular, the position of the >100 MeV γ-ray source can shed light on the origin of high-energy protons that is still controversial. However, the imaging of solar γ -ray sources with the Fermi Large Area Telescope (LAT) is a complex multi-stage process influenced by a number of factors and instrumental effects, which is difficult to fully comprehend a priori. The **SOL2014-09-01** behind-the-limb event was significant, for which the γ -ray source position was not firmly established at once. Following the methodology outlined by the Fermi/LAT team, we estimated the proton power-law indices and γ -ray centroid positions at two temporal intervals of this event, separated by one hour. Our estimates for the first interval are comparable to estimates recently updated by the Fermi/LAT team, thereby confirming the consistency of the analysis applied. Although, in the second interval, corresponding to the decay phase of the flare, the proton power-law index clearly hardened, the presumable position of the fading γ -ray source remained unchanged. Its constancy in both temporal intervals and its proximity to the bases of long coronal loops connected to the flare site support the flare origin of high-energy protons injected into these loops along with electrons and trapped there for a long time. Our experience

analyzing Fermi/LAT data clarifies their complex handling and will hopefully benefit the solar community in their wider use.

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
sci-hub.si/10.3847/1538-4357/ab684e
doi: 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.

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.

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)

The Search for >35 MeV Neutrons from the June 3, 2012 Impulsive Flare

K. **Koga**, S. Masuda, H. Matsumoto, Y. Muraki, T. Obara O. Okudaira, S. Shibata, T. Yamamoto, T. Goka
Proceeding of the 34th International Cosmic Ray Conference in Hague in August, 2015, **2015**
http://arxiv.org/ftp/arxiv/papers/1508/1508.04930.pdf
We analyzed a highly impulsive solar flare observed **on June 3, 2012**. In association with this flare, emissions of hard X-rays, high-energy gamma rays, and neutrons were detected by the detectors onboard the FERMI, RHESSI satellites and the International Space Station. We compared those results with the pictures taken by the UV telescope onboard the Solar Dynamics Observatory satellite and found the crossing structure of two magnetic ropes at two positions on the solar surface almost at the same time. High-energy gamma rays were detected by the Fermi Large Area Telescope satellite, implying that the impulsive flare was one of a major source of proton acceleration processes on the solar surface. At the beginning of research, impulsive solar flares were considered to be the main source of particle acceleration processes; our current observations have confirmed this hypothesis.

Results of a Measurement of Solar Neutrons Emitted on March 5, 2012 using a Fiber-type neutron monitor onboard the SEDA-AP attached to the ISS

K. **Koga**, H. Matsumoto, O. Okudaira, T. Goka, T. Obara, S. Masuda, Y. Muraki, S. Shibata, T. Yamamoto
Proceeding of the 34th International Cosmic Ray Conference in Hague in August, 2015, **2015**
http://arxiv.org/ftp/arxiv/papers/1508/1508.04927.pdf
The solar neutron detector SEDA-FIB onboard the International Space Station (ISS) has detected several events from the solar direction associated with three large solar flares observed on **March 5th (X1.1), 7th (X5.4), and 9th (M6.3) of 2012**. In this study, we present the time profiles of those neutrons and discuss the physics that may be related to a possible acceleration scenario for ions over the solar surface. We compare our data with the dynamical pictures of the flares obtained by the ultra-violet telescope of the space-based Solar Dynamics Observatory.

A STATISTICAL STUDY OF THE SPECTRAL HARDENING OF CONTINUUM EMISSION IN SOLAR FLARES

X. **Kong**1,2, G. Li2, and Y. Chen
2013 ApJ 774 140
The observed hard X-ray and γ-ray continuum in solar flares is interpreted as Bremsstrahlung emission of accelerated non-thermal electrons. It has been noted for a long time that in many flares the energy spectra show hardening at energies around or above 300 keV. In this paper, we first conduct a survey of spectral hardening events that were previously studied in the literature. We then perform a systematic examination of 185 flares from the Solar Maximum Mission. We identify 23 electron-dominated events whose energy spectra show clear double power laws. A statistical study of these events shows that the spectral index below the break (γ1) anti-correlates with the break energy (ε b). Furthermore, γ1 also anti-correlates with Fr, the fraction of photons above the break compared to the total photons. A hardening spectrum, as well as the correlations between (γ1, ε b) and (γ1, Fr), provide stringent constraints on the underlying electron acceleration mechanism. Our results support a recent proposal that electrons are being accelerated diffusively at a flare termination shock with a width of the order of an ion inertial length scale.

The Study of the Cosmic Gamma-Emission Nonstationary Fluxes Characteristics by the AVS-F Apparatus Data

Yu. D. **Kotov**, I. V. Arkhangelskaja, A. I. Arkhangelsky, S. N. Kuznetsov, A. S. Glyanenko, P. A. Kalmykov, D. B. Amandzholova, V. T. Samoylenko, V. N. Yurov, A. V. Pavlov, … show all 12
The Coronas-F Space Mission
Astrophysics and Space Science Library Volume 400, **2014**, pp 175-256
http://link.springer.com/chapter/10.1007/978-3-642-39268-9_7
The AVS-F apparatus (Russian abbreviation for Amplitude-Time Spectrometry of the Sun) is intended for the solar flares' hard X-ray and gamma-ray emission characteristic studies and for the search and detection of the gamma-ray bursts (GRB). At present over 1,100 events with duration more than 2 s without any coordinate relations to Earth Radiation Belts and South Atlantic Anomaly were separated on the results of preliminary analysis of AVS-F experiment database.About 68 % of the identified events were associated with quasistationary equatorial precipitations-15-30 % count rate increases in the low-energy gamma-band of the AVS-F apparatus over its average value obtained by approximation of these parts with polynomials discovered on some equatorial segments in the ranges of geographic latitude of 25∘ up to +30∘. Several short events with duration of 1-16 ms associated with terrestrial gamma-ray flashes were registered during the experiment. These events were detected above the powerful thunderstorm formations.Solar flares with classes stronger than M1.0 according to the GOES classification were

about 7 % of the detected events. Solar flares' hard X-rays and γ-emission were mainly observed during the rise or maximum phases of the emission in the soft X-rays band according to the detectors on board the GOES series satellites data and duration of their registration is less than of the soft X-ray bands. According to the preliminary data analysis gamma-emission with energy over 10 MeV was registered during 12 % of the observed flares. The emission in the energy band E ¿ 100 keV was registered during over 60 faint solar flares (of B and C classes according to the GOES and from several ones γ-quanta with energy up to several tens of MeV were observed.Several spectral line complexes were observed in the spectra of some solar flares stronger than M1.0 in the low-energy gamma-range. Registered spectral features were corresponded to α α-lines, annihilation line, nuclear lines, and neutron capture line on1H (2.223 MeV). In the spectrum of the **January 20, 2005** solar flare the feature in the range of 15-21 MeV was detected for the first time. It can be associated with lines of 15.11 MeV (12C +16O) or 20.58 MeV (from neutron radiative capture on3He), or with their combination. Also several e-dominant flares without any gamma-lines in energy spectra were identified. All detected faint solar flares were e-dominant according to the preliminary data analysis.Thin structure with characteristic timescale of 30-160 s was observed at 99 % significance level on some solar flares stronger than M1.0 temporal profiles in the low-energy gamma-band in the energy ranges corresponding to the identified spectral features or whole gamma-band energy boundaries. According to the results of the preliminary analysis during the flare of January 20, 2005, thin structure with timescale from 7 ms to 35 ms was detected at 99 % confidence level in the energy range of 0.1-20 MeV. Some thin structure with characteristic timescale 50-110 s was observed on temporal profiles of several faint events.About 3 % of the identified events were gamma-ray bursts. During some bursts high-energy gamma-emission was observed, for example Emax = 147 ± 3 MeV for GRB050525.

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

Co-Spatial White Light and Hard X-Ray Flare Footpoints Seen Above the Solar Limb

Säm **Krucker**1,2, Pascal Saint- Hilaire2, Hugh S. Hudson2,3, Margit Haberreiter4, Juan Carlos Martinez-Oliveros2, Martin D. Fivian2, Gordon Hurford1,2, Lucia Kleint1, Marina Battaglia1, Matej Kuhar1, and Nicolas G. Arnold

2015 ApJ 802 19

We report analysis of three solar flares that occur within 1° of limb passage, with the goal to investigate the source height of chromospheric footpoints in white light (WL) and hard X-rays (HXR). We find the WL and HXR (≥30 keV) centroids to be largely co-spatial and from similar heights for all events, with altitudes around 800 km above the photosphere or 300–450 km above the limb height. Because of the extreme limb location of the events we study, emissions from such low altitudes are influenced by the opacity of the atmosphere and projection effects. STEREO images reveal that for **SOL2012-11-20T12:36** the projection effects are smallest, giving upper limits of the absolute source height above the nominal photosphere for both wavelengths of ~1000 km. To be compatible with the standard thick target model, these rather low altitudes require very low ambient densities within the flare footpoints, in particular if the HXR-producing electrons are only weakly beamed. That the WL and HXR

emissions are co-spatial suggests that the observed WL emission mechanism is directly linked to the energy deposition by flare accelerated electrons. If the WL emission is from low-temperature ($\leqslant 10^4$ K) plasma as currently thought, the energy deposition by HXR-producing electrons above ~30 keV seems only to heat chromospheric plasma to such low temperatures. This implies that the energy in flare-accelerated electrons above ~30 keV is not responsible for chromospheric evaporation of hot ($>10^6$ K) plasma, but that their energy is lost through radiation in the optical range.

RHESSI Heliophysics Senior Review 2015
High Energy Solar Spectroscopic Imager

Samuel **Krucker**, Brian Dennis, Albert Shih, Manfred Bester
http://hesperia.gsfc.nasa.gov/senior_review/2015/senior_review_proposal_2015.pdf
- Evolution of Solar Eruptive Events
- Flare-accelerated Electrons
- Flare-accelerated Ions
– Flare-heated Plasma
– Global Structure of the Photosphere

3 Nov 2010, 2011-03-07, 6 Sept 2011, 3 March 2012, 2012 July 19. 13 May 2013, 2014-01-28, March 29, 2014, 2014-04-19, 24 Sept 2014, 24 Oct 2014, 14 Dec 2014

First Images from the Focusing Optics X-Ray Solar Imager

Krucker, Sa"am; Christe, Steven; Glesener, Lindsay; Ishikawa, Shin-nosuke; Ramsey, Brian; Takahashi, Tadayuki; Watanabe, Shin; Saito, Shinya; Gubarev, Mikhail; Kilaru, Kiranmayee; Tajima, Hiroyasu; Tanaka, Takaaki; Turin, Paul; McBride, Stephen; Glaser, David; Fermin, Jose; White, Stephen; Lin, Robert
ApJL **2015**

The Focusing Optics X-ray Solar Imager (**FOXSI**) sounding rocket payload flew for the first time on **2012 November 2**, producing the first focused images of the Sun above 5 keV. To enable hard X-ray (HXR) imaging spectroscopy via direct focusing, FOXSI makes use of grazing-incidence replicated optics combined with fine-pitch solid-state detectors. On its first flight, FOXSI observed several targets that included active regions, the quiet Sun, and a GOES-class B2.7 microflare. This Letter provides an introduction to the FOXSI instrument and presents its first solar image. These data demonstrate the superiority in sensitivity and dynamic range that is achievable with a direct HXR imager with respect to previous, indirect imaging methods, and illustrate the technological readiness for a spaceborne mission to observe HXRs from solar flares via direct focusing optics.

Particle Densities within the Acceleration Region of a Solar Flare

Sa"am **Krucke**r1;2, Marina Battaglia
E-print, Oct **2013**;

The limb flare **SOL2012-07-19**T05:58 (M7.7) provides the best example of a non-thermal above-the-loop-top hard X-ray (HXR) source with simultaneous observations by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamic Observatory (SDO). By combining the two sets of observations, we present the first direct measurement of the thermal proton density and non-thermal electron density within the above-the-loop-top source where particle acceleration occurs. We find that both densities are of the same order of magnitude of a few times 1e9 cm-3, about 30 times lower than the density in the underlying thermal flare loops. The equal densities indicate that the entire electron population within the above-the-loop-top source is energized. While the derived densities depend on the unknown source depth and filling factor, the ratio of these two densities does not. Within the uncertainties, the ratio is one for a low energy cut-off of the non-thermal electron spectrum between 10 and 15 keV. RHESSI observations only constrain the cut-off energy to below ~15 keV, leaving the spectral shape of the electrons within the above-the-loop-top source at lower energies unknown. Nevertheless, these robust results strongly corroborate earlier findings that the above-the-loop-top source is the acceleration region where a bulk energization process acts on all electrons.

Acceleration-region Densities

Sa"m **Krucker** and Marina Battaglia.
RHESSI Science Nugget, No. 205, Aug **2013**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Acceleration-region_Densities

Clean examples of "above-the-loop-top" emission, as in the singular case of the Masuda flare, have been rare. The event discussed here (SOL**2012-07-19**T05:58, M7.7) is one of the best in the RHESSI database, and it had copious supporting observation - specifically, from SDO/AIA with its wonderful images of flare structures as seen in thermal emissions.
At last we have found a very clear example of the Masuda phenomenon, some 20 years after its original discovery (Ref. [1]), and one for which we have a great deal of modern data. This includes RHESSI and AIA, and the combination of these datasets has allowed us to understand the energetics of this new flare much better. We have come to the conclusion that the above-the-loop-top-source, well-observed here, contains a plasma that has a tail-dominated electron distribution function, ie that the acceleration process basically has worked on all of the electrons within its accessible volume: bulk acceleration.

HIGH-RESOLUTION IMAGING OF SOLAR FLARE RIBBONS AND ITS IMPLICATION ON THE THICK-TARGET BEAM MODEL

Säm **Krucker**1,2, H. S. Hudson1,3, N. L. S. Jeffrey3, M. Battaglia3, E. P. Kontar3, A. O. Benz2, A. Csillaghy2 and R. P. Lin
2011 ApJ 739 96
http://iopscience.iop.org/0004-637X/739/2/96/pdf/0004-637X_739_2_96.pdf
We report on high-resolution optical and hard X-ray observations of solar flare ribbons seen during the GOES X6.5 class white-light flare of **2006 December 6**. The data consist of imaging observations at 430 nm (the Fraunhofer G band) taken by the Hinode Solar Optical Telescope with the hard X-rays observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager. The two sets of data show closely similar ribbon structures, strongly suggesting that the flare emissions in white light and in hard X-rays have physically linked emission mechanisms. While the source structure along the ribbons is resolved at both wavelengths (length ~ 30"), only the G-band observations resolve the width of the ribbon, with values between ~05 and ~18. The unresolved hard X-ray observations reveal an even narrower ribbon in hard X-rays (the main footpoint has a width perpendicular to the ribbon of <11 compared to the G-band width of ~18) suggesting that the hard X-ray emission comes from the sharp leading edge of the G-band ribbon. Applying the thick-target beam model, the derived energy deposition rate is >5 × 1012 erg s–1 cm–2 provided by an electron flux of 1 × 1020 electrons s–1 cm–2 above 18 keV. This requires that the beam density of electrons above 18 keV be at least 1 × 1010 cm–3. Even if field lines converge toward the chromospheric footpoints, the required beam in the corona has too high a density to be described as a dilute tail population on top of a Maxwellian core. We discuss this issue and others associated with this extreme event, which poses serious questions to the standard thick target beam interpretation of solar flares.

Hard X–ray emission from the solar corona REVIEW ARTICLE

S. **Krucker** · M. Battaglia · P. J. Cargill · L. Fletcher · H. S. Hudson · A. L. MacKinnon · S. Masuda · L. Sui · M. Tomczak · A. M. Veronig · L. Vlahos · S. M. White
E-print, July-Aug **2008**; Astron Astrophys Rev (**2008**) 16:155–208, **File**
This **review** surveys hard X-ray emissions of non-thermal electrons in the solar corona. These electrons originate in flares and flare-related processes. Hard X-ray emission is the most direct diagnostic of electron presence in the corona, and such observations provide quantitative determinations of the total energy in the non-thermal electrons. The most intense flare emissions are generally observed from the chromosphere at footpoints of magnetic loops. Over the years, however, many observations of hard X-ray and even γ-ray emission directly from the corona have also been reported. These coronal sources are of particular interest as they occur closest to where the electron acceleration is thought to occur. Prior to the actual direct imaging observations, disk occultation was usually required to study coronal sources, resulting in limited physical information. Now RHESSI1 has given us a systematic view of coronal sources that combines high spatial and spectral resolution with broad energy coverage and high sensitivity. Despite the low density and hence low bremsstrahlung efficiency of the corona, we now detect coronal hard X-ray emissions from sources in all phases of solar flares. Because the physical conditions in such sources may differ substantially from those of the usual “footpoint” emission regions, we take the opportunity to revisit the physics of hard X-radiation and relevant theories of particle acceleration.

Coronal [gamma]-Ray Bremsstrahlung from Solar Flare-accelerated Electrons

Sam **Krucker**, G. J. Hurford, A. L. MacKinnon, A. Y. Shih, and R. P. Lin
The Astrophysical Journal Letters, Vol. 678, No. 1: L63-L66, **2008, File**.
http://www.journals.uchicago.edu/doi/pdf/10.1086/588381
The *Reuven Ramaty High Energy Spectroscopic Imager* (*RHESSI*) provides for the first time imaging spectroscopy of solar flares up to the g-ray range. The three *RHESSI* flares with best counting statistics are analyzed in the 200–800 keV range revealing g-ray emission produced by electron bremsstrahlung from footpoints of flare loops, but

also from the corona. Footpoint emission dominates during the g-ray peak, but as the g-ray emission decreases the coronal source becomes more and more prominent. Furthermore, the coronal source shows a much harder spectrum (with power-law indices g between 1.5 and 2) than the footpoints (with g between 3 and 4). These observations suggest that flare accelerated high-energy (~MeV) electrons stay long enough in the corona to lose their energy by collisions producing g-ray emission, while lower energetic electrons precipitate more rapidly to the footpoints.

2.1. ***The 2005 January 20 Flare***
2.2. ***The 2003 October 28 Flare***
2.3. ***The 2005 September 7 Flare***

CORONAL HARD X-RAY EMISSION ASSOCIATED WITH RADIO TYPE III BURSTS

Sa¨m **Krucker**,1 P. Saint-Hilaire,1 S. Christe,1,2 S. M. White,3
A. D. Chavier,4 S. D. Bale,1,2 and R. P. Lin1,2
The Astrophysical Journal, 681:644–649, **2008**
http://www.journals.uchicago.edu/doi/pdf/10.1086/588549

We report on a purely coronal hard X-ray source detected in a partially disk-occulted solar flare by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) that is associated with radio type III bursts and a suprathermal electron event detected near 1 AU by the WIND 3-D Plasma and Energetic Particle (3DP) instrument. Several observational characteristics suggest that the coronal hard X-ray source is thin target bremsstrahlung emission from the escaping electrons that produce the radio type III bursts. The hard X-ray emission correlates in time with the radio type III bursts and originates from a radially elongated source in the corona with a length (_65 Mm) similar to typical coronal density scale heights. Furthermore, the difference between the hardX-ray photon spectral index (_ j 4:1 _ 0:4) and the electron spectral index of the in situ observed event (_in situ j 2:9 _ 0:3) is around 1, consistent with the thin target interpretation. A further test for the thin target scenario is to compare the number of electrons needed to produce the observed hard X-ray emission with the number of in situ observed electrons. However, the number of escaping electrons derived from the single-spacecraft WIND measurement is in the best case an order of magnitude estimate and could easily underestimate the actual number of escaping electrons. Using the WIND observations, the estimated number of escaping electrons is about an order of magnitude too low. Thus, the thin target interpretation only holds if the WIND measurements are significantly underestimating the actual number of escaping electrons. Future multispacecraft observations with STEREO, Solar Orbiter, and Sentinels will resolve this uncertainty.

Hard X-Ray Emissions from Partially Occulted Solar Flares

Sam **Krucker** and R. P. Lin
The Astrophysical Journal, Vol. 673, No. 2: 1181-1187. **2008**. File
http://www.journals.uchicago.edu/doi/pdf/10.1086/524010

Observations of solar flares partially occulted by the solar limb provide diagnostics of coronal hard X-ray (HXR) emissions in the absence of generally much brighter emissions from footpoints of flare loops. In this paper, a statistical survey of 55 partially occulted flares observed by the Reuven RamatyHigh-Energy Solar Spectroscopic Imager (RHESSI) is presented, revealing the existence of two different components of coronal HXR emissions.Below_15 keV thermal HXR emission with a gradual time profile is generally dominant, while at higher energies an additional component is seen in 50 out of 55 events. This additional component shows faster time variations in the order of tens of seconds and is most prominent during the rise of the thermal emission. A comparison of the centroid positions of these two emissions shows that they are most often cospatial within _2000 km, although for a few events clear separations are observed as well. The spectra of the high-energy component show a rather steep (soft) power lawwith indices mostly between _4 and _6. Thin target emission in the corona from flare-accelerated electrons is discussed as a possible origin of the fast time variation component.

SOLAR FLARE HARD X-RAY EMISSION FROM THE HIGH CORONA

Sa¨m **Krucker**,1 S. M. White,2 and R. P. Lin1,3
The Astrophysical Journal, 669: L49–L52, **2007**
http://www.journals.uchicago.edu/doi/pdf/10.1086/523759

One of the largest solar hard X-ray (HXR) flares and solar energetic particle (SEP) events recorded by the *Mars Odyssey* mission while orbiting Mars occurred on **2002 October 27** and is related to a very fast (~2300 km s) coronal mass ejection (CME). From the Earth, the flare site is 40.4_ _ 3.5_ behind the solar limb and only emissions from the high corona at least 1.5 # 10^5 km radially above the main flare site can be seen. Nevertheless, the Earth-orbiting *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) observed

HXR emission up to 60 keV with a relatively flat, nonthermal spectrum (g between 3 and 3.5) that has an onset simultaneous with the main HXR emission observed above 60 keV by the Gamma-Ray Spectrometer (GRS) orbiting Mars.

"*Coronal* gamma-ray sources in giant solar flares",
by S. **Krucker** and G. Hurford,
RHESSI science nugget, Dec. **2006**: http://sprg.ssl.berkeley.edu/~tohban/nuggets/
Gamma-rays from the corona?!

Solar Flare Imaging in X-rays and γ-rays
S. **Krucker**
ILWS WORKSHOP 2006, GOA, FEBRUARY 19-20, **2006, file**
http://cdaw.gsfc.nasa.gov/publications/ilws_goa2006/

Hard X-ray footpoint motions in solar flares: comparing magnetic reconnection models with observations.
Krucker, S., Fivian, M. D., Lin, R. P.
Adv. Space Res. 35, 1707-1711, **2005**.

Hard X-ray source motions in the 2002 July 23 gamma-ray flare.
Krucker, S., Hurford, G. J., Lin, R. P.
ApJ 595, L103-L106, **2003, File**.

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is used to study the Hard X-ray (HXR) source motions of the July 23, 2002 γ-ray flare. Above 30 keV, at least 3 HXR sources are observed during the impulsive phase that can be identified with footpoints of coronal magnetic loops that form an arcade. On the northern ribbon of this arcade, a source is seen that moves systematically along the ribbon for more than 10 minutes. On the other ribbon, at least two sources are seen that do not seem to move systematically for more than half a minute, with different sources dominating at different times. The northern source motions are fast during times of strong HXR flux, but almost absent during periods with low HXR emission. This is consistent with magnetic reconnection if a higher rate of reconnection of field lines (resulting in a higher footpoint speed) produces more energetic electrons per unit time and therefore more HXR emission. The absence of footpoint motion in one ribbon is inconsistent with simple reconnection models, but can be explained if the magnetic configuration there is more complex.

High-Energy Emission from a Solar Flare in Hard X-rays and Microwaves
M.R. **Kundu**, V.V. Grechnev, S.M. White, E.J. Schmahl, N.S. Meshalkina, L.K. Kashapova
E-print, Aug **2009, File**; Solar Phys. **260**, 135
We investigate accelerated electron energy spectra for different sources in a large flare using simultaneous observations obtained with two instruments, the Nobeyama Radio Heliograph (NoRH) at 17 and 34 GHz, and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) at hard X-rays. This flare is one of the few in which emission up to energies exceeding 200 keV can be imaged in hard X-rays. Furthermore, we can investigate the spectra of individual sources up to this energy. We discuss and compare the HXR and microwave spectra and morphology. Although the event overall appears to correspond to the standard scenario with magnetic reconnection under an eruptive filament, several of its features do not seem to be consistent with popular flare models. In

particular we find that (1) microwave emissions might be optically thick at high frequencies despite a low peak frequency in the total flux radio spectrum, presumably due to the inhomogeneity of the emitting source; (2) magnetic fields in high-frequency radio sources might be stronger than sometimes assumed; (3) sources spread over a very large volume can show matching evolution in their hard X-ray spectra that may provide a challenge to acceleration models. Our results emphasize the importance of studies of sunspot-associated flares and total flux measurements of radio bursts in the millimeter range. **17 June 2003**

Coupling between magnetic reconnection, energy release, and particle acceleration in the X17.2 2003 October 28 solar flare

Victoria G. **Kurt** (1), Astrid M. Veronig (2 and 3), Gregory D. Fleishman (4 and 5), Jürgen Hinterreiter (2 and 6), Johannes Tschernitz (2), Alexandra L. Lysenko (7)
A&A, 686, A195 (**2024**)
https://www.aanda.org/articles/aa/pdf/2024/06/aa49130-23.pdf **File**
https://arxiv.org/pdf/2403.08135.pdf
The **2003 October 28** (X17.2) eruptive flare was a unique event. The coronal electric field and the {\pi}-decay {\gamma}-ray emission flux had the highest values ever inferred in solar flares. This study reveals physical links between the magnetic reconnection process, the energy release, and the acceleration of electrons and ions to high energies in the chain of the magnetic energy transformations in the impulsive phase of the solar flare. The global reconnection rate and the local reconnection rate are calculated from flare ribbon separation in H{\alpha} filtergrams and photospheric magnetic field maps. Available results of INTEGRAL and CORONAS-F/SONG observations are combined with Konus-Wind data to quantify time behavior of electron and proton acceleration. Prompt {\gamma}-ray lines and delayed 2.2 MeV line temporal profiles observed with Konus-Wind and INTEGRAL/SPI used to detect and quantify the nuclei with energies of 10-70 MeV. The global and local reconnection rates reach their peaks at the end of the main rise phase of the flare. The spectral analysis of the high-energy {\gamma}-ray emission revealed a close association between the acceleration process efficiency and the reconnection rates. High-energy bremsstrahlung continuum and narrow {\gamma}-ray lines were observed in the main rise phase. In the main energy release phase, the upper energy of the bremsstrahlung spectrum was significantly reduced and the pion-decay {\gamma}-ray emission appeared abruptly. We discuss the reasons why the change of the acceleration regime occurred along with the large-scale magnetic field restructuration of this flare. We argue that the main energy release and proton acceleration up to subrelativistic energies began just when the reconnection rate was going through the maximum, i.e., after a major change of the flare topology.

CORONAS-F observation of gamma-ray emission from the solar flare on 2003 October 29

Kurt, Victoria G.; Yushkov, Boris Yu.; Galkin, Vladimir I.; Kudela, Karel; Kashapova, Larisa K
New Astronomy, Volume 56, p. 102-112, **2017**
https://arxiv.org/ftp/arxiv/papers/1808/1808.02627.pdf
https://sci-hub.tw/10.1016/j.newast.2017.05.002
Appreciable hard X-ray (HXR) and gamma-ray emissions in the 0.04-150 MeV energy range associated with the **2003 October 29** solar flare (X10/3B) were observed at 20:38-20:58 UT by the SONG instrument onboard the CORONAS-F mission. To restore flare gamma-ray spectra we fitted the SONG energy loss spectra with a three-component model of the incident spectrum: (1) a power law in energy, assumed to be due to electron bremsstrahlung; (2) a broad continuum produced by prompt nuclear de-excitation gamma-lines; and (3) a broad gamma-line generated from pion-decay. We also restored spectra from the RHESSI data, compared them with the SONG spectra and found a reasonable agreement between these spectra in the 0.1-10 MeV energy range. The pion-decay emission was observed from 20:44:20 UT and had its maximum at 20:48-20:51 UT. The power-law spectral index of accelerated protons estimated from the ratio between intensities of different components of gamma rays changed with time. The hardest spectrum with a power-law index S = -3.5 - 3.6 was observed at 20:48-20:51 UT. Time histories of the pion-decay emission and proton spectrum were compared with changes of the locations of flare energy release as shown by RHESSI hard X-ray images and remote and remote Hα brightenings. An apparent temporal correlation between processes of particle acceleration and restructuring of flare magnetic field was found. In particular, the protons were accelerated to subrelativistic energies after radical change of the character of footpoint motion from a converging motion to a separation motion.

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.

Dynamics and energetics of the thermal and nonthermal components in the solar flare of January 20, 2005, based on data from hard electromagnetic radiation detectors onboard the CORONAS-F satellite

Kurt, V. G.; Svertilov, S. I.; Yushkov, B. Yu.; Bogomolov, A. V.; Grechnev, V. V.; Galkin, V. I.; Bogomolov, V. V.; Kudela, K.; Logachev, Yu. I.; Morozov, O. V.; Myagkova, I. N.
Astronomy Letters, Volume 36, Issue 4, pp.280-291, **2010**

Based on data from the SONG and SPR-N multichannel hard electromagnetic radiation detectors onboard the CORONAS-F space observatory and the X-ray monitors onboard GOES satellites, we have distinguished the thermal and nonthermal components in the X-ray spectrum of an extreme solar flare on **January 20, 2005**. In the impulsive flare phase determined from the time of the most efficient electron and proton acceleration, we have obtained parameters of the spectra for both components and their variations in the time interval 06:43-06:54 UT. The spectral index in the energy range 0.2-2 MeV for a single-power-law spectrum of accelerated electrons is shown to have been close to 3.4 for most of the time interval under consideration. We have determined the time dependence of the lower energy cutoff in the energy spectrum of nonthermal photons $E_{\gamma 0}(t)$ at which the spectral

flux densities of the thermal and nonthermal components become equal. The power deposited by accelerated electrons into the flare volume has been estimated using the thick-target model under two assumptions about the boundary energy E 0 of the electron spectrum: (i) E 0 is determined by E γ0(t) and (ii) E 0 is determined by the characteristic heated plasma energy (≈5 kT (t)). The reality of the first assumption is proven by the fact that plasma cooling sets in at a time when the radiative losses begin to prevail over the power deposited by electrons only in this case. Comparison of the total energy deposited by electrons with a boundary energy E γ0(t) with the thermal energy of the emitting plasma in the time interval under consideration has shown that the total energy deposited by accelerated electrons at the beginning of the impulsive flare phase before 06:47 UT exceeds the thermal plasma energy by a factor of 1.5-2; subsequently, these energies become approximately equal and are ˜(4-5) × 1030 erg under the assumption that the filling factor is 0.5-0.6.

ПАЖ, 36(4), 292-303, **2010**

По данным многоканальных детекторов жесткого электромагнитного излучения СОНГ и СПР-Н на космической обсерватории “КОРОНАС-Ф” и рентгеновских мониторов спутников GOES были выделены тепловой и нетепловой компоненты в спектре рентгеновского излучения экстремальной солнечной вспышки **20 января 2005** г. В импульсной фазе вспышки, определенной по времени наиболее эффективного ускорения электронов и протонов, получены параметры спектров обоих компонентов и их вариации в интервале времени 06:43–06:54 UT. Показано, что при одностепенном представлении спектра ускоренных электронов спектральный индекс в области энергий 0.2–2 МэВ был близок к значению 3.4 в течение большей части рассматриваемого промежутка времени. Определена зависимость от времени величины нижней границы обрезания спектра энергии нетепловых фотонов , при которой сравниваются значения спектральной плотности теплового и нетеплового компонентов. Сделаны оценки мощности, вносимой ускоренными электронами во вспышечной объем, в рамках модели толстой мишени в двух предположениях о значении граничной энергии спектра электронов: а) определяется значениями , б) определяется характерной энергией нагретой плазмы (. Реальность первого предположения доказывается тем фактом, что только в этом случае охлаждение плазмы наступает в момент времени, когда радиационные потери начинают превалировать над мощностью, вносимой электронами. Сравнение полной энергии, внесенной электронами с граничной энергией , с тепловой энергией излучающей плазмы в рассматриваемом интервале времени показало, что в начале импульсной фазы вспышки до 06:47 UT полная энергия, внесенная ускоренными электронами, в 1.5–2 раза превышает тепловую энергию плазмы, затем эти энергии становятся примерно равными и составляют эрг в предположении, что коэффициент заполнения равен 0.5–0.6.

VYSOKOENERGIChNOE GAMMA-IZLUChENIE SOLNEChNYKh VSPYShEK KAK INDIKATOR USKORENIYa PROTONOV VYSOKIKh ENERGII

Viktoriya G. **Kurt**1, B. Yu. Yushkov1, K. Kudela2, V. I. Galkin1

Kosmicheskie issledovaniya, - tom 48, № 1, **2010**, S. 72-80

S pomoshch'yu detektora SONG na ISZ KORONAS-F bylo zaregistrirovano gamma-izluchenie vysokikh energii (>100 MeV) v chetyrekh solnechnykh vspyshkakh. Vydelenie v posledovatel'nykh spektrakh gamma-izlucheniya osobennosti, obuslovlennoi generatsiei i raspadom neitral'nykh pionov, pozvolilo s vysokoi tochnost'yu opredelit' momenty poyavleniya v solnechnoi atmosfere protonov, uskorennykh do energii svyshe 300 MeV.

Origin of the high energy gamma-ray emission in the March 26, 1991 solar flare

Kurt, Viktoria; Akimov, V. V.; Leikov, N. G.

High energy solar physics. AIP Conference Proceedings, Volume 374, pp. 237-245 (**1996**).

sci-hub.si/10.1063/1.50959

The solar flare on March 26, 1991 presents a unique case when high energy (up to 300 MeV) gamma radiation was registered in both, impulsive and delayed, phases of the flare. The radiation in the delayed phase has been attributed to neutral pions decay (1) analogous to the high energy gamma-ray emission at the late stages of the solar flares on June 11 and June 15, 1991 (2), (3), (4). On the contrary, spectra of the emission in the impulsive phase of the March 26 flare definitely indicate a bremsstrahlung origin of this emission. From the position of the flare close to the center of the disc we conclude that the high energy gamma-rays could be radiated only by moving upward electrons. We compare time profiles of the gamma-ray and the microwave emissions and show that the high and the low energy electrons responsible for these emissions were accelerated in the same acts. We put forward arguments in favour of an acceleration of the electrons in the upper chromosphere or in the transition layer.

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

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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.

Gamma-Ray and High-Energy-Neutron Measurements on CORONAS-F during the Solar Flare of 28 October 2003

Sergei N. **Kuznetsov** · Victoria G. Kurt · Boris Y. Yushkov · Karel Kudela · Vladimir I. Galkin

Solar Phys (**2011**) 268: 175–193; **File**

The solar flare of **28 October 2003** (X17.2/4B) was recorded by the SONG instrument onboard the CORONAS-F satellite. A description of the SONG instrument, its in-orbit operation and the principal data reduction methods used to derive the flare gamma-ray properties are presented. Appreciable gamma-ray emission was observed in the 0.2 – 300 MeV energy range. Several time intervals were identified which showed major changes in the intensity and spectral shape of the flare gamma-ray emission. The primary bremsstrahlung proves to be extended to 90 MeV and dominates during 11:02:11 – 11:03:50 UT time interval, *i.e.* at the beginning of the flare impulsive phase. Afterwards, the SONG response was consistent with detection of the pion-decay gamma emission. A sharp increase in the piondecay-generated gamma-ray emission was observed at 11 : 03 : 51±2 s UT, implying a substantial change in the spectrum of accelerated ions, which testified the appearance of protons with energies of > 300 MeV on the Sun. This emission lasted at least 8 – 9 min until the end of our measurements. The ion acceleration to high energies was also proved by the detection of neutrons with energies > 500 MeV. It was found that the most efficient acceleration of high-energy protons coincides in time with the highest rate of the magnetic-flux change rate. The maximum gamma-ray flux at 100 MeV was 1.1Ч10−2 photons cm−2 s−1 MeV−1, exceeding all the fluxes that have ever been recorded.

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**

Kuznetsov, S.N., Kurt, V.G., Myagkova, I.N., Yushkov, B.Y., Kudela, K.: **2006,** Gamma-ray emission and neutrons from solar flares recorded by the SONG instrument in 2001{2004. *Solar Sys. Res.* **40**, 104. DOI. ADS.

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.

Estimation of the solar flare neutron worst-case fluxes and fluences for missions traveling close to the Sun

D. **Lario**

Space Weather, Vol. 10, No. 3, S03002, **2012**

http://dx.doi.org/10.1029/2011SW000732

A method to estimate the total fluence of solar flare neutrons at a spacecraft traveling in the innermost part of the heliosphere (at heliocentric radial distances of <1 AU) is presented. The results of the neutron production and emissivity codes of Hua and Lingenfelter (1987a, 1987b) scaled to one of the largest solar neutron events ever observed at the Earth are used to derive a conservative estimate of the energy spectrum of neutrons emitted from the Sun after a large solar flare. By taking into account the survival probability of a neutron to reach a certain heliocentric distance, we evaluate the observed time-integrated spectrum of solar neutrons as a function of the heliocentric distance of the observer. By considering (1) a working relationship between the soft X-ray class of a flare and the flare's production of solar neutrons, and (2) the number and size of soft X-ray flares that may occur during a mission traveling close to the Sun, we compute an upper limit for the total fluence of solar neutrons at energies >1 MeV, >10 MeV, >100 MeV and >1000 MeV to which such a mission may be exposed. We apply this method to the Solar Probe Plus mission. Although our method gives a conservative estimate of neutron fluxes, the predicted mission-integrated fluence of solar neutrons at Solar Probe Plus is orders of magnitude below that of solar energetic protons.

Powerful solar signatures of long-lived dark mediators

Leane, Rebecca K.; Ng, Kenny C. Y.; Beacom, John F.

Physical Review D, Volume 95, Issue 12, id.123016, **2017**

http://sci-hub.tw/10.1103/PhysRevD.95.123016

Dark matter capture and annihilation in the Sun can produce detectable high-energy neutrinos, providing a probe of the dark matter-proton scattering cross section. We consider the case when annihilation proceeds via long-lived dark mediators, which allows gamma rays to escape the Sun and reduces the attenuation of neutrinos. For gamma rays, there are exciting new opportunities, due to detailed measurements of GeV solar gamma rays with Fermi, and unprecedented sensitivities in the TeV range with HAWC and LHAASO. For neutrinos, the enhanced flux, particularly at higher energies (˜TeV) , allows a more sensitive dark matter search with IceCube and KM3NeT. We show that these search channels can be extremely powerful, potentially improving sensitivity to the dark matter spin-dependent scattering cross section by several orders of magnitude relative to present searches for high-energy solar neutrinos, as well as direct detection experiments.

CORONAL THICK TARGET HARD X-RAY EMISSIONS AND RADIO EMISSIONS

Jeongwoo **Lee**1,2, Daye Lim2, G. S. Choe2, Kap-Sung Kim2, and Minhwan Jang

2013 ApJ 769 L11

A distinctive class of hard X-ray (HXR) sources located in the corona was recently found, which implies that the collisionally thick target model (CTTM) applies even to the corona. We investigated whether this idea can be independently verified by microwave radiations which have been known as the best companion to HXRs. This study is conducted on the GOES M2.3 class flare which occurred on **2002 September 9** and was observed by the Reuven Ramaty High-Energy Solar Spectroscopic Imager and the Owens Valley Solar Array. Interpreting the observed energy-dependent variation of HXR source size under the CTTM, the coronal density should be as high as 5 × 1011 cm–3 over a distance of up to 12". To explain the cutoff feature of the microwave spectrum at 3 GHz, however, we require a density no higher than 1 × 1011 cm–3. Additional constraints must be placed on the temperature and magnetic field of the coronal source in order to reproduce the microwave spectrum as a whole. First, a spectral feature called the Razin suppression requires a magnetic field in a range of 250-350 G along with high viewing angles around 75°. Second, to avoid excess fluxes at high frequencies due to the free-free emission that was not observed, we need a high temperature ≥2 × 107 K. These two microwave spectral features, Razin suppression and free-free emissions, become more significant at regions of high thermal plasma density and are essential for validating and determining additional parameters of the coronal HXR sources.

Parallel Motions of Coronal Hard X-ray Source and H® Ribbons

Jeongwoo **Lee** and Dale E. Gary

E-print, Aug 2008; Astrophysical Journal Letters, Vol. 685, No. 1: L87-L90, **2008**

http://solar.physics.montana.edu/cgi-bin/eprint/index.pl?entry=7776

http://www.journals.uchicago.edu/doi/abs/10.1086/592292

During solar flares H® ribbons form and often move away from the local magnetic polarity inversion line (PIL). While the motion perpendicular to the PIL has been taken as evidence for coronal magnetic reconnection in the so-called CSHKP standard model, the other velocity component parallel to the PIL is much less adopted as a property of the magnetic reconnection process. In this Letter we report an event in which the motion parallel to the PIL is found in both H® ribbons and a thermal hard X-ray source. Such commonality would indicate a link between the coronal magnetic reconnection and footpoint emissions as in the standard solar flare model. However, its direction implies a reconnection region that is increasing in length, a feature missing from the standard two-dimensional model. We present a modi¯ed framework in which the variation along the third dimension is allowed, in order to assess the e®ect of such a proper motion on estimation of the magnetic reconnection rate. Data used are hard X-ray maps from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), H® ¯ltergrams of Big Bear Solar Observatory (BBSO), and the SOHO Michelson Doppler Imager (MDI) magnetogram obtained for the 2004 March 30 flare.

Energy spectra of solar flare gamma-ray emission in the range 0.03-2 GeV registered by gamma-1 telescope

Leikov N.G.; Akimov, V. V.; Volsenskaya, V. A.; et al.
Advances in Space Research, Volume 13, Issue 9, p. 249-253. **1993**
sci-hub.si/10.1016/0273-1177(93)90486-U
The gamma-ray telescope GAMMA-1 has registered gamma-emission in the range 30 - 2000 MeV from two solar flares. Spectral analysis with the use of maximum likelihood and maximum entropy methods has revealed the difference of gamma-ray production mechanism. In contrast with impulsive **March 26, 1991** event where high energy gamma-rays originate exclusively as a bremstrahlung of primary accelerated electrons, at the extended phase of **June 15, 1991** flare mainly the decay of neutral pions is responsible for the observed gamma-emission. An average spectral index for primary nucleons was -3.6. Evolution of the spectra for both flares shows tendency to a decrease of the primary particles mean energies with time.

Spectral characteristics of high energy gamma ray solar flares

Leikov, N. G.; Akimov, V. V.; Volzhenskaia, V. A. and 7 more
Astronomy and Astrophysics Supplement Series , vol. 97, no. 1, p. 345-348. **1993**
The gamma-ray telescope GAMMA-1 has registed gamma-emission in the range 30-2000 MeV from two solar flares. Spectral analysis with the use of maximum likelihood and maximum entropy methods has revealed differences in gamma-ray production mechanisms. In the impulsive **March 26, 1991** event high energy gamma-rays originate exclusively as a bremsstrahlung of primary accelerated electrons. In contrast, the gamma ray emission of the extended phase of **June 15, 1991** flare is mainly due to the decay of neutral pions. The average spectral index for primary nucleons was -3.6. Evolution of the spectra for both flares shows tendency to a decrease of the primary particles mean energies with time.

Small-Scale Magnetic Fields are Critical to Shaping Solar Gamma-Ray Emission

Jung-Tsung **Li**, John F. Beacom, Spencer Griffith, Annika H. G. Peter
ApJ **961** 167 **2024**
https://arxiv.org/pdf/2307.08728.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ad158f/pdf
The Sun is a bright gamma-ray source due to hadronic cosmic-ray interactions with solar gas. While it is known that incoming cosmic rays must generally first be reflected by solar magnetic fields to produce outgoing gamma rays, theoretical models have yet to reproduce the observed spectra. We introduce a simplified model of the solar magnetic fields that captures the main elements relevant to gamma-ray production. These are a flux tube, representing the network elements, and a flux sheet, representing the intergranule sheets. Both the tube and sheet have a horizontal size of order 100 km and serve as sites where cosmic rays are reflected and gamma rays are produced. Despite having no tuning to match gamma-ray data, our model produces a gamma-ray spectrum that reasonably matches both the hard spectrum seen by Fermi-LAT data at 1--200 GeV and the considerably softer spectrum seen by HAWC at near 103 GeV. We show that lower-energy ($\lesssim$10 GeV) gamma rays are primarily produced in the network elements and higher-energy ($\gtrsim$few$\times$10 GeV) gamma rays in the intergranule sheets. Notably, the spectrum softening observed by HAWC results from the limited effectiveness of capturing and reflecting $\sim$104 GeV cosmic rays by the finite-sized intergranule sheets. Our study is important for understanding cosmic-ray transport in the solar atmosphere and will lead to insights about small-scale magnetic fields in the quiet photosphere.

Quasi-periodic Accelerations of Energetic Particles during a Solar Flare

Dong **Li**, Wei Chen

ApJL **931** L28 **2022**
https://arxiv.org/abs/2205.07423
https://iopscience.iop.org/article/10.3847/2041-8213/ac6fd2/pdf
We report the observation of non-stationary Quasi-Periodic Pulsations (QPPs) in high-energy particles during the impulsive phase of an X4.8 flare on 2002 July 23 (SOL2002-07-23T00:35). The X4.8 flare was simultaneously measured by the Reuven Ramaty High Energy Solar Spectroscopic Imager, Nobeyama Radio Polarimeters, and Nobeyama Radioheliograph. The quasi-period of about 50 s, determined by the wavelet transform, is detected in the Gamma-ray line emission. Using the same method, a quasi-period of about 90 s is found in Gamma-ray continuum, hard X-ray (HXR) and radio emissions during almost the same time. Our observations suggest that the flare QPPs should be associated with energetic ions and nonthermal electrons that quasi-periodically accelerated by the repetitive magnetic reconnection. The different quasi-periods between Gamma-ray line and continuum/HXR/radio emissions indicate an apparent difference in acceleration or propagation between energetic ions and nonthermal electrons of this solar flare. **2002 July 23**

Simulating gamma-ray production from cosmic rays interacting with the solar atmosphere in the presence of coronal magnetic fields

Zhe **Li**, Kenny C. Y. Ng, Songzhan Chen, Yuncheng Nan, Huihai He
2020
https://arxiv.org/pdf/2009.03888.pdf
Cosmic rays can interact with the solar atmosphere and produce a slew of secondary messengers, making the Sun a bright gamma-ray source in the sky. Detailed observations with Fermi-LAT have shown that these interactions must be strongly affected by solar magnetic fields in order to produce the wide range of observational features, such as high flux and hard spectrum. However, the detailed mechanisms behind these features are still a mystery. In this work, we tackle this problem by performing particle-interaction simulations in the solar atmosphere in the presence of coronal magnetic fields modeled using the potential field source surface (PFSS) model. We find that the low-energy (~GeV) gamma-ray production is significantly enhanced by the coronal magnetic fields, but the enhancement decreases rapidly with energy. The enhancement is directly correlated with the production of gamma rays with large deviation angles relative to the input cosmic-ray direction. We conclude that coronal magnetic fields are essential for correctly modeling solar disk gamma rays below 10GeV, but above that the effect of coronal magnetic fields diminishes. Other magnetic field structures are needed to explain the high-energy disk emission.

Quasi-periodic pulsations of gamma-ray emissions from a solar flare on 2017 September 06

D. **Li**, D. Y. Kolotkov, V. M. Nakariakov, L. Lu, Z. J. Ning
ApJ **888** 53 **2020**
https://arxiv.org/pdf/1912.01145.pdf
https://doi.org/10.3847/1538-4357/ab5e86
We investigate quasi-periodic pulsations (QPPs) of high-energy nonthermal emissions from an X9.3 flare (SOL2017-Sep-06T11:53), the most powerful flare since the beginning of solar cycle 24. The QPPs are identified as a series of regular and repeating peaks in the light curves in the gamma- and hard X-ray (HXR) channels recorded by the Konus-Wind, as well as the radio and microwave fluxes measured by the CALLISTO radio spectrograph during the impulsive phase. The periods are determined from the global wavelet and Fourier power spectra, as 24-30 s in the HXR and microwave channels which are associated with nonthermal electrons, and ~20 s in the gamma-ray band related to nonthermal ions. Both nonthermal electrons and ions may be accelerated by repetitive magnetic reconnection during the impulsive phase. However, we could not rule out other mechanisms such as the MHD oscillation in a sausage mode. The QPP detected in this study is useful for understanding the particle acceleration and dynamic process in solar flares and also bridging the gap between stellar and solar flares since the energy realm of the X9.3 solar flare is almost compared with a typical stellar flare.

Quasi-periodic pulsations with multiple periods in hard X-ray emission

Dong **Li**, Qingmin Zhang
MNRAS **2017**
https://arxiv.org/pdf/1706.01680.pdf
We explore the quasi-periodic pulsations (QPPs) with multiple periods in hard X-ray (HXR) emission from Fermi/GBM during the impulsive phase of solar flare (SOL**2014-09-10)**. The completely new observational result is that the shorter periods appear at lower energies of the X-ray photons at the beginning and the longer periods appear at higher energies at the end, with some intersection of the periods at medium energies. We also find the shorter and then the longer periods during the same phase of this flare. Using the wavelet power spectrum and fast Fourier transform (FFT) spectrum, we analyze the normalized rapidly varying signal divided by its slowly varying signal, which is the smoothed original HXR flux. The periods of 27 s and 37 s are derived at lower energy channels between 17:25 UT and 17:29 UT, i.e., 12.0-27.3 keV and 27.3-50.9 keV. Then the periods of 27 s, 46 s and 60 s are

observed at medium-energy channel from 17:26 UT to 17:33 UT, such as 50.9-102.3 keV. And the period of 80 s is detected at higher energy channel from 17:28 UT to 17:33 UT, such as 102.3-296.4 keV.

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).

RHESSI observations of particle acceleration and energy release in an intense solar gamma-ray line flare.

Lin, R. P., Krucker, S., Hurford, G. J., et al.

ApJL 595, L69-L72, **2003, File**.

https://iopscience.iop.org/article/10.1086/378932/pdf

We summarize RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) hard X-ray (HXR) and *γ*-ray imaging and spectroscopy observations of the intense (X4.8) *γ*-ray line flare of **23 July 2002**. In the inital rise, a new type of coronal HXR source dominates that has a steep double power-law X-ray spectrum and no evidence for thermal emission above 10 keV, indicating substantial electron acceleration to tens of keV early in the flare. In the subsequent impulsive phase, three footpoint sources with much flatter double power-law HXR spectra appear, together with a coronal superhot (T ~ 40 MK) thermal source. The north footpoint and the coronal source both move systematically to the north-northeast at speeds up to ~50 km/s. This footpoint's HXR flux varies approximately with its speed, consistent with magnetic reconnection models, provided the rate of electron acceleration varies with the reconnection rate. The other footpoints show similar temporal variations, but do not move systematically, contrary to simple reconnection models.

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.

First Observations of Solar Disk Gamma Rays over a Full Solar Cycle

Tim **Linden**, John F. Beacom, Annika H. G. Peter, Benjamin J. Buckman, Bei Zhou, Guanying Zhu

PHYSICAL REVIEW D (PRD) Volume 105, Issue 6, article id.063013 **2022**

https://arxiv.org/pdf/2012.04654.pdf

DOI 10.1103/PhysRevD.105.063013

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.105.063013

The solar disk is among the brightest gamma-ray sources in the sky. It is also among the most mysterious. No existing model fully explains the luminosity, spectrum, time variability, and morphology of its emission. We perform the first analysis of solar-disk gamma rays over a full 11-year solar cycle, utilizing a powerful new method to differentiate solar signals from astrophysical backgrounds. We produce: (i) a robustly measured spectrum from 100 MeV to 100 GeV, reaching a precision of several percent in the 1-10 GeV range, (ii) new results on the anti-correlation between solar activity and gamma-ray emission, (iii) strong constraints on short-timescale variability, ranging from hours to years, and (iv) new detections of the equatorial and polar morphologies of high-energy gamma rays. Intriguingly, we find no significant energy dependence in the time variability of solar-disk emission, indicating that strong magnetic-field effects close to the solar surface, rather than modulation throughout the heliosphere, must primarily control the flux and morphology of solar-disk emission.

Evidence for a New Component of High-Energy Solar Gamma-Ray Production

Tim **Linden**, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C. Y. Ng, Qing-Wen Tang
Physical Review Letters **2018**
https://arxiv.org/pdf/1803.05436.pdf
The observed multi-GeV gamma-ray emission from the solar disk --- sourced by hadronic cosmic rays interacting with gas, and affected by complex magnetic fields --- is not understood. Utilizing an improved analysis of the Fermi-LAT data that includes the first resolved imaging of the disk, we find strong evidence that this emission is produced by two separate mechanisms. Between 2010-2017 (the rise to and fall from solar maximum), the gamma-ray emission is dominated by a polar component. Between 2008-2009 (solar minimum) this component remains present, but the total emission is instead dominated by a new equatorial component with a brighter flux and harder spectrum. Most strikingly, although 6 gamma rays above 100 GeV are observed during the 1.4 years of solar minimum, none are observed during the next 7.8 years. These features, along with a 30-50 GeV spectral dip which will be discussed in a companion paper, were not anticipated by theory. To understand the underlying physics, Fermi and HAWC observations of the imminent Cycle 25 solar minimum are crucial.

See:

Mysterious High Energy Gamma Rays Might Help Explain What Drives Solar Cycles

Gregory S **Glenn**
2019
https://arxiv.org/ftp/arxiv/papers/1901/1901.10574.pdf

CONJUGATE HARD X-RAY FOOTPOINTS IN THE 2003 OCTOBER 29 X10 FLARE: UNSHEARING MOTIONS, CORRELATIONS, AND ASYMMETRIES

Wei **Liu**12, Vah´e Petrosian2, Brian R. Dennis1, and Gordon D. Holman1
E-print, May 2008; ApJ
We present a detailed imaging and spectroscopic study of the conjugate hard X-ray (HXR) footpoints (FPs) observed with RHESSI in the **2003 October 29** X10 flare. The double FPs first move toward and then away from each other, mainly parallel and perpendicular to the magnetic neutral line, respectively. The transition of these two phases of FP unshearing motions coincides with the direction reversal of the motion of the loop-top (LT) source, and with the minima of the estimated loop length and LT height. The FPs show temporal correlations in HXR flux, spectral index, and magnetic field strength. The HXR flux exponentially correlates with the magnetic field strength which also anti-correlates with the spectral index before the second HXR peak's maximum, suggesting that particle acceleration sensitively depends on the magnetic field strength and/or reconnection rate. Asymmetries are observed between the FPs: on average, the eastern FP is 2.2 times brighter in HXR flux and 1.8 times weaker in magnetic field strength, and moves 2.8 times faster away from the neutral line than the western FP; the estimated coronal column density to the eastern FP from the LT source is 1.7 times smaller. The two FPs have marginally different spectral indexes. The eastern-to-western FP HXR flux ratio and magnetic field strength ratio are anti-correlated only before the second HXR peak's maximum. Neither magnetic mirroring nor column density alone can explain these observations when taken together, but their combination, together with other transport effects, may play a role.

Characteristics of Solar Flare Hard X-ray Emissions: Observations and Models, Thesis,

RHESSI, **Wei Liu, E-print, Dec 2006, file**

Liu, W., Jiang, Y. W., Liu, S, Petrosian, V. **RHESSI observations of a simple large X-Ray flare on 2003 November 3.** ApJ 611, L53-L56, 2004.

THE SPATIAL DISTRIBUTION OF HARD X-RAY SPECTRAL INDEX AND LOCAL MAGNETIC RECONNECTION RATE
CHANG **LIU**,1 JEONGWOO LEE,2 JU JING,2 DALE E. GARY,2 AND HAIMIN WANG
E-print, Nov 2007, ApJL, Vol. 672, No. 1: L69–L72.
The rare phenomenon of ribbon-like hard X-ray (HXR) sources up to 100 keV found in the **2005 May 13** M8.0 flare observed with the Reuven Ramaty High Energy Solar Spectroscopic Imager provides detailed information on the spatial distribution of flare HXR emission.

THE RIBBON-LIKE HARD X-RAY EMISSION IN A SIGMOIDAL SOLAR ACTIVE REGION (13 May 2005 event)
CHANG **LIU**, JEONGWOO LEE, DALE E. GARY, AND HAIMIN WANG
SUBMITTED TO THE ASTROPHYSICAL JOURNAL LETTERS, 2006 NOVEMBER, file

"**Ribbon-like Hard X-ray Source**",
Chang **Liu**
RHESSI science nugget,
http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=40
May 13, 2005

Catalog of Hard X-ray Solar Flares Detected with Mars Odyssey/HEND from the Mars Orbit in 2001-2016
M.A. **Livshits**, I.V. Zimovets, D.V. Golovin, B.A. Nizamov, V.I. Vybornov, I.G. Mitrofanov, A.S. Kozyrev, M.L. Litvak, A.B. Sanin, V.I. Tretyakov
Astronomy Reports **2017**
https://arxiv.org/pdf/1706.01116.pdf
The study of nonstationary processes in the Sun is of great interest, and lately, multiwavelength observations and registration of magnetic fields are carried out by means of both ground-based telescopes and several specialized spacecraft (SC) on near-Earth orbits. However the acquisition of the new reliable information on their hard X-ray radiation remains demanded, in particular if the corresponding SC provide additional information, e.g. in regard to the flare observations from the directions other than the Sun-Earth direction. In this article we present a catalog of powerful solar flares registered by the High Energy Neutron Detector (HEND) device designed in the Space Research Institute (IKI) of Russian Academy of Sciences. HEND is mounted onboard the 2001 Mars Odyssey spacecraft. It worked successfully during the flight to Mars and currently operates in the near-Mars orbit. Besides neutrons, the HEND instrument is sensitive to the hard X-ray and gamma radiation. This radiation is registered by two scintillators: the outer one is sensitive to the photons above 40 keV and the inner one to the photons above 200 keV. The catalog was created with the new procedure of the data calibration. For most powerful 60 solar flares on the visible and on the far sides of the Sun (in respect to a terrestrial observer), we provide time profiles of flare radiation, summed over all the channels of X-ray and in some cases of gamma-ray bands as well as the spectra and characteristics of their power law approximation. We briefly discuss the results of the previous articles on the study of the Sun with HEND instrument and the potential of the further use of these data. **14 Jul 2005 , 12-Feb-2010**
TABLE II: Catalog of powerful solar flares (2001-2015).

The Sun: Light Dark Matter and Sterile Neutrinos
Ilídio **Lopes**
Astrophysical Journal **2020**, Volume 905, Issue 1, id.22, 9 pp
https://arxiv.org/pdf/2101.00210.pdf
Next-generation experiments allow for the possibility to testing the neutrino flavor oscillation model to very high levels of accuracy. Here, we explore the possibility that the dark matter in the current universe is made of two particles, a sterile neutrino and a very light dark matter particle. By using a 3+1 neutrino flavor oscillation model, we study how such a type of dark matter imprints the solar neutrino fluxes, spectra, and survival probabilities of electron neutrinos. The current solar neutrino measurements allow us to define an upper limit for the ratio of the mass of a light dark matter particle $m\phi$ and the Fermi constant $G\phi$, such that $G\phi/m\phi$ must be smaller than $1030 GFeV^{-1}$ to be in agreement with current solar neutrino data from the Borexino, Sudbury Neutrino Observatory, and Super-Kamiokande detectors. Moreover, for models with a very small Fermi constant, the amplitude of the time variability must be lower than 3% to be consistent with current solar neutrino data. We also found that solar neutrino detectors like Darwin, able to measure neutrino fluxes in the low energy-range with high

accuracy, will provide additional constraints to this class of models that complement the ones obtained from the current solar neutrino detectors.

New neutrino physics and the altered shapes of solar neutrino spectra

Ilídio **Lopes**
Phys. Rev. D **2017**
https://arxiv.org/pdf/1702.00447v1.pdf
Neutrinos coming from the Sun's core are now measured with a high precision, and fundamental neutrino oscillations parameters are determined with a good accuracy. In this work, we estimate the impact that a new neutrino physics model, the so-called generalized Mikheyev-Smirnov-Wolfenstein (MSW) oscillation mechanism, has on the shape of some of leading solar neutrino spectra, some of which will be partially tested by the next generation of solar neutrino experiments. In these calculations, we use a high-precision standard solar model in good agreement with helioseismology data. We found that the neutrino spectra of the different solar nuclear reactions of the proton-proton chains and carbon-nitrogen-oxygen cycle have quite distinct sensitivities to the new neutrino physics. The HeP and 8B neutrino spectra are the ones for which their shapes are more affected when neutrinos interact with quarks in addition to electrons. The shape of the 15O and 17F neutrino spectra are also modified, although in these cases the impact is much smaller. Finally, the impact in the shape of the PP and 13N neutrino spectra is practically negligible.

KW-Sun: The Konus-Wind Solar Flare Database in Hard X-Ray and Soft Gamma-Ray Ranges

A. L. **Lysenko**1, M. V. Ulanov1, A. A. Kuznetsov2, G. D. Fleishman3, D. D. Frederiks1, L. K. Kashapova2, Z. Ya. Sokolova1, D. S. Svinkin1, and A. E. Tsvetkova1
2022 ApJS 262 32
https://iopscience.iop.org/article/10.3847/1538-4365/ac8b87/pdf
We present a database of solar flares registered by the Konus-Wind instrument during more than 27 yr of operation, from 1994 November to now (2022 June). The constantly updated database (hereafter KW-Sun) contains over 1000 events detected in the instrument's triggered mode and is accessible online at http://www.ioffe.ru/LEA/kwsun/. For each flare, the database provides time-resolved energy spectra in energy range from ~20 keV to ~15 MeV in FITS format along with count-rate light curves in three wide-energy bands, G1 (~20–80 keV), G2 (~80–300 keV), and G3 (~300–1200 keV), with high time resolution (down to 16 ms) in ASCII and IDL SAV formats. This article focuses on the instrument capabilities in the context of solar observations, the structure of the KW-Sun data, and their intended usage. The presented homogeneous data set obtained in the broad energy range with high temporal resolution during more than two full solar cycles is beneficial for both statistical and case studies as well as a source of context data for solar flare research. **2017 September 6, 20 Jan 2022**
RHESSI Science Nuggets №437 **2022** https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/KW-Sun:_The_Konus-Wind_Solar_Flare_Database_in_Hard_X-Ray_and_Soft_Gamma-Ray_Ranges

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**

Gamma-ray emission from the impulsive phase of the 2017 September 06 X9.3 flare

Alexandra L. **Lysenko** (1), Sergey A. Anfinogentov (2), Dmitry D. Svinkin (1), Dmitry D. Frederiks (1), Gregory D. Fleishman
ApJ **877** 145 **2019**
https://arxiv.org/pdf/1904.10017.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ab1be0/pdf

We report hard X-ray and gamma-ray observations of the impulsive phase of the SOL2017-09-06T11:55 X9.3 solar flare. We focus on a high-energy part of the spectrum, >100 keV, and perform time resolved spectral analysis for a portion of the impulsive phase, recorded by the Konus-Wind experiment, that displayed prominent gamma-ray emission. Given a variety of possible emission components contributing to the gamma-ray emission, we employ a Bayesian inference to build the most probable fitting model. The analysis confidently revealed contributions from nuclear deexcitation lines, electron-positron annihilation line at 511 keV, and a neutron capture line at 2.223 MeV along with two components of the bremsstrahlung continuum. The revealed time evolution of the spectral components is particularly interesting. The low-energy bremsstrahlung continuum shows a soft-hard-soft pattern typical for impulsive flares, while the high-energy one shows a persistent hardening at the course of the flare. The neutron capture line emission shows an unusually short time delay relative to the nuclear deexcitation line component, which implies that the production of neutrons was significantly reduced soon after the event onset. This in turn may imply a prominent softening of the accelerated proton spectrum at the course of the flare, similar to the observed softening of the low-energy component of the accelerated electrons responsible for the low-energy bremsstrahlung continuum. We discuss possible physical scenarios, which might result in the obtained relationships between these gamma-ray components.

A remarkable, but confused, coronal hard X-ray source

Alexandra **Lysenko**, Larisa Kashapova, Hugh Hudson
RHESSI Science Nuggets #325 June **2018**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/A_remarkable,_but_confused,_coronal_hard_X-ray_source
We report a probable occulted event in 1999 that had gone un-noticed previously, and could identify it spatially with SSRT as well as characterize its hard X-ray spectral evolution with Konus/WIND. It may be difficult to do much quantitative analysis on this particular event because of source confusion and the lack of RHESSI or even Yohkoh hard X-ray imaging, but this event adds one more case to the limited catalog of occulted solar hard X-ray coronal events. **1999-06-05, 2014-09-01**

KW-Sun: The Konus/WIND Hard X-ray Solar Flare Database

Alexandra **Lysenko** and the Konus/WIND Team
RHESSI Science Nuggets #287 Dec **2016**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/KW-Sun:_The_Konus/WIND_Hard_X-ray_Solar_Flare_Database
A Hale Cycle's worth of hard X-ray and soft gamma-ray flare observations.
We describe here KW-Sun, a large database of solar flare hard X-ray and soft γ-ray emission accumulated by the Konus/WIND experiment (Ref. [1]). Konus/WIND is a joint Russian-US experiment launched on November 1, 1994 for γ-ray burst and solar flare studies. The instrument has operated in interplanetary space since July of 2004, near the Lagrangian point L1, so it sees the Sun 24 hours a day, and thanks to being far from the Earth's magnetosphere it has an exceptionally stable background.
During more than 22 years of observations Konus/WIND has detected more than 1000 solar flares in trigger mode (Figure 1), which constitute the database. The KW-Sun database can be accessed via "http://www.ioffe.ru/LEA/kwsun/" (at the time of writing only the data for years 2012-2016 are available, the remaining data will be added shortly).
20 Dec 2002

FLUKA Simulations of Pion Decay Gamma-radiation from Energetic Flare Ions

A L **MacKinnon** (1), S. Szpigel (2), G. Gimenez de Castro (2,3), J Tuneu (2)
Solar Phys. **295**, Article number: 174 **2020**
https://arxiv.org/pdf/2009.00414.pdf
https://link.springer.com/content/pdf/10.1007/s11207-020-01699-9.pdf
Gamma-ray continuum at > 10 MeV photon energy yields information on > 0.2 - 0.3 GeV/nucleon ions at the Sun. We use the general-purpose Monte Carlo code FLUKA (FLUktuierende KAskade) to model the transport of ions injected into thick and thin target sources, the nuclear processes that give rise to pions and other secondaries and the escape of the resulting photons from the atmosphere. We give examples of photon spectra calculated with a range of different assumptions about the primary ion velocity distribution and the source region. We show that FLUKA gives results for pion decay photon emissivity in agreement with previous treatments. Through the directionality of secondary products, as well as Compton scattering and pair production of photons prior to escaping the Sun, the predicted spectrum depends significantly on the viewing angle. Details of the photon spectrum in the 100 MeV range may constrain the angular distribution of primary ions and the depths at which they interact. We display a set of thick-target spectra produced making various assumptions about the incident ion energy and angular distribution and the viewing angle. If ions are very strongly beamed downward, or ion energies do not extend much above 1 GeV/nucleon, the photon spectrum is highly insensitive to details of the ion distribution. Under the simplest

assumptions, flares observed near disc centre should not display significant radiation above 1 GeV photon energy. We give an example application to Fermi Large Area Telescope data from the flare of **12 June 2010**.
RHESSI Science Nugget, No. **402**, Mar **2021**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/FLUKA_as_a_tool_for_interpreting_flare_gamma-rays

Solar flare neutrons observed on the ground and in space

Alexander **MacKinnon**
RHESSI Science Nuggets #280 Aug **2016**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Solar_flare_neutrons_observed_on_the_ground_and_in_space
2014-07-08

Speed and Acceleration of CMEs Associated with Sustained Gamma-Ray Emission Events Observed by Fermi/LAT

P. **Mäkelä**, N. Gopalswamy, S. Akiyama, H. Xie, S. Yashiro
ApJ **954** 79 **2023**
https://arxiv.org/pdf/2307.05585.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ace627/pdf **File**
The sustained gamma-ray emission (SGRE) from the Sun is a prolonged enhancement of >100 MeV gamma-ray emission that extends beyond the flare impulsive phase.The origin of the >300 MeV protons resulting in SGRE is debated, both flares and shocks driven by coronal mass ejections (CMEs) being the suggested sites of proton acceleration. We compared the near-Sun acceleration and space speed of CMEs with 'Prompt' and 'Delayed' (SGRE) gamma-ray components (Ajello et al. 2021). We found that 'Delayed'-component-associated CMEs have higher initial acceleration and space speed than 'Prompt-only'-component-associated CMEs. We selected halo CMEs (HCMEs) associated with type II radio bursts (shock-driving HCMEs) and compared the average acceleration and space speed between HCME populations with or without SGRE events, major solar energetic particle (SEP) events, metric, or decameter-hectometric (DH) type II radio bursts. We found that the SGRE-producing HCMEs associated with a DH type II radio burst and/or a major SEP event have higher space speeds and especially initial accelerations than those without an SGRE event. We estimated the radial distance and speed of the CME-driven shocks at the end time of the 2012 January 23 and March 07 SGRE events using white-light images of STEREO Heliospheric Imagers and radio dynamic spectra of Wind WAVES. The shocks were at the radial distances of 0.6-0.8 au and their speeds were high enough (~975 km s−1 and ~750 km s−1, respectively) for high-energy particle acceleration. Therefore, we conclude that our findings support the CME-driven shock as the source of >300 MeV protons. **2012: January 23 and March 07**
Table A. CME and X-ray flare data for Fermi/LAT solar flares 2010-2017
Table B. Cycle 24 HCMEs with type II radio bursts 2010-2017

High-Energy Gamma-Ray Emission from Pion Decay in a Solar Flare Magnetic Loop

Mandzhavidze, N., & Ramaty, R.
1992, ApJ, 389, 739,
doi: 10.1086/171247
https://ui.adsabs.harvard.edu/link_gateway/1992ApJ...389..739M/ADS_PDF
The production of high-energy gamma rays resulting from pion decay in a solar flare magnetic loop is investigated. Magnetic mirroring, MHD pitch-angle scattering, and all of the relevant loss processes and photon production mechanisms are taken into account. The transport of both the primary ions and the secondary positrons resulting from the decay of the positive pions, as well as the transport of the produced gamma-ray emission are considered. The distributions of the gamma rays as a function of atmospheric depth, time, emission angle, and photon energy are calculated and the dependence of these distributions on the model parameters are studied. The obtained angular distributions are not sufficiently anisotropic to account for the observed limb brightening of the greater than 10 MeV flare emission, indicating that the bulk of this emission is bremsstrahlung from primary electrons.

First NuSTAR Limits on Quiet Sun Hard X-Ray Transient Events

Andrew J. **Marsh**1, David M. Smith1, Lindsay Glesener2 …….
2017 ApJ 849 131
https://arxiv.org/pdf/1711.05385.pdf
We present the first results of a search for transient hard X-ray (HXR) emission in the quiet solar corona with the Nuclear Spectroscopic Telescope Array (NuSTAR) satellite. While NuSTAR was designed as an astrophysics mission, it can observe the Sun above 2 keV with unprecedented sensitivity due to its pioneering use of focusing optics. NuSTAR first observed quiet-Sun regions on **2014 November 1**, although out-of-view active regions contributed a notable amount of background in the form of single-bounce (unfocused) X-rays. We conducted a

search for quiet-Sun transient brightenings on timescales of 100 s and set upper limits on emission in two energy bands. We set 2.5–4 keV limits on brightenings with timescales of 100 s, expressed as the temperature T and emission measure EM of a thermal plasma. We also set 10–20 keV limits on brightenings with timescales of 30, 60, and 100 s, expressed as model-independent photon fluxes. The limits in both bands are well below previous HXR microflare detections, though not low enough to detect events of equivalent T and EM as quiet-Sun brightenings seen in soft X-ray observations. We expect future observations during solar minimum to increase the NuSTAR sensitivity by over two orders of magnitude due to higher instrument livetime and reduced solar background.

Extremely Microwave-Rich Solar Flare Observed with Nobeyama Radioheliograph

S. **Masuda**, M. Shimojo, T. Kawate, S. Ishikawa, and M. Ohno
Publ. Astron. Soc. Japan 65, 1 [6 pages] (**2013**) http://pasj.asj.or.jp/v65/sp1/65S001/65S001.pdf
A compact flare was observed with Nobeyama Radioheliograph (NoRH) slightly behind the west limb on **2011 March 10**. The microwave peak flux values at 17 and 34 GHz were about 210 and 133 sfu, respectively. From the correlation between the 17 GHz peak flux and the GOES 1–8 ˚A soft X-ray peak flux, M1.5-class is expected for this microwave flux. However, only the B1-level enhancement was detected in the GOES 1–8 ˚A soft X-ray light curve on the C1-level background during the flare period. In addition to microwaves, Suzaku detected hard X-ray emissions, even in the energy range above 100 keV. It is clear that high-energy electrons were effectively produced in this flare, while the thermal emission was very weak. Why did this flare have this unique feature? The following two cases are considered. One is the case that a magnetic trap for electrons works effectively, and that each electron continues to emit microwaves in its relatively long lifetime. The other is that the magnetic field around the looptop region is intense, and relatively a large number of lower-energy electrons emit microwaves. Considering the observational facts, such as the short duration and the small flare loop, the latter case is more plausible.

The high-energy Sun - probing the origins of particle acceleration on our nearest star **Review**

S. A **Matthews**1 · H. A. S. Reid1 · D. Baker1 · D. S. Bloomfield2 · P. K. Browning3 · A. Calcines4 · G. Del Zanna5 · R. Erdelyi6,7,8 ·L. Fletcher9,10 · I. G. Hannah9 · N. Jeffrey2 · L. Klein11 · S. Krucker12 · E. Kontar9 · D. M. Long1 · A. MacKinnon9 · G. Mann13 ·M. Mathioudakis14 · R. Milligan14 · V. M. Nakariakov15 ·M. Pesce-Rollins16 · A. Y. Shih17 · D. Smith18 · A. Veronig19 · N. Vilmer11
Experimental Astronomy (**2021**)
https://doi.org/10.1007/s10686-021-09798-6
https://link.springer.com/content/pdf/10.1007/s10686-021-09798-6.pdf
As a frequent and energetic particle accelerator, our Sun provides us with an excellent astrophysical laboratory for understanding the fundamental process of particle acceleration. The exploitation of radiative diagnostics from electrons has shown that acceleration operates on sub-second time scales in a complex magnetic environment, where direct electric fields, wave turbulence, and shock waves all must contribute, although precise details are severely lacking. Ions were assumed to be accelerated in a similar manner to electrons, but γ-ray imaging confirmed that emission sources are spatially separated from X-ray sources, suggesting distinctly different acceleration mechanisms. Current X-ray and γ-ray spectroscopy provides only a basic understanding of accelerated particle spectra and the total energy budgets are therefore poorly constrained. Additionally, the recent detection of relativistic ion signatures lasting many hours, without an electron counterpart, is an enigma. We propose a single platform to directly measure the physical conditions present in the energy release sites and the environment in which the particles propagate and deposit their energy. To address this fundamental issue, we set out a suite of dedicated instruments that will probe both electrons and ions simultaneously to observe; high (seconds) temporal resolution photon spectra (4 keV – 150 MeV) with simultaneous imaging (1 keV – 30 MeV), polarization measurements (5–1000 keV) and high spatial and temporal resolution imaging spectroscopy in the UV/EUV/SXR (soft X-ray) regimes. These instruments will observe the broad range of radiative signatures produced in the solar atmosphere by accelerated particles.

Searching for sub-populations within the gamma-ray solar flares catalog: a graph-based clustering analysis

Jonathan **Mauro**, Gwenhaël de Wasseige
Presented at the 38th International Cosmic Ray Conference (ICRC2023) **2023**
https://arxiv.org/pdf/2310.16011.pdf
https://pos.sissa.it/444/1292/pdf
Solar flares are highly energetic events that happen in the solar atmosphere. They are mostly observed as X-ray or gamma-ray bursts located on the Sun's surface. While they are known to be sites of particle acceleration, the acceleration process(es) responsible for the observed fluxes remain unsure. The diversity in shape and duration of the gamma-ray fluxes suggests the existence of distinct phases of hadronic acceleration. Moreover, different

acceleration processes could explain the differences observed among flares. In this work we search for the evidence of sub-populations within the catalog of gamma-ray solar flares observed by Fermi-LAT. We aim at grouping flares with similar physical properties to be able to probe theoretical models for neutrino production within different classes of flares. We use measurements of the X-ray and gamma-ray fluxes, as well as CMEs and SEPs, to cluster the events using a graph-based algorithm. Furthermore, we investigate the most representative features that characterise the identified sub-populations to allow for qualitative analysis and model development.

Radio Emissions from Double RHESSI TGFs terrestrial gamma-ray flashes

Andrey **Mezentsev**, Thomas Gjesteland
RHESSI Science Nuggets №295, March **2017**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Radio_Emissions_from_Double_RHESSI_TGFs
RHESSI detects gamma rays emerging from the atmosphere; these are the byproduct of the bremsstrahlung of relativistic runaway electrons produced deep in the thunderstorm cloud system. Here the electric fields can be high enough to produce the runaway, and the potential difference large enough (millions of volts) to produce gamma rays.

Particle acceleration and gamma rays in solar flares: Recent observations and new modeling

L.I. **Miroshnichenko**, W.Q. Gan
Advances in Space Research, Volume 50, Issue 6, 15 September **2012**, Pages 736–756
Experiments on SMM, GAMMA, Yohkoh, GRANAT, Compton GRO, INTEGRAL, RHESSI and CORONAS-F satellites over the past three decades have provided copious data for fundamental research relating to particle acceleration, transport and energetics of flares and to the ambient abundance of the solar corona, chromosphere and photosphere. We summarize main results of solar gamma-astronomy (including some results of several joint Russian–Chinese projects) and try to appraise critically a real contribution of those results into modern understanding of solar flares, particle acceleration at the Sun and some properties of the solar atmosphere. Recent findings based on the RHESSI, INTEGRAL and CORONAS-F measurements (source locations, spectrum peculiarities, 3He abundance etc.) are especially discussed. Some unusual features of extreme solar events (e.g., 28 October 2003 and 20 January 2005) have been found in gamma-ray production and generation of relativistic particles (solar cosmic rays, or SCR). A number of different plausible assumptions are considered concerning the details of underlying physical processes during large flares: (1) existence of a steeper distribution of surrounding medium density as compared to a standard astrophysical model (HSRA) for the solar atmosphere; (2) enhanced content of the 3He isotope; (3) formation of magnetic trap with specific properties; (4) prevailing non-uniform (e.g., fan-like) velocity (angular) distributions of secondary neutrons, etc. It is emphasized that real progress in this field may be achieved only by combination of gamma-ray data in different energy ranges with multi-wave and energetic particle observations during the same event. We especially note several promising lines for the further studies: (1) resonant acceleration of the 3He ions in the corona; (2) timing of the flare evolution by gamma-ray fluxes in energy range above 90 MeV; (3) separation of gamma-ray fluxes from different sources at/near the Sun (e.g., different acceleration sources/episodes during the same flare, contribution of energetic particles accelerated by the CME-driven shocks etc.); (4) asymmetric magnetic geometry and new magnetic topology models of the near-limb flares; (5) modeling of self-consistent time scenario of the event.

Solar neutrinos with CEvNS and flavor-dependent radiative corrections

Nityasa **Mishra**, Louis E. Strigari
2023
https://arxiv.org/pdf/2305.17827.pdf
We examine solar neutrinos in dark matter detectors including the effects of flavor-dependent radiative corrections to the CEvNS cross section. Working within a full three-flavor framework, and including matter effects within the Sun and Earth, detectors with thresholds $\lesssim$1 keV and exposures of $\sim$100 ton-year could identify contributions to the cross section beyond tree level. The differences between the cross sections for the flavors, combined with the difference in fluxes, would provide a new and unique method to study the muon and tau components of the solar neutrino flux. Flavor-dependent corrections induce a small day-night asymmetry of $<|3\times10-4|$ in the event rate, which if ultimately accessible would provide a novel probe of flavor oscillations.

IS⊙IS Solar γ-Ray Measurements: Initial Observations and Calibrations

J. G. **Mitchell**1, G. A. de Nolfo1, E. R. Christian1, R. A. Leske2, J. M. Ryan3, J. T. Vievering4, M. E. Hill4, A. W. Labrador2, M. E. Wiedenbeck5, D. J. McComas6Show full author list
2024 ApJ 968 33
https://iopscience.iop.org/article/10.3847/1538-4357/ad3fb2/pdf

High-energy neutral solar radiation in the form of γ-rays and neutrons is produced as secondary products in solar flares. The characteristics of this emission can provide key information regarding the energization of charged particles, particularly when primary particles remain trapped in the corona. The Integrated Science Investigation of the Sun (IS⊙IS) suite on Parker Solar Probe is composed of instruments primarily intended to measure energetic charged particles. However, the High Energy Telescope (HET) in IS⊙IS was also designed with a supplementary neutral mode intended to measure γ-rays and neutrons. HET observed its first clear solar γ-ray event in connection with a hard X-ray flare, the eruption of a coronal mass ejection, and a solar energetic particle event on **2022 September 5**. The X-ray spectral shape was observed to harden over the course of the event, culminating with the observation of γ-rays by HET. A coincident enhancement in the lower-energy Energetic Particle Instrument (EPI-Lo) was also observed, likely produced by incident solar γ-rays despite the EPI-Lo instrument not having any special neutral measurement capabilities. We use Monte Carlo modeling to reconstruct the incident γ-ray spectrum based on the measured spectrum to demonstrate that the combination of IS⊙IS instruments can measure hard X-rays and γ-rays from ~60 keV–7 MeV. Despite the fact that this is a supplemental science goal of the mission, the capability of the IS⊙IS instruments to measure γ-rays is important for the study of this population due to the very limited instruments currently observing the Sun in γ-rays.

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.

Analysis of Solar Gamma Rays and Solar Neutrons detected on March 7th and September 25th of 2011 by Ground Level Neutron Telescopes, SEDA-FIB and FERMI-LAT

Y. **Muraki**, J.V. Galicia, X. Gonzalez, K. Kamiya, Y. Katayose, K. Koga, H. Matsumoto, S. Masuda, Y. Matsubara, Y. Nagai, M. Ohnishi, S. Ozawa, T. Sako, S. Shibata, M. Takita, Y. Tanaka, H. Tsuchiya, K. Watanabe and J. Zhang

Proc. of 35th International Cosmic Ray Conference — ICRC2017 10–20 July, **2017** Bexco, Busan, Korea

https://pos.sissa.it/301/136/pdf

At the 33rd ICRC, we reported the possible detection of solar gamma rays by a ground level detector and later re-examined this event. On **March 7, 2011**, the solar neutron telescope (SNT) located at Mt. Sierra Negra, Mexico (4,600 m) observed enhancements of the counting rate from19:49 to 20:02 UT and from 20:50 to 21:01 UT. The statistical significance was 9.7σ and 8.5σ, respectively. This paper discusses the possibility of using this mountain detector to detect solar gamma rays. In association with this event, the solar neutron detector SEDA-FIB onboard the International Space Station has also detected solar neutrons with a statistical significance of 7.5σ. The FERMI-LAT detector also observed high-energy gamma rays from this flare with a statistical significance of 6.7σ. We thus attempted to make a unified model to explain this data. We also report on another candidate for solar gamma rays detected on **September 25th, 2011** by the SNT located in Tibet (4,300 m) from 04:37 to 04:47 UT with a statistical significance of 8.0σ (by the Li-Ma method).

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 Physics, 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 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.
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).

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.

Compton Scattering of Deexcitation-Line and Continuum Gamma Rays in Solar Flares

Ron **Murphy**, Gerry Share
Solar Physics December **2018**, 293:163
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1386-2.pdf
sci-hub.tw/10.1007/s11207-018-1386-2
Measurements of solar-flare electron-bremsstrahlung X-rays are affected by Compton scattering in the solar atmosphere of the downward-directed radiation. Here we study how Compton-scattered and energy-degraded radiation from nuclear-deexcitation gamma-ray lines and continua affect the measurements of the gamma-ray radiation. Deexcitation-line photons with trajectories directed away from the Sun escape without significant interactions even for flares at the limb. We calculate the Compton-scattered component spectrum from downward-directed deexcitation lines for typical solar-flare accelerated-ion kinetic-energy spectra. The scattered component only a makes a significant contribution to the emerging spectrum at energies below ≈ 600 keV and is most prominent for flares occurring near the center of the solar disk. We study Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spectra obtained from the **28 October 2003** disk-centered flare when the electron-bremsstrahlung contribution was relatively weak. We find that inclusion of the scattered component does not significantly affect any of the derived flare parameters. This is true, in part, because the scattered component is not detectable over the significant RHESSI detector count continuum due to partial energy depositions of higher-energy solar photons. The scattered component may affect flare spectral measurements obtained with gamma-ray detectors having a more “diagonal” response.

Neutron Production in Solar Flares

Ron **Murphy**, Gerry Share
RHESSI Science Nuggets #338 November **2018**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Neutron_Production_in_Solar_Flares
Measurements of solar-flare neutrons, along with measurements of other flare emissions, are important diagnostic tools for understanding the flare process in general and ion acceleration in particular. There have been several RHESSI Nuggets written about detections of neutrons from solar flares (e.g. A, B, C). In this Nugget we discuss the physics of neutron production, and describe comparison of neutron calculations with measurements can be used to learn about ion acceleration in solar flares.
In the standard solar-flare model (Ref. [1]), electrons and ions are accelerated somehow via [magnetic reconnection], probably near the tops of closed coronal magnetic loops. These particles travel down the loop legs

and interact with material at the loop footpoints. Nuclear interactions of the ions then produce excited and radioactive nuclei, neutrons, and pions.

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.

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.

Solar X-ray Emission Measured by the VernovMission During September – October of 2014

N. **Myagkova**, A. V. Bogomolov, L. K. Kashapova, V. V. Bogomolov, S. I. Svertilov, M. I. Panasyuk, E. A. Kuznetsova, G. V. Rozhkov
Solar Phys. **2016**
Solar hard X-ray and γγ-ray emissions were measured by the Detector of the Roentgen and Gamma-ray Emissions (DRGE) instrument, which is part of the RELEC set of instruments operated onboard the Russian satellite Vernov, from July 8, 2014 until December 10, 2014 (on a solar-synchronous orbit with an apogee of 830 km, perigee of 640 km, and an inclination of 98.4∘98.4∘). RELEC measurements of 18 flares with X-ray energy >30 keV>30 keV, taken in September – October 2014, were connected with the same active region with the number AR 12172 during the first rotation and AR 12192 during the next one. These measurements were compared to the data obtained with RHESSI, Konus-Wind, Fermi Observatory, Radio Solar Telescope Net(RSTN), and the Nobeyama Radioheliograph (NoRH) operating at the same time. Quasi-periodicities with similar periods of 7±2 s7±2 s were found in about one third of all flares measured by RELEC (Vernov) from September 24 until October 30, 2014.

History of Solar Neutrino Observations **Review**

Masayuki **Nakahata**
PTEP **2022**
https://arxiv.org/pdf/2202.12421.pdf
The first solar neutrino experiment led by Raymond Davis Jr. showed a deficit of neutrinos relative to the solar model prediction, referred to as the "solar neutrino problem" since the 1970s. The Kamiokande experiment led by Masatoshi Koshiba successfully observed solar neutrinos, as first reported in 1989. The observed flux of solar neutrinos was almost half the prediction and confirmed the solar neutrino problem. This problem was not resolved

for some time due to possible uncertainties in the solar model. In 2001, it was discovered that the solar neutrino problem is due to neutrino oscillations by comparing the Super-Kamiokande and Sudbury Neutrino Observatory results, which was the first model-independent comparison. Detailed studies of solar neutrino oscillations have since been performed, and the results of solar neutrino experiments are consistent with solar model predictions when the effect of neutrino oscillations are taken into account. In this article, the history of solar neutrino observations is reviewed with the contributions of Kamiokande and Super-Kamiokande detailed.

TeV Solar Gamma Rays as a probe for the Solar Internetwork Magnetic Fields

Kenny C.Y. **Ng**, Andrew Hillier, Shin'ichiro Ando

2024

https://arxiv.org/pdf/2405.17549

The magnetic fields that emerge from beneath the solar surface and permeate the solar atmosphere are the key drivers of space weather and, thus, understanding them is important to human society. Direct observations, used to measure magnetic fields, can only probe the magnetic fields in the photosphere and above, far from the regions the magnetic fields are being enhanced by the solar dynamo. Solar gamma rays produced by cosmic rays interacting with the solar atmosphere have been detected from GeV to TeV energy range, and revealed that they are significantly affected by solar magnetic fields. However, much of the observations are yet to be explained by a physical model. Using a semi-analytic model, we show that magnetic fields at and below the photosphere with a large horizontal component could explain the ∼1 TeV solar gamma rays observed by HAWC. This could allow high-energy solar gamma rays to be a novel probe for magnetic fields below the photosphere.

First Observation of Time Variation in the Solar-Disk Gamma-Ray Flux with Fermi

Kenny C. Y. **Ng**, John F. Beacom, Annika H. G. Peter, Carsten Rott

2015

http://arxiv.org/pdf/1508.06276v1.pdf

The solar disk is a bright gamma-ray source. Surprisingly, its flux is about one order of magnitude higher than predicted. As a first step toward understanding the physical origin of this discrepancy, we perform a new analysis in 1-100 GeV using 6 years of public Fermi-LAT data. Compared to the previous analysis by the Fermi Collaboration, who analyzed 1.5 years of data and detected the solar disk in 0.1-10 GeV, we find two new and significant results: 1. In the 1-10 GeV flux (detected at >5σ), we discover a significant time variation that anticorrelates with solar activity. 2. We detect gamma rays in 10- 30 GeV at >5σ, and in 30- 100 GeV at >2σ. The time variation strongly indicates that solar-disk gamma rays are induced by cosmic rays and that solar atmospheric magnetic fields play an important role. Our results provide essential clues for understanding the underlying gamma-ray production processes, which may allow new probes of solar atmospheric magnetic fields, cosmic rays in the solar system, and possible new physics. Finally, we show that the Sun is a promising new target for ground-based TeV gamma-ray telescopes such as HAWC and LHAASO.

The Sun at GeV--TeV Energies: A New Laboratory for Astroparticle Physics

M.U. **Nisa**, J.F. Beacom, S.Y. BenZvi, R.K. Leane, T. Linden, K.C.Y. Ng, A.H.G. Peter, B. Zhou

Astro2020 Decadal Survey on Astronomy and Astrophysics **2019**

https://arxiv.org/pdf/1903.06349.pdf

The Sun is an excellent laboratory for astroparticle physics but remains poorly understood at GeV--TeV energies. Despite the immense relevance for both cosmic-ray propagation and dark matter searches, only in recent years has the Sun become a target for precision gamma-ray astronomy with the Fermi-LAT instrument. Among the most surprising results from the observations is a hard excess of GeV gamma-ray flux that strongly anti-correlates with solar activity, especially at the highest energies accessible to Fermi-LAT. Most of the observed properties of the gamma-ray emission cannot be explained by existing models of cosmic-ray interactions with the solar atmosphere. GeV--TeV gamma-ray observations of the Sun spanning an entire solar cycle would provide key insights into the origin of these gamma rays, and consequently improve our understanding of the Sun's environment as well as the foregrounds for new physics searches, such as dark matter. These can be complemented with new observations with neutrinos and cosmic rays. Together these observations make the Sun a new testing ground for particle physics in dynamic environments.

Solar Hard X-ray Source Sizes in a Beam-Heated and Ionised Chromosphere

A. **O'Flannagain**, J. C. Brown, P. T. Gallagher

2014

http://arxiv.org/pdf/1411.5168v1.pdf

Solar flare hard X-rays (HXRs) are produced as bremsstrahlung when an accelerated population of electrons interacts with the dense chromospheric plasma. HXR observations presented by using the Ramaty High-Energy

Solar Spectroscopic Imager (RHESSI) have shown that HXR source sizes are 3-6 times more extended in height than those predicted by the standard collisional thick target model (CTTM). Several possible explanations have been put forward including the multi-threaded nature of flare loops, pitch-angle scattering, and magnetic mirroring. However, the nonuniform ionisation (NUI) structure along the path of the electron beam has not been fully explored as a solution to this problem. Ionised plasma is known to be less effective at producing nonthermal bremsstrahlung HXRs when compared to neutral plasma. If the peak HXR emission was produced in a locally ionised region within the chromosphere, the intensity of emission will be preferentially reduced around this peak, resulting in a more extended source. Due to this effect, along with the associated density enhancement in the upper chromosphere, injection of a beam of electrons into a partially ionised plasma should result in a HXR source which is substantially more vertically extended relative to that for a neutral target. Here we present the results of a modification to the CTTM which takes into account both a localised form of chromospheric NUI and an increased target density. We find 50 keV HXR source widths, with and without the inclusion of a locally ionised region, of ~3 Mm and ~0.7 Mm, respectively. This helps to provide a theoretical solution to the currently open question of overly-extended HXR sources

Hard X-rays in Descent

Aidan **O'Flannagain**, John Brown and Peter Gallagher
RHESSI Science Nugget No. 201, May **2013**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Hard_X-rays_in_Descent
A novel test of the cold thick-target model for flare X-ray emission
We outline an attempt to make an observation of this previously unseen phenomenon: the height variation of the HXR centroid during the burst evolution.

Electron Energy Partition in the Above-the-looptop Solar Hard X-Ray Sources

Mitsuo **Oka**1, Säm Krucker1,2, Hugh S. Hudson1,3, and Pascal Saint-Hilaire
ApJ 799 129 **2015**
Solar flares produce non-thermal electrons with energies up to tens of MeVs. To understand the origin of energetic electrons, coronal hard X-ray (HXR) sources, in particular above-the-looptop sources, have been studied extensively. However, it still remains unclear how energies are partitioned between thermal and non-thermal electrons within the above-the-looptop source. Here we show that the kappa distribution, when compared to conventional spectral models, can better characterize the above-the-looptop HXRs ($\gtrsim$15 keV) observed in four different cases. The widely used conventional model (i.e., the combined thermal plus power-law distribution) can also fit the data, but it returns unreasonable parameter values due to a non-physical sharp lower-energy cutoff Ec. In two cases, extreme-ultraviolet data were available from SDO/AIA and the kappa distribution was still consistent with the analysis of differential emission measure. Based on the kappa distribution model, we found that the **2012 July 19** flare showed the largest non-thermal fraction of electron energies about 50%, suggesting equipartition of energies. Considering the results of particle-in-cell simulations, as well as density estimates of the four cases studied, we propose a scenario in which electron acceleration is achieved primarily by collisionless magnetic reconnection, but the electron energy partition in the above-the-looptop source depends on the source density. In low-density above-the-looptop regions (few times 109 cm–3), the enhanced non-thermal tail can remain and a prominent HXR source is created, whereas in higher-densities (>1010 cm–3), the non-thermal tail is suppressed or thermalized by Coulomb collisions.

Above-the-Looptop Sources

Mitsuo **Oka** and Sa"m Krucker.
RHESSI Science Nugget No. 244, Jan **2015**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Above-the-Looptop_Sources
While previous studies suggested that all electrons are accelerated to form a power-law (See the Nugget "Acceleration-region Densities"), we have proposed that the kappa distribution model (i.e., a Maxwellian-like core combined with a power-law tail) can equally fit the X-ray data from the above-the-looptop source (see our previous nugget "Kappa Distribution"). In this Nugget (See also Ref.[2]), we report an expanded study of the above-the-looptop sources, finding two cases with significantly enhanced non-thermal tail (hard X-ray) distributions, and two cases of less-enhanced non-thermal tail (Figure 2). With the kappa distribution model, we found that the flare **SOL2012-0719** showed the largest non-thermal fractions of electron number density (20%) and electron energy density (50%) whereas the **SOL2013-05-13** event showed the smallest non-thermal fractions of electron number density (6%) and electron energy density (16%). These results can be discussed in the context of magnetic reconnection, as described below.
Electron distribution functions in coronal sources explained.

KAPPA DISTRIBUTION MODEL FOR HARD X-RAY CORONAL SOURCES OF SOLAR FLARES

M. **Oka**1, S. Ishikawa1,2, P. Saint-Hilaire1, S. Krucker1,3, and R. P. Lin

2013 ApJ 764 6

Solar flares produce hard X-ray emission, the photon spectrum of which is often represented by a combination of thermal and power-law distributions. However, the estimates of the number and total energy of non-thermal electrons are sensitive to the determination of the power-law cutoff energy. Here, we revisit an "above-the-loop" coronal source observed by RHESSI on **2007 December 31** and show that a kappa distribution model can also be used to fit its spectrum. Because the kappa distribution has a Maxwellian-like core in addition to a high-energy power-law tail, the emission measure and temperature of the instantaneous electrons can be derived without assuming the cutoff energy. Moreover, the non-thermal fractions of electron number/energy densities can be uniquely estimated because they are functions of only the power-law index. With the kappa distribution model, we estimated that the total electron density of the coronal source region was ~2.4 × 1010 cm–3. We also estimated without assuming the source volume that a moderate fraction (~20%) of electrons in the source region was non-thermal and carried ~52% of the total electron energy. The temperature was 28 MK, and the power-law index δ of the electron density distribution was –4.3. These results are compared to the conventional power-law models with and without a thermal core component.

Searching for neutrinos from solar flares across solar cycles 23 and 24 with the Super-Kamiokande detector as a Review

K. **Okamoto**, K. Abe, Y. Hayato, K. Hiraide, K. Hosokawa, K. Ieki, M. Ikeda, J. Kameda,++++++

ApJ **2022**

https://arxiv.org/pdf/2210.12948.pdf

Neutrinos associated with solar flares (solar-flare neutrinos) provide information on particle acceleration mechanisms during the impulsive phase of solar flares. We searched using the Super-Kamiokande detector for neutrinos from solar flares that occurred during solar cycles 23 and 24, including the largest solar flare (X28.0) on November 4th, 2003. In order to minimize the background rate we searched for neutrino interactions within narrow time windows coincident with γ-rays and soft X-rays recorded by satellites. In addition, we performed the first attempt to search for solar-flare neutrinos from solar flares on the invisible side of the Sun by using the emission time of coronal mass ejections (CMEs). By selecting twenty powerful solar flares above X5.0 on the visible side and eight CMEs whose emission speed exceeds 2000 kms−1 on the invisible side from 1996 to 2018, we found two (six) neutrino events coincident with solar flares occurring on the visible (invisible) side of the Sun, with a typical background rate of 0.10 (0.62) events per flare in the MeV-GeV energy range. No significant solar-flare neutrino signal above the estimated background rate was observed. As a result we set the following upper limit on neutrino fluence at the Earth $\Phi<1.1\times106 cm^{-2}$ at the 90% confidence level for the largest solar flare. The resulting fluence limits allow us to constrain some of the theoretical models for solar-flare neutrino emission. **7 Nov 2003, November 4th, 2003, 24 Jul 2005, 4 Jun 2011, 23 Jul 2013, September 6th, 2017**

Development of a method for determining the search window for solar flare neutrinos

K. **Okamoto**, Y. Nakano, S. Masuda, Y. Itow, M. Miyake, T. Terasawa, S. Ito, M. Nakahata

Solar Phys. **295**, Article number: 133 **2019**

https://arxiv.org/pdf/1909.10715.pdf

https://link.springer.com/content/pdf/10.1007/s11207-020-01706-z.pdf

Neutrinos generated during solar flares remain elusive. However, after 50 years of discussion and search, the potential knowledge unleashed by their discovery keeps the search crucial. Neutrinos associated with solar flares provide information on otherwise poorly known particle acceleration mechanisms during solar flare. For neutrino detectors, the separation between atmospheric neutrinos and solar flare neutrinos is technically encumbered by an energy band overlap. To improve differentiation from background neutrinos, we developed a method to determine the temporal search window for neutrino production during solar flares. Our method is based on data recorded by solar satellites, such as Geostationary Operational Environmental Satellite (GOES), Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), and GEOTAIL. In this study, we selected **23 solar flares above the X5.0 class** that occurred between 1996 and 2018. We analyzed the light curves of soft X-rays, hard X-rays, γ-rays, line γ-rays from neutron capture as well as the derivative of soft X-rays. The average search windows are determined as follows: 4,178 s for soft X-ray, 700 s for derivative of soft X-ray, 944 s for hard X-ray (100-800 keV), 1,586 s for line γ-ray from neutron captures, and 776 s for hard X-ray (above 50 keV). This method allows neutrino detectors to improve their sensitivity to solar flare neutrinos. **July 23, 2002, October 28, 2003, October 29, 2003, November 2, 2003, November 4, 2003, January 20, 2005**

Table 3. List of solar flares selected for this study.

Imaging Spectroscopy of a White-Light Solar Flare

J.C. Martínez **Oliveros** · S. Couvidat · J. Schou · S. Krucker · C. Lindsey · H.S. Hudson · P. Scherrer

Solar Phys (**2011**) 269: 269–281

We report observations of a white-light solar flare (**SOL2010-06-12T00:57, M2.0**) observed by the Helioseismic Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). The HMI data give us the first space-based high-resolution imaging spectroscopy of a white-light flare, including continuum, Doppler, and magnetic signatures for the photospheric Fe i line at 6173.34 Å and its neighboring continuum. In the impulsive phase of the flare, a bright white-light kernel appears in each of the two magnetic footpoints. When the flare occurred, the spectral coverage of the HMI filtergrams (six equidistant samples spanning ±172 mÅ around nominal line center) encompassed the line core and the blue continuum sufficiently far from the core to eliminate significant Doppler crosstalk in the latter, which is otherwise a possibility for the extreme conditions in a white-light flare. RHESSI obtained complete hard X-ray and γ-ray spectra (**this was the first γ-ray flare of Cycle 24**). The Fe i line appears to be shifted to the blue during the flare but does not go into emission; the contrast is nearly constant across the line profile. We did not detect a seismic wave from this event. The HMI data suggest stepwise changes of the line-of-sight magnetic field in the white-light footpoints.

Fermi-LAT observations of the 2017 September 10th solar flare

Nicola **Omodei**, Melissa Pesce-Rollins, Francesco Longo, Alice Allafort, Säm Krucker

ApJL **865** L7 **2018**

https://arxiv.org/pdf/1803.07654.pdf

https://sci-hub.tw/10.3847/2041-8213/aae077

The Fermi-Large Area Telescope detection of the X8.2 GOES class solar flare of **2017 September 10** provides for the first time observations of a long-duration high-energy gamma-ray flare associated with a ground-level enhancement (GLE). The >100 MeV emission from this flare lasted for more than 12 hr covering both the impulsive and extended phases. We present the localization of the gamma-ray emission and find that it is consistent with the active region from which the flare occurred over a period lasting more than 6 hr. The temporal variation of the gamma-ray flux and of the proton index inferred from the gamma-ray data seems to suggest three phases in acceleration of the proton population. Based on timing arguments we interpret the last phase to be tied to the acceleration mechanism powering the powering the production of the GLE particles.

StellarICS: Inverse Compton Emission from the Quiet Sun and Stars from keV to TeV

Review

Elena **Orlando**, Andrew Strong

Journal of Cosmology and Astroparticle Physics (JCAP) 04, 004 **2021**

https://arxiv.org/pdf/2012.13126.pdf

The study of the quiet Sun in gamma rays started over a decade ago, and rapidly gained a wide interest. Gamma rays from the quiet Sun are produced by Cosmic Rays (CRs) interacting with its surface (disk component) and with its photon field (spatially extended inverse-Compton component, IC). The latter component is maximum close to the Sun and it is above the background even at large angular distances, extending over the whole sky. First detected with EGRET, it is studied now with Fermi-LAT with high statistical significance.

Observations of the IC component allow us to obtain information on CR electrons and positrons close to the Sun and in the heliosphere for the various periods of solar activity and polarity. They allow to learn about CR interactions and propagation close to stars, in the heliosphere and on the solar surface, and to understand the Sun itself, its environment, and its activity. Analyses of solar observations are usually model-driven. Hence advances in model calculations and constraints from precise CR measurements are timely and needed.

Here we present our StellarICS code to compute the gamma-ray IC emission from the Sun and also from single stars. The code is publicly available and it is extensively used by the scientific community to analyze Fermi-LAT data. It has been used by the Fermi-LAT collaboration to produce the solar models released with the FSSC Fermi Tools. Our modeling provides the basis for analyzing and interpreting high-energy data of the Sun and of stars. After presenting examples of updated solar IC models in the Fermi-LAT energy range that account for the various CR measurements, we extend the models to keV, MeV, and TeV energies for predictions for future possible telescopes such as AMEGO, GECCO, e-ASTROGAM, HAWC, LHAASO, SWGO, and present X-ray telescopes. We also present predictions for some of the closest and most luminous stars.

Gamma-ray emission from the solar halo and disk: a study with EGRET data

E. **Orlando** and A. W. Strong

A&A 480, 847-857 (**2008**)

http://sci-hub.tw/10.1051/0004-6361:20078817

*Context.*The Sun has recently been predicted to be an extended source of gamma-ray emission, produced by inverse-Compton (IC) scattering of cosmic-ray (CR) electrons on the solar radiation field. The emission was predicted to be extended and a confusing foreground for the diffuse extragalactic background even at large angular distances from

the Sun. The solar disk is also expected to be a steady gamma-ray source. While these emissions are expected to be readily detectable in the future by GLAST, the situation for available EGRET data is more challenging.
*Aims.*The theory of gamma-ray emission from IC scattering on the solar radiation field by Galactic CR electrons is given in detail. This is used as the basis for detection and model verification using EGRET data.
*Methods.*We present a detailed study of the solar emission using the EGRET database, accounting for the effect of the emission from 3C 279, the moon, and other sources, which interfere with the solar emission. The analysis was performed for 2 energy ranges, above 300 MeV and for 100-300 MeV, as well as for the combination to improve the detection statistics. The technique was tested on the moon signal, with our results consistent with previous work.
*Results.*Analyzing the EGRET database, we find evidence of emission from the solar disk and its halo. The observations are compared with our model for the extended emission. The spectrum of the solar disk emission and the spectrum of the extended emission have been obtained. The spectrum of the moon is also given.
*Conclusions.*The observed intensity distribution and the flux are consistent with the predicted model of IC gamma-rays from the halo around the Sun.

Konus- Wind and Helicon- Coronas-F observations of solar flares

Pal'shin, V. D.; Charikov, Yu. E.; Aptekar, R. L.; Golenetskii, S. V.; Kokomov, A. A.; Svinkin, D. S.; Sokolova, Z. Ya.; Ulanov, M. V.; Frederiks, D. D.; Tsvetkova, A. E.
Geomagnetism and Aeronomy, Volume 54, Issue 7, pp.943-948 **2014**
https://arxiv.org/pdf/1412.2015.pdf
https://link.springer.com/content/pdf/10.1134/S0016793214070093.pdf
Results of solar flare observations obtained in the Konus- Wind experiment from November, 1994 to December, 2013 and in the Helicon Coronas-F experiment during its operation from 2001 to 2005, are presented. For the periods indicated Konus- Wind detected in the trigger mode 834 solar flares, and Helicon- Coronas-F detected more than 300 solar flares. A description of the instruments and data processing techniques are given. As an example, the analysis of the spectral evolution of the flares SOL**2012-11-08**T02:19 (M 1.7) and SOL**2002-03-10**T01:34 (C5.1) is made with the Konus- Wind data and the flare SOL**2003-10-26**T06:11 (X1.2) is analyzed in the 2.223 MeV deuterium line with the Helicon- Coronas-F data.

Scale Invariance in Gamma-Ray Flares of the Sun and 3C 454.3

Fang-Kun **Peng**1, Jun-Jie Wei2,3, and Hai-Qin Wang1
2023 ApJ 959 109
https://iopscience.iop.org/article/10.3847/1538-4357/acfcb2/pdf
Using the gamma-ray flare samples of the Sun and 3C 454.3 observed by the Fermi telescope, we investigate the statistical properties of sizes including fluence (energy), peak flux (luminosity), duration time, and waiting time in this work. We find that the cumulative distribution of the fluctuations of these sizes follow well the Tsallis q-Gaussian function. The obtained q values from q-Gaussian distribution remain stable around 2 without any significant change, implying that there is a scale invariance structure in gamma-ray flares of the Sun and 3C 454.3. This scale invariance characteristics of the Sun and 3C 454.3 indicated by q values are also comparable to those of earthquakes, soft gamma repeaters, fast radio burst (FRB 20121102), and X-ray flares of gamma-ray bursts. On top of that, we verify the relationship between q values and the power-law indices α from the size frequency distributions, which is expressed as $q = (\alpha + 2)/\alpha$. These statistical findings could be well explained within the physical framework of a self-organizing criticality system.

Self-organized criticality in solar GeV flares

Fang-Kun **Peng**, Fa-Yin Wang, Xin-Wen Shu, Shu-Jin Hou
Monthly Notices of the Royal Astronomical Society, 518, Issue 3, January **2023**, Pages 3959–3965,
https://doi.org/10.1093/mnras/stac3308
The Sun emits significant flares in X-ray, ultraviolet, and radio wavelengths. It is thought to originate from the magnetic reconnection activity, which is capable of accelerating particles to high energies. The magnetic process can be described by the avalanche model of self-organized criticality (SOC), and it is evidenced by the observation. Here, we study the frequency distribution of fluence, peak flux, and duration time for solar GeV flares detected first by Fermi-Large Area Telescope. Their cumulative distributions show a power-law behaviour. The exponents are also consistent with those derived from the observations at low-energy bands, and follow the predictions of the fractal-diffuse SOC model. In the meantime, the waiting time shows power-law distribution, and agrees a non-stationary Poission process. We then explore the correlation between energy (fluence) and duration time using a two-variable regression analysis. The correlation is found to be $T_{Duration} \propto F_{0.38\pm0.08GeV} T_{Duration} \propto F_{GeV}^{0.38\pm0.08}$ with the solar GeV flare sample, which is comparable to that of the solar X-ray flares and gamma-ray bursts (GRBs) and could be understood in an SOC model. These facts suggest that, similar to the physical process accounting for the X-ray emission of solar flares and prompt emission of GRBs, magnetic reconnection may still dominate the energy-release process and particle acceleration for solar flares at GeV energies.

Evidence for flare-accelerated particles in large scale loops in the behind-the-limb gamma-ray solar flare of September 29, 2022

Melissa **Pesce-Rollins**, Karl-Ludwig Klein, Säm Krucker, Alexander Warmuth, M. Astrid Veronig, Nicola Omodei, Christian Monstein

A&A 683, A208 **2024**

https://arxiv.org/pdf/2402.08380.pdf

https://www.aanda.org/articles/aa/pdf/2024/03/aa48088-23.pdf **File**

We report on the detection of the gamma-ray emission above 100 MeV from the solar flare of **September 29, 2022**, by Fermi LAT with simultaneous coverage in HXR by Solar Orbiter STIX. The Solar Orbiter-Earth separation was 178∘ at the time of the flare as seen from Earth, with Solar Orbiter observing the east limb. Based on STIX imaging, the flare was located 16∘ behind the eastern limb as seen from Earth. The STIX and GBM non-thermal emission and the LAT emission above 100 MeV all show similarly shaped time profiles, and the Fermi profiles peaked only 20 seconds after the STIX signal from the main flare site, setting this flare apart from all the other occulted flares observed by Fermi LAT. The radio spectral imaging based on the Nançay Radioheliograph and ORFEES spectrograph reveal geometries consistent with a magnetic structure that connects the parent active region behind the limb to the visible disk. We studied the basic characteristics of the gamma-ray time profile, in particular, the rise and decay times and the time delay between the gamma-ray and HXR peak fluxes. We compared the characteristics of this event with those of four Fermi LAT behind-the-limb flares and with an on-disk event and found that this event is strikingly similar to the impulsive on-disk flare. Based on multiwavelength observations, we find that the gamma-ray emission above 100 MeV originated from ions accelerated in the parent active region behind the limb and was transported to the visible disk via a large magnetic structure connected to the parent active region behind the limb. ***Our results strongly suggest that the source of the emission above 100 MeV from the September 29, 2022 flare cannot be the CME-driven shock.*** September 6, 2011

The coupling of an EUV coronal wave and ion acceleration in a Fermi-LAT behind-the-limb solar flare

Melissa **Pesce-Rollins**, Nicola Omodei, Sam Krucker, Niccol`o Di Lalla, Wen Wang, Andrea F. Battaglia, Alexander Warmuth, Astrid M. Veronig, Luca Baldini

ApJ 929 172 **2022**

https://arxiv.org/pdf/2205.04760.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac5f0c/pdf

We present the Fermi-LAT observations of the behind-the-limb (BTL) flare of **July 17, 2021** and the joint detection of this flare by STIX onboard Solar Orbiter. The separation between Earth and the Solar Orbiter was 99.2∘ at 05:00 UT, allowing STIX to have a front view of the flare. The location of the flare was ~S20E140 in Stonyhurst heliographic coordinates making this the most distant behind-the-limb flare ever detected in >100 MeV gamma-rays. The LAT detection lasted for ∼16 minutes, the peak flux was 3.6±0.8 (10−5) ph cm−2 s−1 with a significance >15σ. A coronal wave was observed from both STEREO-A and SDO in extreme ultraviolet (EUV) with an onset on the visible disk in coincidence with the LAT onset. A complex type II radio burst was observed by GLOSS also in coincidence with the onset of the LAT emission indicating the presence of a shock wave. We discuss the relation between the time derivative of the EUV wave intensity profile at 193\angstrom\ as observed by STEREO-A and the LAT flux to show that the appearance of the coronal wave at the visible disk and the acceleration of protons as traced by the observed >100 MeV gamma-ray emission are coupled. We also report how this coupling is present in the data from 3 other BTL flares detected by Fermi-LAT suggesting that the protons driving the gamma-ray emission of BTL solar flares and the coronal wave share a common origin. **2013-10-11, 2014-09-01, 2021-07-17, 2021-09-17**

Probing Particle Acceleration through Gamma-ray Solar Flare Observations **Review**

Melissa **Pesce-Rollins**, Nicola Omodei, Vahe' Petrosian, Francesco Longo

37th International Cosmic Ray Conference (ICRC2021) proceedings **2021**

https://arxiv.org/pdf/2109.13535.pdf **File**

High-energy solar flares have shown to have at least two distinct phases: prompt-impulsive and delayed-gradual. Identifying the mechanism responsible for accelerating the electrons and ions and the site at which it occurs during these two phases is one of the outstanding questions in solar physics. Many advances have been made over the past decade thanks to new observational data and refined simulations that together help to shed light on this topic. For example, the detection by Fermi Large Area Telescope (LAT) of GeV emission from solar flares originating from behind the visible solar limb and >100 MeV emission lasting for more than 20 hours have suggested the need for a spatially extended source of acceleration during the delayed emission phase. In this work we will review some of the major results from Fermi-LAT observations of the 24th solar cycle and how this new observational channel combined with observations from across the electromagnetic spectrum can provide a unique opportunity to diagnose

the mechanisms of high-energy emission and particle acceleration in solar flares. **1991 June 4, 1991 June 11, 2005 Jan 16, 2012 March 7, 2014 February 25, 2017 September 10**

Fermi Large Area Telescope observations of solar flares during the 24th solar cycle

Melissa **Pesce-Rollins**
Presentation at the Fleishman Webinar Nov. 13, **2019**
http://www.ioffe.ru/LEA/SF_AR/files/FermiLATSolarFlares_webinar.pdf
https://www.youtube.com/watch?v=VVqgPQDpF0g&feature=youtu.be
Fermi-LAT Solar Flare (FSF) Catalog contains 45 flares
--18 with a prompt component synchronized with HXI
--37 with some delayed component beyond HXR
-- 21 exhibit delayed emission lasting longer than 2 hours
-- 16 exhibit delayed emission lasting less than 2 hours
-- 4 exhibit only delayed emission–no prompt emission detected
-- 8 with only a prompt component - 3 behind the limb
2010-06-12, 2011-03-07, 2011-09-06, 2012-01-23, 2012-03-07, 2012-03-09, 2013-05-14, 2013-05-15, 2013-10-11, 2014-01-06, 2014-02-25, 2014-09-01, 2015-06-21, 2017-09-06, 2017-09-10

Fermi Large Area Telescope observations of high-energy gamma-ray emission from behind-the-limb solar flares

Melissa **Pesce-Rollins**, Nicola Omodei, Vahe' Petrosian, Wei Liu, Fatima Rubio da Costa, Alice Allafort, for the Fermi-LAT Collaboration
The 34th International Cosmic Ray Conference Proceedings **2015**
http://arxiv.org/pdf/1507.04303v1.pdf
https://pos.sissa.it/236/128/pdf
Fermi-LAT >30 MeV observations have increased the number of detected solar flares by almost a factor of 10 with respect to previous space observations. These sample both the impulsive and long duration phases of GOES M and X class flares. Of particular interest is the recent detections of three solar flares whose position behind the limb was confirmed by the STEREO-B spacecraft. While gamma-ray emission up to tens of MeV resulting from proton interactions has been detected before from occulted solar flares, the significance of these particular events lies in the fact that these are the first detections of >100 MeV gamma-ray emission from footpoint-occulted flares. We will present the Fermi-LAT, RHESSI and STEREO observations of these flares and discuss the various emission scenarios for these sources and implications for the particle acceleration mechanisms.
2013 Oct 11, 2014 Jan 06, 2014 Sep 01

First detection of >100 MeV gamma rays associated with a behind-the-limb solar flare

Melissa **Pesce-Rollins**, Nicola Omodei, Vahe' Petrosian, Wei Liu, Fatima Rubio da Costa, Alice Allafort, Qingrong Chen
ApJL **805** L15 **2015**
http://arxiv.org/pdf/1505.03480v1.pdf **File**
https://iopscience.iop.org/article/10.1088/2041-8205/805/2/L15/pdf
We report the first detection of >100 MeV gamma rays associated with a behind-the-limb solar flare, which presents a unique opportunity to probe the underlying physics of high-energy flare emission and particle acceleration. On **2013 October 11** a GOES M1.5 class solar flare occurred ~ 9.9 degrees behind the solar limb as observed by STEREO-B. RHESSI observed hard X-ray emission above the limb, most likely from the flare loop-top, as the footpoints were occulted. Surprisingly, the Fermi Large Area Telescope (LAT) detected >100 MeV gamma-rays for ~30 minutes with energies up to GeV. The LAT emission centroid is consistent with the RHESSI hard X-ray source, but its uncertainty does not constrain the source to be located there. The gamma-ray spectra can be adequately described by bremsstrahlung radiation from relativistic electrons having a relatively hard power-law spectrum with a high-energy exponential cutoff, or by the decay of pions produced by accelerated protons and ions with an isotropic pitch-angle distribution and a power-law spectrum with a number index of ~3.8. We show that high optical depths rule out the gamma rays originating from the flare site and a high-corona trap model requires very unusual conditions, so a scenario in which ***some of the particles accelerated by the CME shock travel to the visible side of the Sun to produce the observed gamma rays may be at work.***

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).

Implications of loop-top origin for microwave, hard X-ray, and low-energy gamma-ray emissions from behind the limb flares

Vahé **Petrosian**
ApJ **2018**
https://arxiv.org/pdf/1808.07161.pdf
The Fermi gamma-ray Space Telescope (Fermi) has detected hard X-ray (HXR) and gamma-ray photons from three flares, which according to \stereo occurred in active regions behind the limb of the Sun as delineated by near Earth instruments. For two of these flares \r has provided HXR images with sources located just above the limb, presumably from the loop top (LT) region of a relatively large loop. Fermi-Gamma-ray Burst Monitor has detected HXRs and gamma-rays, and RSTN has detected microwaves emissions with similar light curves. This paper presents a quantitative analysis of these multi-wavelength observations assuming that HXRs and microwaves are produced by electrons accelerated at the LT source, with emphasize on the importance of the proper treatment of escape of the particles from the acceleration-source region and the trans-relativistic nature of the analysis. The observed spectra are used to determine the magnetic field and relativistic electron spectra. It is found that a simple power-law in momentum (with cut off above a few 100 MeV) agrees with all observations, but in energy space a broken power law spectrum (steepening at rest mass energy) may be required. It is also shown that the production of the >100 MeV photons detected by The Fermi-Large Area Telescope at the LT source would require more energy compared to photospheric emission. These energies are smaller than that required for electrons, so that the possibility that all the emissions originate in the LT cannot be ruled out on energetic grounds. However, the differences in the light curves and emission centroids of HXRs and >100 MeV gamma-rays favour a different source for the latter. **2013 − 10 – 11, 2014 − 09 − 01**

Luminous solar neutrinos II: Mass-mixing portals

Ryan **Plestid**
2020
https://arxiv.org/pdf/2010.09523.pdf
Solar neutrinos can be efficiently upscattered to MeV scale heavy neutral leptons (HNLs) within the Earth's mantle. HNLs can then decay to electron-positron pairs leading to energy deposition inside large-volume detectors. In this paper we consider mass-portal upscattering of solar neutrinos to HNLs of mass 20 MeV $\geq m_N \geq 2m_e$. The large volume of the Earth compensates for the long decay-length of the HNLs leading to observable rates of $N \to \nu_\alpha e^+ e^-$ in large volume detectors. We find that searches for mantle-upscattered HNLs can set the novel limits on mixing with third generation leptons, $|U_{\tau N}|$ for masses in the MeV regime; sensitivity to mixing with first- and second-generation leptons is not competitive with existing search strategies.

Luminous solar neutrinos I: Dipole portals

Ryan **Plestid**
2020
https://arxiv.org/pdf/2010.04193.pdf
Solar neutrinos upscattering inside the Earth can source unstable particles that can decay inside terrestrial detectors. Contrary to naive expectations we show that when the decay length is much shorter than the radius of the \emph{Earth} (rather than the detector), the event rate is independent of the decay length. In this paper we study a transition dipole operator (neutrino dipole portal) and show that Borexino's existing data probes previously

untouched parameter space in the 0.5--20 MeV regime, complementing recent cosmological and supernova bounds. We briefly comment on similarities and differences with luminous dark matter and comment on future prospects for analogous signals stemming from atmospheric neutrinos.

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**

https://arxiv.org/pdf/1703.07563.pdf **File**

https://www.aanda.org/articles/aa/pdf/2017/12/aa30804-17.pdf

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**

Solar Neutrino Measurements

Andrea **Pocar** et al.

"XXXVIII International Symposium on Physics in Collision, Bogot\'a, Colombia, 11-15 september 2018" **2018**

https://arxiv.org/pdf/1812.02326.pdf

We present the most recent results from the two currently running solar neutrino experiments, Borexino at the Gran Sasso laboratory in Italy and SuperK at Kamioka mine in Japan. SuperK has released the most precise yet measurement of the 8B solar neutrino interaction rate, with a precision better than 2\%, consistent with a constant solar neutrino emission over more than a decade. Borexino has released refined measurements of all neutrinos produced in the pp fusion chain. For the first time, one single detector has measured the entire range of solar neutrinos at once. These new data weakly favor a high-metallicity Sun. Prospects for measuring CNO solar neutrinos with Borexino are discussed, and a brief outlook on the field provided.

Role of magnetic arcades in explaining the puzzle of the gamma-ray emission from the solar disk as a Review

Eleonora **Puzzoni**, Federico Fraschetti, József Kóta, Joe Giacalone

ApJ **973** 118 **2024**

https://arxiv.org/pdf/2407.16859

https://iopscience.iop.org/article/10.3847/1538-4357/ad65ea/pdf

The interpretation of gamma-ray emission originating from the solar disk (0.5∘ in angular size) as due to the interaction of Galactic Cosmic Rays (GCRs) with the solar atmosphere has remained a central challenge in solar physics. After the seminal work by Seckel, Stanev, and Gaisser (SSG91) based on GCRs magnetic mirroring, discrepancies between models and observations persist, indicating the need for a novel approach. The present work focuses on exploring the impact of a closed magnetic field geometry in the low photosphere on the observed gamma-ray flux. We track numerically with the PLUTO code the trajectories of test-particle protons within a static ∼20 Mm scale height magnetic arcade adjacent to jets. By making use of numerical vertical density profiles we inject particles at distinct chromospheric/photospheric altitudes, mimicking the migration of GCRs from neighboring flux tubes into closed arcades. Remarkably, our model reproduces a flat gamma-ray spectrum

below ~33 GeV, a nearly-isotropic emission at ~10 GeV, both consistent with Fermi-LAT observations, and a near-limb emission at ~1 TeV. Our model can also reproduce the flux-drop detected by HAWC (~1 TeV). Finally, we argue that the spectral dip observed at ~ 40 GeV may result from the flux suppression at low energy due to the cross-field diffusion, which would produce a cutoff. These findings underscore the pivotal role of closed magnetic field structures in shaping the solar disk gamma-ray emission.

Hard X-ray Spikes Observed by RHESSI

Jiong **Qiu**
RHESSI Science Nugget, No. 191, **2013**
New software allows RHESSI to study rapid time variations, in spite of the image modulation.
RHESSI capabilities have allowed us to continue the decades-long effort to study rapidly evolving hard X-ray bursts. These observations may hold the key to uncover fundamental scales of energy release in solar flares. The most prominent hard X-ray spikes from a sample of RHESSI flares exhibit similar temporal properties as those discovered in SMM flares in the 70s and BATSE flares in the 90s. **17 March 2002**

On the Origin of the Pion-Decay Radiation in the 1982 June 3 Solar Flare

Ramaty, R. ; Murphy, R. J. ; Dermer, C. D.
Astrophysical Journal Letters v.316, p.L41 **1987**
https://articles.adsabs.harvard.edu/pdf/1987ApJ...316L..41R
The 1982 June 3 flare produced a wealth of observed gamma-ray, energetic particle, and neutron emissions. The authors show that the predictions of an interaction model developed for the June 3 flare by Murphy, Dermer, and Ramaty in 1987 compare favorably with new data on the time-dependent flux of pion-decay emission from this flare. It is concluded that the particles which produced the bulk of the pions could have the same origin as the particles observed in interplanetary space from the June 3 flare.

Extended gamma-ray emission of the solar flares in june 1991

Rank, G. ; Ryan, J. ; Debrunner, H. ; McConnell, M. ; Schönfelder, V.
Astronomy and Astrophysics, v.378, p.1046-1066 (**2001**)
https://www.aanda.org/articles/aa/pdf/2001/42/aah2902.pdf
During the solar flares on **9, 11, and 15 June 1991** the COMPTEL instrument measured extended gamma -radiation in the 2.223 MeV neutron-capture line, in prompt nuclear deexcitation lines and in pion-decay radiation for several hours after the flares. The long-term time profiles can be described by a double exponential decay with decay constants on the order of 10 min for the fast and several 100 min for the slow components. We studied the 11 June 1991 flare in more detail and found that during the extended phase the accelerated proton and ion spectrum is harder, the e/p ratio is lower, and the emission profile is smoother, compared to those of the impulsive phase. Pion-decay radiation was not detected before the onset of the extended emission phase. When comparing the three flares to one another, we found a striking similarity in the time profiles of the nuclear line and the neutron capture line emission. However, the pion-decay radiation varied in intensity significantly from flare to flare. The impulsive-phase emissions of the flares show no such similarity. Our measurements indicate that the processes taking place during the extended phase differ from those during the impulsive phase, or in other gamma -ray line flares. Based on these results long-term trapping of energetic particles from the impulsive phase seems unlikely, as opposed to continuous particle acceleration.

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.

Exploring the capabilities of the Anti-Coincidence Shield of the INTEGRAL spectrometer to study solar flares

R. **Rodr.ıguez-Gas.en**1,2 · J. Kiener1 · V. Tatischeff1 · N. Vilmer2 · C. Hamadache1 · K.-L. Klein2
E-print, Sept **2013**; Solar Phys. May **2014**, Volume 289, Issue 5, pp 1625-1641

http://arxiv.org/pdf/1308.3350v1.pdf
INTEGRAL is a hard X-ray/gamma-ray observatory for astrophysics (ESA) covering photon energies from 15 keV to 10 MeV. It was launched in 2002 and since then the BGO detectors of the Anti-Coincidence shield (ACS) of the SPI spectrometer have detected many hard X-ray (HXR) bursts from the Sun, producing lightcurves at photon energies above ~ 100 keV. The spacecraft has a highly elliptical orbit, providing a long uninterrupted observing time (about 90% of the orbital period) with nearly constant background due to the reduction of the crossing time of the Earth's radiation belts. However, due to technical constraints, INTEGRAL cannot point to the Sun and high-energy solar photons are always detected in non-standard observation conditions. To make the data useful for solar studies, we have undertaken a major effort to specify the observing conditions through Monte-Carlo simulations of the response of ACS for several selected flares. We check the performance of the model employed for the Monte-Carlo simulations using RHESSI observations for the same sample of solar flares. We conclude that, despite the fact that INTEGRAL was not designed to perform solar observations, ACS is a useful instrument in solar flare research. In particular, its relatively large effective area allows the determination of good-quality HXR/gamma-ray lightcurves for X- and M-class solar flares and, in some cases, probably also for C-class flares.

Table

The Large Imaging Spectrometer for Solar Accelerated Nuclei (LISSAN): A Next-Generation Solar γ-ray Spectroscopic Imaging Instrument Concept

Ryan, DF ; Musset, S ; Reid, HAS ; Krucker, S ; Battaglia, AF; +++
AEROSPACE Volume 10 Issue 12 Article Number 985 **2023**
DOI 10.3390/aerospace10120985
Models of particle acceleration in solar eruptive events suggest that roughly equal energy may go into accelerating electrons and ions. However, while previous solar X-ray spectroscopic imagers have transformed our understanding of electron acceleration, only one resolved image of gamma-ray emission from solar accelerated ions has ever been produced. This paper outlines a new satellite instrument concept-the large imaging spectrometer for solar accelerated nuclei (LISSAN)-with the capability not only to observe hundreds of events over its lifetime, but also to capture multiple images per event, thereby imaging the dynamics of solar accelerated ions for the first time. LISSAN provides spectroscopic imaging at photon energies of 40 keV-100 MeV on timescales of less than or similar to 10 s with greater sensitivity and imaging capability than its predecessors. This is achieved by deploying high-resolution scintillator detectors and indirect Fourier imaging techniques. LISSAN is suitable for inclusion in a multi-instrument platform such as an ESA M-class mission or as a smaller standalone mission. Without the observations that LISSAN can provide, our understanding of solar particle acceleration, and hence the space weather events with which it is often associated, cannot be complete.

Fifty-year Anniversary of the First Detection of Gamma rays from a Solar Flare

Jim **Ryan**, Brian Dennis, and Phil Dunphy
RHESSI Science Nuggets №434 **2022** https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Fifty-year_Anniversary_of_the_First_Detection_of_Gamma_rays_from_a_Solar_Flare
1972-08-04

Modeling the 2017 September 10 Long Duration Gamma Ray Flare

Ryan, J. M.; de Nolfo, G. A.; Gary, D. E.
36th International Cosmic Ray Conference -ICRC2019- July 24th - August 1st, **2019** Madison, WI, U.S.A. Vol. 36, 1144
https://pos.sissa.it/358/1144/pdf
doi: 10.22323/1.358.01144
The large flares from 2017 September 4 to 10 were significant microwave events with revealing multi-wavelength images of the flare environment. The event on September 10 was a large long-duration, gamma-ray flare (LDGRF). The event also produced a Ground Level Enhancement (GLE). Using the constraints from the microwave imaging data from the Expanded Owens Valley Solar Array (EOVSA) we interpret and model the behavior of the energetic-flare protons of September 10 as measured with the Large Area Telescope (LAT) on the Fermi mission. We do this in the context of stochastic acceleration in a large coronal bipolar structure to produce the high-energy long-duration gamma-ray emission. Our preliminary analysis suggests that the acceleration of the GeV protons takes place in a large structure about 1.4 R$\odot$ in length. The requirements for the magnetic field and turbulence in this structure will be presented.

Modeling the September 2017 SEP and LDGRF Events

Ryan, J. M.; de Nolfo, G. A.; Gary, D. E.

American Geophysical Union, Fall Meeting **2018**, abstract #SH51C-2829
https://ui.adsabs.harvard.edu/abs/2018AGUFMSH51C2829R/abstract
The large flares of September 4 to 10 were significant microwave events with revealing multi-wavelength images of the flare environment. The event on September 6 was a large long-duration, gradual rise-and-fall, gamma-ray (LDGRF) event, as was the even bigger September 10 event. The finale of the sequence on September 10 also produced a Ground Level Enhancement (GLE). We interpret and model the behavior of the energetic flare protons of September 6 and 10 events in the context of stochastic acceleration in a large coronal structure to produce the high-energy long-duration gamma-ray emission, using constraints from microwave imaging spectroscopy from the Expanded Owens Valley Solar Array.

What the High-Energy Flares and CMEs of 2012 March 7 Can Tell Us About Long Duration Gamma-Ray Flares

Ryan, James M.; De Nolfo, Georgia
42nd COSPAR Scientific Assembly. Held 14-22 July **2018**, in Pasadena, California, USA, Abstract id. D2.1-20-18.
https://ui.adsabs.harvard.edu/abs/2018AGUFMSH51C2829R/abstract
Two X-class flares occurred on 2012 March 7, an X5.3 and an X1.1. The earlier X5 flare gathered much attention, initiating a powerful and fast CME from the eastern hemisphere. The "forgotten" X1 flare exhibited much smaller CME from the same active region one hour later. However, extended high-energy gamma emission was present for almost the entire day of 2012 March 7. We have resolved the gamma emission into two separate, but overlapping extended occurrences, being from the two sequential X-class flares. Somewhat surprisingly, we find that the later X1 event was twice as prolific in gamma emission, mostly due to its duration, despite being much weaker in soft x rays. We attribute the entirety of the gamma emission from particle precipitation from the footpoints two separate quasi-static large-scale (of order 1 solar radius) coronal loops and not from either of the associated CMEs accelerating the high-energy particles. Using constraints from ancillary data, we estimate the bounds in parameter space of the loop sizes and embedded turbulence necessary to accelerate protons and ions to high energies producing the gamma emission.

Properties of Long Duration High-Energy Gamma-Ray Flares

Ryan, James Michael; Lee, Martin A.; de Nolfo, Georgia; Anderson, Emily; Nair, Arvind
Joint American Astronomical Society/American Geophysical Union Triennial Earth-Sun Summit, meeting #1, id.205.04, **2015** Abstract
Long duration high-energy gamma-ray flares, recognized the first time in the 1982 June 3 flare, were thought to be rare. However, the Fermi mission with superior gamma-ray sensitivity, has registered almost two dozen such flares. This number allows for investigations into the distribution of the relevant parameters governing these events, in part mitigating some of the observational bias due to instrument sensitivity. We report progress in quantifying key solar parameters that characterize these events. The context for interpreting the gamma-ray data is a stochastic acceleration diffusion model that predicts the precipitation of high-energy ions accelerated in large loops. Two versions of this model are used: a leaky box and one that explicitly includes the spatial diffusion into the denser parts of the solar atmosphere.

Long-Duration Solar Gamma-Ray Flares **Review**

Ryan J.M.
Space Science Reviews, v. 93, Issue 3/4, p. 581-610 (**2000**) **File**
https://link.springer.com/content/pdf/10.1023%2FA%3A1026547513730.pdf
Long-duration solar γ-ray flares are those in which high-energy photon emission is present well beyond the impulsive phase, indicating the presence of either stored or continuously accelerated ions. We review both the observations and the current theories or models that can explain this unusual phenomenon. The present situation favors either acceleration of protons and ions for long periods of time by second order Fermi acceleration in large coronal loops or acceleration in large-scale, CME-associated reconnection sheets. Observations in the upcoming solar maximum may resolve this problem. **3 June 1982, 24 May 1990, 4 June 1991, 11 June 1991, 15 June 1991**

On the Transport and Acceleration of Solar Flare Particles in a Coronal Loop

Ryan, James M.; Lee, Martin A.
Astrophysical Journal v.368, p.316, **1991**
http://articles.adsabs.harvard.edu/pdf/1991ApJ...368..316R
The turbulent environment of a flaring solar coronal loop directly affects the population of particles to be accelerated or already accelerated. Under the assumption of a uniform turbulent MHD wave field within the loop, the behavior of a particle distribution as it interacts with the turbulence is discussed, including particle precipitation to the footpoints of the loop and the evolution of the energy distribution as the particles undergo second-order

stochastic acceleration. Two cases are discussed in detail: (1) particles spatially diffusing within the loop and precipitating with minimal acceleration in the short time scale of an impulsive event and (2) particles diffusing in both real and momentum space in a long duration event. Collisional losses due to ambient electrons are included. The gamma-ray flare of June 3, 1982 is modeled, and good agreement is obtained between predicted and observed time profiles if the loop length is 100,000 km with an intrinsic spatial diffusion time of 100-450 s. It follows that the production of high-energy neutrons and pi mesons extends over a time scale of 1000 s as observed.

A Statistical Survey of Hard X-ray Spectral Characteristics of Solar Flares with Two Footpoints

P. **Saint-Hilaire**, S. Krucker, R. P. Lin
Solar Physics, Volume 250, Number 1, Page: 53 – 73, **2008**
http://www.springerlink.com/content/x777015114813531/fulltext.pdf
Using RHESSI data, we have analyzed 172 hard X-ray (HXR) peaks during 53 solar flares that exhibited a double-footpoint structure. Fitting both footpoints with power laws, we find that spectral index differences $\Delta\gamma$ range mostly between 0 to 0.6, and only rarely go beyond. Asymmetries between footpoints were not observed to be significantly dependent on their mean heliographic position, their relative position with respect to each other, nor their orientation with respect to the solar equator. By assuming a symmetric acceleration process, it is also clear that differences in footpoint spectral indices and footpoint flux ratios can seldom be attributed to a difference in column densities between the two legs of a coronal loop. Our results corroborate better the magnetic mirror trap scenario. Moreover, footpoint asymmetries are more marked during times of peak HXR flux than when averaging over the whole HXR burst, suggesting that the magnetic configuration evolves during individual HXR bursts. **We also observed a linear correlation between the peak 50-keV flux and the peak GOES 1–8 Å channel flux** and that HXR burst duration seem correlated with loop length.

Long-lived Solar Neutron Emission in Comparison with Electron-produced Radiation in the 2005 September 7 Solar Flare

T. **Sako**, K. Watanabe, Y. Muraki, Y. Matsubara, H. Tsujihara, M. Yamashita, T. Sakai, S. Shibata, J. F. Valdes-Galicia, L. X. Gonzalez, A. Hurtado, O. Musalem, P. Miranda, N. Martinic, R. Ticona, A. Velarde, F. Kakimoto, S. Ogio, Y. Tsunesada, H. Tokuno, Y. T. Tanaka, I. Yoshikawa, T. Terasawa, Y. Saito, T. Mukai, and M. Gros,
The Astrophysical Journal, 651:L69-L72, **2006, File**

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 fromfootpoints 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 flareswith 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.

YOHKOH/WBS Recalibration and a Comprehensive Catalogue of Solar Flares Observed by YOHKOH SXT, HXT and WBS Instruments

J. **Sato**, Y. Matsumoto, K. Yoshimura, S. Kubo, J. Kotoku, S. Masuda, M. Sawa, K. Suga, M. Yoshimori, T. Kosugi & T. Watanabe
Solar Physics, Volume 236, Issue 2, pp.351-368, **2006**
https://link.springer.com/content/pdf/10.1007/s11207-006-1831-5.pdf
The flare catalogue of the Yohkoh mission is compiled and linked to this article as an electronic supplement. For showing flare characteristics over wide energy range concisely, we provide the images of Hard X-ray Telescope (HXT) and the Soft X-ray Telescope (SXT), and the spectra of Hard X-ray Spectrometer (HXS) and Gamma-Ray

Spectrometer (GRS) with the Wide Band Spectrometer (WBS) time profiles. The energy versus pulse height (PH) data channels in HXS and GRS are re-calibrated by using the data of the whole mission period. Secular gain changes are recognized in HXS, and the characteristics of power-law flare spectra simultaneously observed by HXT and HXS confirms the trend. The GRS gains are different for the flare observations during the previous maximum and for the current maximum. The total of 33 γ -ray events are observed, and for 12 of them γ-ray flare spectra are obtained. **27 Oct 1991, 16 Jul 1992, 6 Nov 1997**

Schmahl, E. J., Hurford, G. J. **RHESSI observations of the size scales of solar hard X-ray sources.** Sol. Phys. 210, 273-286, 2002.

Analysis of RHESSI Flares Using a Radio Astronomical Technique
E. J. **Schmah**l, R. L. Pernak, G. J. Hurford, J. Lee, S. Bong
Solar Phys. 240 (2), Page: 241 – 252, 2007
The hard X-ray visibilities, which are mathematically identical to the visibilities of radio imaging, were input to software developed for mapping solar flares in the microwave domain using the Maximum Entropy Method (MEM).

HARD–SOFT–HARD FLARE SPECTRA AND THEIR ENERGY DEPENDENCE IN SPECTRAL EVOLUTION OF A SOLAR HARD X-RAY FLARE
Chengwen **Shao**1,2 and Guangli Huang
Astrophysical Journal, 694:L162–L165, **2009**
In this Letter, we studied the time evolution of the energy-dependent spectral indices for the 2004 November 3 solar hard X-ray flare observed by *RHESSI*. The common soft–hard–soft (SHS) pattern spectra were found at the lower energies, while a new feature, hard–soft–hard (HSH), was found at higher energies for each subpeak. As the energy increases, the SHS pattern is gradually converted into the HSH pattern. Some possible explanations for the spectral evolution and its energy dependence are discussed, such as the return current.

Solar Gamma-Ray Evidence for a Distinct Population of > 1 MeV Flare-Accelerated Electrons
Gerald H. **Share**, Ronald J. Murphy, Brian R. Dennis, Justin D. Finke
ApJ **2024**
https://arxiv.org/pdf/2412.19586 **File**
Significant improvements in our understanding of nuclear γ-ray line production and instrument performance allow us to better characterize the continuum emission from electrons at energies ≳ 300 keV during solar flares. We represent this emission by the sum of a power-law extension of hard X-rays (PL) and a power law times an exponential function (PLexp). We fit the γ-ray spectra in 25 large flares observed by SMM, RHESSI, and Fermi with this summed continuum along with calculated spectra of all known nuclear components. The PL, PLexp, and nuclear components are separated spectroscopically. A distinct origin of the PLexp is suggested by significant differences between its time histories and those of the PL and nuclear components. RHESSI imaging/spectroscopy of the 2005 January 20 flare, reveals that the PL and nuclear components come from the footpoints while the PLexp component comes from the corona. While the index and flux of the anisotropic PL component are strongly dependent on the flares' heliocentric angle, the PLexp parameters show no such dependency and are consistent with a component that is isotropic. The PLexp spectrum is flat at low energies and rolls over at a few MeV. Such a shape can be produced by inverse Compton scattering of soft X-rays by 10--20 MeV electrons and by thin-target bremsstrahlung from electrons with a spectrum that peaks between 3 -- 5 MeV, or by a combination of the two processes. These electrons can produce radiation detectable at other wavelengths. **4 Jun 1980, 27 Apr 1981, 15 Jun 1982, 7 Dec 1982, 6 Feb 1986, 6 Mar 1989, 10 Mar 1989, 19 Oct 1989,19 Dec 1989, 23 Jul 2002, 28 Oct 2003, 2 Nov 2003, 20 Jan 2005, 6 Dec 2006**
Table 1. Details of the Fits to 25 Nuclear-Line Flares 1981-2017

Characteristics of Late-phase >100 MeV Gamma-Ray Emission in Solar Eruptive Events
G. H. **Share**1,2, R. J. Murphy3, S. M. White4, A. K. Tolbert5,6, B. R. Dennis5, R. A. Schwartz5,6, D. F. Smart7, and M. A. Shea7
2018 ApJ 869 182 **File**
https://iopscience.iop.org/article/10.3847/1538-4357/aaebf7/pdf
See ApJ Supplement **2018**
http://www.astro.umd.edu/~share/publications/share_apj_accepted.pdf **File**
https://arxiv.org/pdf/1711.01511.pdf
We characterize and catalog 30 solar eruptive events observed by the Fermi Large Area Telescope (LAT) having late-phase >100 MeV γ-ray emission (LPGRE), identified 30 yr ago in what were called long-duration gamma-ray flares. We show that LPGRE is temporally and spectrally distinct from impulsive phase emission in these events.

The spectra are consistent with the decay of pions produced by >300 MeV protons and are not consistent with primary electron bremsstrahlung. Impulsive >100 keV X-ray emission was observed in all 27 LPGRE events where observations were made. All but two of the LPGRE events were accompanied by a fast and broad coronal mass ejection (CME). The LPGRE start times range from CME onset to 2 hr later. Their durations range from ~0.1 to 20 hr and appear to be correlated with durations of >100 MeV solar energetic particle (SEP) proton events. The power-law spectral indices of the >300 MeV protons producing LPGRE range from ~2.5 to 6.5 and vary during some events. Combined γ-ray line and LAT measurements indicate that LPGRE proton spectra are steeper above 300 MeV than they are below 300 MeV. The number of LPGRE protons >500 MeV is typically about 10× the number in the impulsive phase of the solar eruptive event and ranges in nine events from ~0.01× to 0.5× the number in the accompanying SEP event, with large systematic uncertainty. What appears to be late-phase electron bremsstrahlung with energies up to ~10 MeV was observed in one LPGRE event. We discuss how current models of LPGRE may explain these characteristics.

Table 1 Solar Eruptive Events from June 2008 to December 2016 with >100 MeV LPGRE
Table 2 Onset Times of CME, Type II Radio, and LPGRE
Table 3 Spectral Characteristics of LPGRE Events
Table 4 Solar Eruptive Events from June 2008 to May 2012
Table 6 Number of >500 MeV SEP Protons
Table 7 Radio Bursts from LPGRE Events

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 869 182 **2018**
doi: 10.3847/1538-4357/aaebf7
http://www.astro.umd.edu/~share/publications/share_apj_accepted.pdf **File**
https://arxiv.org/pdf/1711.01511.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/aaebf7/pdf

We characterize and catalog 30 solar eruptive events (SEEs) observed by Fermi LAT having late phase >100 MeV γ-ray emission (LPGRE), identified 30 years ago in what were called Long Duration Gamma Ray Flares. We show that LPGRE is temporally and spectrally distinct from impulsive phase emission in these events. The spectra are consistent with decay of pions produced by >300 MeV protons and are not consistent with primary electron bremsstrahlung. Impulsive >100 keV Xray emission was observed in all 27 LPGRE events where observations were made. All but two of the LPGRE events were accompanied by a fast and broad coronal mass ejection (CME). LPGRE start times range from CME onset to two hours later. Their durations range from ∼0.1–20 hours and appear to be correlated with durations of >100 MeV solar energetic particle (SEP) proton events. The powerlaw spectral indices of the>300 MeV protons producing LPGRE range from ∼2.5–6.5 and vary during some events. Combined γ-ray line and LAT measurements indicate that LPGRE proton spectra are steeper above 300 MeV than they are below 300 MeV. The number of LPGRE protons >500 MeV is typically about 10× the number in the impulsive phase of the SEE and ranges in 9 events from ∼0.01–0.5× the number in the accompanying SEP event, with large systematic uncertainty. What appears to be late phase electron bremsstrahlung with energies up to ∼10 MeV was observed in one LPGRE event. We discuss how current models of LPGRE may explain these characteristics.

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

Misidentification of the source of a neutron transient detected by MESSENGER on 2011 June 4†

Gerald H. **Share**1,*, Ronald J. Murphy2, Allan J. Tylka3, Brian R. Dennis4 and James M. Ryan
JGR, Volume 120, Issue 1, pages 1–11, **2015**
http://onlinelibrary.wiley.com/doi/10.1002/2014JA020663/pdf

Low energy (1-10 MeV) neutrons emanating from the Sun provide unique information about accelerated ions with steep energy spectra that may be produced in weak solar flares. However, observation of these solar neutrons can only be made in the inner heliosphere where measurement is difficult due to high background rates from neutrons produced by energetic ions interacting in the spacecraft. These ions can be from solar energetic particle events or produced in passing shocks associated with fast coronal mass ejections. Therefore, it is of the utmost importance

that investigators rule out these secondary neutrons before making claims about detecting neutrons from the Sun. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (tect MESSENGER) Neutron Spectrometer recorded an hour-long neutron transient beginning at 15:45 UTC on 2011 June 4 for which [13] claim there is “strong evidence" that the neutrons were produced by the interaction of ions in the solar atmosphere. We studied this event in detail using data from the MESSENGER neutron spectrometer, gamma-ray spectrometer, X-ray Spectrometer, and Energetic Particle Spectrometer, and from the particle spectrometers on STEREO A. We demonstrate that the transient neutrons were secondaries produced by energetic ions, probably accelerated by a passing shock, that interacted in the spacecraft. We also identify significant faults with the authors’ arguments in favor of a solar neutron origin for the transient.

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**
http://arxiv.org/pdf/1409.7725v1.pdf
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.

Solar flares with similar soft but different hard X-ray emissions: case and statistical studies

Ivan N. **Sharykin**, Alexei B. Struminsky, Ivan V. Zimovets, Wei-Qun Gan
Research in Astronomy and Astrophysics (RAA) Vol 16, No 1 (**2016**) paper 5
From the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) catalog we select events which have approximately the same GOES class (high C - low M or 500–1200 counts s−1within the RHESSI 6–12 keV energy band), but with different maximal energies of detected hard X-rays. The selected events are subdivided into two groups: (1) flares with X-ray emissions observed by RHESSI up to only 50 keV and (2) flares with hard X-ray emission observed also above 50 keV. The main task is to understand observational peculiarities of these two flare groups. We use RHESSI X-ray data to obtain spectral and spatial information in order to find differences between selected groups. Spectra and images are analyzed in detail for six events (case study). For a larger number of samples (85 and 28 flares in the low-energy and high-energy groups respectively) we only make some generalizations. In spectral analysis we use the thick-target model for hard X-ray emission and one temperature assumption for thermal soft X-ray emission. RHESSI X-ray images are used for determination of flare region sizes. Although thermal and spatial properties of these two groups of flares are not easily distinguishable, power law

indices of hard X-rays show significant differences. Events from the high-energy group generally have a harder spectrum. Therefore, the efficiency of chromospheric evaporation is not sensitive to the hardness of nonthermal electron spectra but rather depends on the total energy flux of nonthermal electrons.

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**
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.

Vertical position of the Sun with γ-rays

Thomas **Siegert**
A&A Letters **2019**
https://arxiv.org/pdf/1910.09575.pdf

We illustrate a method for estimating the vertical position of the Sun above the Galactic plane by γ-ray observations. Photons of γ-ray wavelengths are particularly well suited for geometrical and kinematic studies of the Milky Way because they are not subject to extinction by interstellar gas or dust. Here, we use the radioactive decay line of 26Al at 1.809MeV to perform maximum likelihood fits to data from the spectrometer SPI on board the INTEGRAL satellite as a proof-of-concept study. Our simple analytic 3D emissivity models are line-of-sight integrated, and varied as a function of the Sun's vertical position, given a known distance to the Galactic centre. We find a vertical position of the Sun of z0=15±17pc above the Galactic plane, consistent with previous studies, finding z0 in a range between 5 and 29pc. Even though the sensitivity of current MeV instruments is several orders of magnitude below that of telescopes for other wavelengths, this result reveals once more the disregarded capability of soft γ-ray telescopes. We further investigate possible biases in estimating the vertical extent of γ-ray emission if the Sun's position is set incorrectly, and find that the larger the true extent, the less is it affected by the observer position. In the case of 26Al with an exponential scale height of 150,pc (700pc) in the inner (full) Galaxy, this may lead to misestimates of up to 25%.

Millimeter Observation of Solar Flares with Polarization

Silva, D. F.; Valio, A. B. M.
Ground-based Solar Observations in the Space Instrumentation Era
ASP Conference Series, Vol. 504, p. 55, **2016**
http://aspbooks.org/publications/504/055.pdf

We present the investigation of two solar flares on **February 17 and May 13, 2013**, studied in radio from 5 to 405 GHz (RSTN, POEMAS, SST), and in X-rays up to 300 keV (FERMI and RHESSI). The objective of this work is to study the evolution and energy distribution of the population of accelerated electrons and the magnetic field configuration. For this we constructed and fit the radio spectrum by a gyro synchrotron model. The optically thin spectral indices from radio observations were compared to that of the hard X-rays, showing that the radio spectral index is harder than the latter by 2. These flares also presented 10-15 % circular polarized emission at 45 and 90 GHz that suggests that the sources are located at different legs of an asymmetric loop.

Too few? Too many?

Simoes, P. J. A. and Kontar, E. P.

RHESSI Science Nugget, No. 200, **2013**
We analysed four well-observed events in which the common loop structure could be identified in HXR: two footpoint sources at higher photon energies and a looptop source at lower energies.
Our conclusion is that the accelerated electrons must be subject to magnetic trapping and/or pitch-angle scattering, keeping a fraction of the population trapped inside the coronal loops.
2002 July 23, 2003 Nov 02, 2011 Feb 24, 2011 Sept 24

Consequences of the MSW mechanism with Super-Kamiokande oscillation parameters and of the volume distribution of neutrino sources in the Sun

L.M.**Slad**
2020
https://arxiv.org/pdf/2003.04057.pdf
The knowledge of the parameters of the solar neutrino oscillation model, provided by the SNO and Super-Kamiokande collaborations, allows us to obtain, on the basis of Wolfenstein's equation, a simple and clear analytical and numerical picture of the transformation of the neutrino state during its movement inside the Sun. We show that the picture obtained is not implicated in the characteristics of the neutrino state at the surface of the Sun and at the surface of the Earth. This circumstance with taking into account the volume distribution of solar neutrino sources indicates a contradiction between the consequences of the MSW mechanism with parameters from SNO and Super-Kamiokande and the results of all observed processes with solar neutrinos.

Solar neutrino problem as evidence of new interaction

L.M. **Slad**
2019
https://arxiv.org/pdf/1901.02320.pdf
A new concept is proposed to solve the solar neutrino problem, that is based on a hypothesis about the existence of a new interaction of electron neutrinos with nucleons mediated by massless pseudoscalar bosons. At every collision of a neutrino with nucleons of the Sun, its handedness changes from left to right and vice versa, and its energy decreases. The postulated hypothesis, having only one free parameter, provides a good agreement between the calculated and experimental characteristics of all five observed processes with solar neutrinos.

Solar neutrinos: Oscillations or No-oscillations?

A. Yu. **Smirnov**
2016
http://arxiv.org/pdf/1609.02386v1.pdf
The Nobel prize in physics 2015 has been awarded "... for the discovery of neutrino oscillations which show that neutrinos have mass". While SuperKamiokande (SK), indeed, has discovered oscillations, SNO observed effect of the adiabatic (almost non-oscillatory) flavor conversion of neutrinos in the matter of the Sun. Oscillations are irrelevant for solar neutrinos apart from small ve regeneration inside the Earth. Both oscillations and adiabatic conversion do not imply masses uniquely and further studies were required to show that non-zero neutrino masses are behind the SNO results. Phenomena of oscillations (phase effect) and adiabatic conversion (the MSW effect driven by the change of mixing in matter) are described in pedagogical way.

Impulsive and Gradual Eruptive Gamma Flares and Associated CMEs

Alexei **Struminsky,** Irina GRIGORIEVA and Andrei SADOVSKI
RHESSI Nuggets #413 **2021**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Impulsive_and_Gradual_Eruptive_Gamma_Flares_and_Associated_CMEs
Based on these observations we conclude that: 1) the CME associated with the gradual flare, SOL**2011-03-07** (with weaker chromospheric effects and GOES class only M3.7) was accelerated for a longer period but at a smaller rate. The non-thermal electrons did not reach the chromosphere (coronal sources of HXR and radio emission were observed when the CME was at Rs>2); 2) the CME associated with impulsive flare (strong chromospheric effects) - X6.9 SOL**2011-08-09** was accelerated quickly during the period of effective chromospheric evaporation (between Tmax and EMmax), and decelerating after that; 3) maximal velocity of both CMEs is ~2100 km/s and corresponds to the Alfven velocity available in the CME acceleration region. Finally, *4) Since the properties of the LDGRFs reflect the characteristics of the flares, but not the CMEs, the >100 MeV γ -ray emission is caused by protons accelerated during the flares.*

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**
https://iopscience.iop.org/article/10.1088/1742-6596/632/1/012081/pdf
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

Comparative Analysis of Super-Kamiokande Solar Neutrino Measurements and Geological Survey of Israel Radon Decay Measurements

Peter **Sturrock**, Oksana Piatibratova, and Felix Scholkmann
Front. Phys., **2021** |
https://www.frontiersin.org/articles/10.3389/fphy.2021.718306/full
https://doi.org/10.3389/fphy.2021.718306
Analyses of neutrino measurements acquired by the Super-Kamiokande Neutrino Observatory (SK, in operation 1996–2001) and radon decay measurements acquired by the Geological Survey of Israel (GSI, in operation 2007–2017) yield strikingly similar detections of an oscillation with frequency 9.43 ± 0.04 year−1 (SK), 9.44 ± 0.04 year−1 (GSI); amplitude 6.8 ± 1.7% (SK), 7.0 ± 1.0% (GSI); and phase 124 ± 15° (SK), 124 ± 9° (GSI). This remarkably close correspondence supports the proposition that neutrinos may somehow influence nuclear decays. It is interesting to note that an oscillation at this frequency has also been reported by (Alexeyev EN, Gavrilyuk YM, Gangapshev AM, Phys Particles Nuclei, 2018 49(4):557–62) in the decay of 214Po. The physical process responsible for this influence of neutrinos on nuclear processes is currently unknown. Related oscillations in GSI data at 7.45 ± 0.03 year−1 and 8.46 ± 0.03 year−1 suggest that these three oscillations are attributable to a solar core that rotates with a sidereal rotation rate of 8.44 ± 0.03 year−1 about an axis almost orthogonal to that of the convection zone. We briefly discuss possible implications of these results.

A STATISTICAL STUDY OF RHESSI FLARES –
YANG **SU**, W. Q. GAN and Y. P. LI, E-print, Oct **2006**
Solar Physics, Volume 238 Number 1, p. 61-72, **2006**.
12-25 keV: Count rate and frequency power-law distribution

Sui, L., Holman, G. D., Dennis, B. R. **Evidence for magnetic reconnection in three homologous solar flares observed by RHESSI.** ApJ 612, 546-556, 2004.

An Unexpected Dip in the Solar Gamma-Ray Spectrum
Qing-Wen **Tang**, Kenny C. Y. Ng, Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter
(Submitted on 18 Apr **2018**
https://arxiv.org/pdf/1804.06846.pdf
The solar disk is a bright source of multi-GeV gamma rays, due to the interactions of hadronic cosmic rays with the solar atmosphere. However, the underlying production mechanism is not understood, except that its efficiency must be greatly enhanced by magnetic fields that redirect some cosmic rays from ingoing to outgoing before they interact. To elucidate the nature of this emission, we perform a new analysis of solar atmospheric gamma rays with 9 years of Fermi-LAT data, which spans nearly the full 11-year solar cycle. We detect significant gamma-ray emission from the solar disk from 1 GeV up to $\gtrsim$200 GeV. The overall gamma-ray spectrum is much harder ($\sim E^{-2.2\gamma}$) than the cosmic-ray spectrum ($\sim E^{-2.7}$CR). We find a clear anticorrelation between the solar cycle phase and the gamma-ray flux between 1-10 GeV. Surprisingly, we observe a spectral dip between ~30-50 GeV in an otherwise power-law spectrum. This was not predicted, is not understood, and may provide crucial clues to the gamma-ray emission mechanism. The flux above 100 GeV, which is brightest during the solar minimum, poses exciting opportunities for HAWC, LHAASO, IceCube, and KM3NeT.

Energy release rates of H-alpha flare ribbons and locations of HXR sources -- **Temmer**, M., Veronig, A., Vrsnak, B., Miklenic, C.
E-print, Sep 2006
Local reconnection and energy release rates for an X3.8 flare that occurred on 17 January, 2005 are derived.

The YOHKOH survey of partially occulted flares in hard X-rays
M. **Tomczak**
A&A 502, 665-678 (**2009**)
Context. Modern solar X-ray imagers do not completely resolve the problem of deriving detailed diagnostics of faint hard X-ray sources in the presence of stronger ones. This is the case for the impulsive phase of solar flares in which footpoint sources are usually stronger than loop-top ones.
Aims. Flares that are partially occulted by the solar limb provide the most hopeful source of knowledge about hard X-ray loop-top sources. This work attempts to fill the gap between the published survey of partially occulted flares observed by RHESSI (Krucker & Lin 2008, ApJ, 673, 1181) and the extensive *Yohkoh* database.
Methods. Among the 1286 flares in the *Yohkoh* Hard X-ray Telescope Flare Catalogue (Sato et al. 2006, Sol. Phys., 236, 351), for which the hard X-ray images were presented, we identified 98 events that occurred behind the solar limb. We investigated their hard X-ray spectra and spatial structure.
Results. In most cases, we found that the hard X-ray spectrum of partially occulted flares consists of two components, non-thermal and thermal, which are cospatial to within 4 arcsec. For rest events, the components are separated, the non-thermal component clearly appearing to be situated higher. The photon energy spectra of the partially occulted flares are systematically steeper than spectra of the non-occulted flares. We can explain this difference as a consequence of intrinsically dissimilar conditions in coronal parts of flares, in comparison with the footpoints that usually dominate the hard X-ray emission of disk flares. At least two reasons for the difference should be taken into consideration: (1) stronger contamination of hard X-rays by emission from thermal plasma; and (2) different mechanisms in which non-thermal electrons radiate their energy. For events unbiased by the thermal component, the difference, $\Delta\gamma = \bar{\gamma}_{LT} - \bar{\gamma}_{FP}$, equals 1.5. We found a lack of correlation between the altitude of flares and the hard X-ray power-law index γ.
Conclusions. A schematic picture, in which a thin-target mechanism is responsible for the hard X-ray emission of loop-top sources and a thick-target mechanism for emission by footpoint sources, is modified by the presence of some coronal thick-target sources. Some of these sources exhibit evidence of magnetic trapping. For the characteristics of flares is conclusive the local magnetic configuration in which they occur.

The *Ulysses* Catalog of Solar Hard X-Ray Flares

C. **Tranquille** · K. Hurley · H.S. Hudson

Solar Phys (**2009**) 258: 141–166

Ulysses was launched in October 1990, and its Solar X-ray/Cosmic Gamma-Ray Burst Experiment (GRB) has provided more than 13 years of uninterrupted observations of solar X-ray flare activity. Due to the large variation of the relative solar latitude and longitude of the spacecraft orbit with respect to the Earth, the perspective of the GRB instrument often differed significantly from that of X-ray instruments on Earth-orbiting satellites. During extended periods the GRB experiment made direct observations of flares on the hidden face of the Sun, providing a unique record of events not visible to other instruments. The small detector area of GRB and its optimization for very high counting rates minimized the effects of pulse pile-up. We interpret the spectra, time histories, and occurrence distribution patterns of GRB data in terms of “thermal feed-through”, the confusion of thermal soft X-rays and non-thermal hard X-rays. This effect is a systematic problem for scintillation-counter spectrometers observing the solar hard X-ray spectrum. This paper provides a definitive catalog of the *Ulysses* X-ray flare observations and discusses various features of this unique database. For the equivalent GOES range X2 –X25, we find a power-law fit for the (differential) occurrence frequency at >25 keV with slope −1.61 ± 0.04, with no evidence for a downturn at the highest event magnitudes (for the relatively small sample of such events available in this study). If the nine most intense events are excluded because of concerns about the effects of pulse pile-up, the slope steepens to −1.75±0.08.

Radio Submillimeter and Gamma-ray Observations of the 2003 October 28 Solar Flare

G. **Trottet**, S. Krucker, T. Luthi, A. Magun

E-print, Dec 2007; Ap.J. 678:509-514, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/528787

Radio observations at 210~GHz taken by the BErnese Multibeam RAdiometer for KOSMA (BEMRAK) are combined with hard X-ray and gamma-ray observations from the SONG instrument onboard CORONA-F and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) to investigate high energy particle acceleration during the energetic solar flare of 2003 October 28. Two distinct components at submillimeter wavelengths are found. The first is a gradual, long-lasting (>30 min) component with large apparent source sizes (~60 arcsec). Its spectrum below ~200 GHz is consistent with synchrotron emission from flare-accelerated electrons producing hard X-ray and $gamma$-ray bremsstrahlung assuming a magnetic field strength of >200 G in the radio source and a confinement time of the radio-emitting electrons in the source of less than 30 s. At even higher frequencies, the spectrum deviates from synchrotron emission and is increasing with frequency, as also seen in other large flares, but the interpretation is unclear. The other component is impulsive and starts simultaneously with high energy (>200 MeV/nucleon) proton acceleration and the production of pions. The derived radio source size is compact (<10 arcsec) and, within the uncertainties, the emission is co-spatial with the location of precipitating flare-accelerated >30 MeV protons as seen in Gamma-ray imaging of the 2.2 MeV line emission. The close correlation in time and space of radio emission with the production of pions suggests that synchrotron emission of positrons produced in charged-pion decay might be responsible for the observed compact radio source. However, order-of-magnitude approximations rather suggest that the derived numbers of positrons from charged-pion decay are probably too small compared to what is needed to produce the observed radio emission. Synchrotron emission from energetic electrons therefore appears as the most likely emission mechanism for the compact radio source seen in the impulsive phase although it does not account for its close correlation, in time and space, with pion production.

INTEGRAL serendipitous observations of solar and terrestrial X-rays and gamma rays

Marc **Türler**, Vincent Tatischeff, Volker Beckmann, Eugene Churazov

"15 years of INTEGRAL" Volume of New Astronomy Reviews **2021**

https://arxiv.org/pdf/2104.06073.pdf

ESA's INTEGRAL space mission has achieved unique results for solar and terrestrial physics, although spacecraft operations nominally excluded the possibility to point at the Sun or the Earth. The Earth avoidance was, however, exceptionally relaxed for special occultation observations of the Cosmic X-ray Background (CXB), which on some occasions allowed the detection of strong X-ray auroral emission. In addition, the most intense solar flares can be bright enough to be detectable from outside the field of view of the main instruments. This article presents for the first time the auroral observations by INTEGRAL and reviews earlier studies of the most intense solar flares. We end by briefly summarising the studies of the Earth's radiation belts, which can be considered as another topic of serendipitous science with INTEGRAL. **October 28, 2003**

Self-consistent Modelling of Gamma-Ray Spectra from Solar Flares with the Monte Carlo Simulation Package FLUKA

Daneele S. **Tusnski**, Sergio Szpigel, Carlos Guillermo Giménez de Castro, Alexander L. MacKinnon, Paulo José A. Simões
Solar Phys. 294:103 **2019**
https://arxiv.org/pdf/1907.11575.pdf
https://doi.org/10.1007/s11207-019-1499-2
https://link.springer.com/content/pdf/10.1007/s11207-019-1499-2.pdf
We use the Monte Carlo particle physics code FLUKA (Fluktuierende Kaskade) to calculate γ-ray spectra expected from solar flare energetic ion distributions. The FLUKA code includes robust physics-based models for electromagnetic, hadronic and nuclear interactions, sufficiently detailed for it to be a useful tool for calculating nuclear de-excitation, positron annihilation and neutron capture line fluxes and shapes, as well as ≈GeV continuum radiation from pion decay products. We show nuclear de-excitation γ-ray line model spectra from a range of assumed primary accelerated ion distributions and find them to be in good agreement with those found using the code of Murphy et al. (2009). We also show full γ-ray model spectra which exhibit all the typical structures of γ-ray spectra observed in solar flares. From these model spectra we build templates which are incorporated into the software package Objective Spectral Executive (OSPEX) and used to fit the combined Fermi Gamma-ray Burst Monitor (GBM)/Large Area Telescope (LAT) spectrum of the **2010 June 12** solar flare, providing a statistically acceptable result. To the best of our knowledge, the fit carried out with the FLUKA templates for the full γ-ray spectrum can be regarded as the first attempt to use a single code to implement a self-consistent treatment of the several spectral components in the photon energy range from ≈100s keVto ≈100s MeV.
RHESSI Science Nugget, No. **402**, Mar **2021**

The First AGILE Solar Flare Catalog

Alessandro **Ursi**, Nicolò Parmiggiani, Mauro Messerotti, Alberto Pellizzoni, Carlotta Pittori, Francesco Longo, Francesco Verrecchia, Andrea Argan, Andrea Bulgarelli, Marco Tavani, Patrizio Tempesta, Fabio D'Amico
ApJS **267** 9 **2023**
https://arxiv.org/pdf/2305.14957.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/acd4b6/pdf
We report the Astrorivelatore Gamma ad Immagini LEggero (AGILE) observations of solar flares, detected by the on board anticoincidence system in the 80-200 keV energy range, from 2007 May 1st to 2022 August 31st. In more than 15 yr, AGILE detected 5003 X-ray, minute-lasting transients, compatible with a solar origin. A cross-correlation of these transients with the Geostationary Operational Environmental Satellites (GOES) official solar flare database allowed to associate an intensity class (i.e., B, C, M, or X) to 3572 of them, for which we investigated the main temporal and intensity parameters. The AGILE data clearly revealed the solar activity covering the last stages of the 23rd cycle, the whole 24th cycle, and the beginning of the current 25th cycle. In order to compare our results with other space missions operating in the high-energy range, we also analyzed the public lists of solar flares reported by RHESSI and Fermi Gamma-ray Burst Monitor. This catalog reports 1424 events not contained in the GOES official dataset, which, after statistical comparisons, are compatible with low-intensity, short-duration solar flares.
Besides providing a further dataset of solar flares detected in the hard X-ray range, this study allowed to point out two main features: a longer persistence of the decay phase in the high-energy regime, with respect to the soft X-rays, and a tendency of the flare maximum to be reached earlier in the soft X-rays with respect to the hard X-rays. ***Both these aspects support a two-phase acceleration mechanism of electrons in the solar atmosphere.*** **2013 April 24**

Solar neutron events as a tool to study particle acceleration at the Sun

J.F. **Valdés-Galicia**, Y. Muraki[b, c], K. Watanabe[b], Y. Matsubara[b], T. Sako[b], L.X. Gonzalez[a], O. Musalem[a] and A. Hurtado
Advances in Space Research
Volume 43, Issue 4, 16 February **2009**, Pages 565-572
The Sun provides unique opportunities to study particle acceleration mechanisms using data from detectors placed on the Earth's surface and on board spacecrafts. Particles may gain high energies by several physical mechanisms. Differentiating between these possibilities is a fundamental problem of cosmic ray physics. Energetic neutrons provide us with information that keeps the signatures of the acceleration site. A summary of some representative solar neutron events observed on the Earth's surface, including associated X and γ-ray observations from spacecrafts is presented. We discuss evidence of acceleration of particles by the Sun to energies up to several tens of GeV. In addition, a recent solar neutron event that occurred on **September 7th 2005** and detected by several observatories at Earth is analyzed in detail.

Effects of a revised 7Be e−-capture rate on solar neutrino fluxes⋆

D. **Vescovi**1,2, L. Piersanti3,2, S. Cristallo3,2, M. Busso4,2, F. Vissani5, S. Palmerini4,2, S. Simonucci6,2 and S. Taioli
A&A 623, A126 (**2019**)
https://doi.org/10.1051/0004-6361/201834993
Context. Electron-capture on 7Be is the main production channel for 7Li in several astrophysical environments. Theoretical evaluations have to account for not only the nuclear interaction, but also the processes in the plasma in which 7Be ions and electrons interact. In recent decades several estimates were presented, pointing out that the theoretical uncertainty in the rate is in general of a few percent.
Aims. In the framework of fundamental solar physics, we consider a recent evaluation for the 7Be+e− rate, which has not been used up to now, in the estimate of neutrino fluxes.
Methods. We analyzed the effects of the new assumptions on standard solar models (SSMs) and compared the results obtained by adopting the revised 7Be+e− rate to those obtained by that reported in a widely used compilation of reaction rates (ADE11).
Results. We found that new SSMs yield a maximum difference in the efficiency of the 7Be channel of about −4% with respect to what is obtained with the previously adopted rate. This fact affects the production of neutrinos from 8B, increasing the relative flux up to a maximum of 2.7%. Negligible variations are found for the physical and chemical properties of the computed solar models.
Conclusions. The agreement with the Sudbury Neutrino Observatory measurements of the neutral current component of the 8B neutrino flux is improved.

Evidence for a Spatially Extended Component of Gamma Rays from Solar Flares

Vestrand, W. T. ; Forrest, David J.
Astrophysical Journal Letters v.409, p.L69–L72 **1993**
https://articles.adsabs.harvard.edu/pdf/1993ApJ...409L..69V
We present gamma-ray measurements of a large solar flare that occurred beyond the western solar limb on September 29, 1989. The gamma-ray spectrum shows a neutron capture line which is much stronger than predicted by limb-darkening curves that fit the measurements for flares on the visible hemisphere. We show that this strong neutron capture line can be explained if, in addition to the compact impulsive phase component that normally dominates the total fluence, there is a spatially extended component. For the **September 29, 1989** flare we find that such a spatially extended region must subtend more than about 30 deg on the solar surface. We suggest that the extended component could be powered by particles that diffuse from a compact impulsive region or by particles that diffuse into the lower solar atmosphere from a large-scale acceleration site.

ENERGETIC PARTICLES IN THE SOLAR ATMOSPHERE **Review**

N. **Vilmer**1 and S. Musset2
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 283-289
http://sf2a.eu/proceedings/2019/2019/vilmer.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. **23 July 2002, 21 May 2004, 15 Feb 2011, 2014 February 25**

Solar Flares and Energetic Particles **A Review**

N. **Vilmer**
E-print, Oct **2012**; Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 370, issue 1970, pp. 3241-3268 Published in Jul **2012**
sci-hub.se/10.1098/rsta.2012.0104

Solar flares are now observed at all wavelengths from γ-rays to decametre radio waves. They are commonly associated with efficient production of energetic particles at all energies. These particles play a major role in the active Sun because they contain a large amount of the 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, produce radio emissions (electrons) and may eventually reach the Earth's orbit. I shall review here the available information on energetic particles provided by X-ray/γ-ray observations, with particular emphasis on the results obtained recently by the mission Reuven Ramaty High-Energy Solar Spectroscopic Imager. I shall also illustrate how radio observations contribute to our understanding of the electron acceleration sites and to our knowledge on the origin and propagation of energetic particles in the interplanetary medium. I shall finally briefly review some recent progress in the theories of particle acceleration in solar flares and comment on the still challenging issue of connecting particle acceleration processes to the topology of the complex magnetic structures present in the corona. **25 August 2001, 20 Feb 2002 , 23 July 2002 , 28 October 2003 , 17 Jan 2005, 20 January 2005**

Properties of Energetic Ions in the Solar Atmosphere from γ-Ray and Neutron Observations

N. **Vilmer**, A. L. MacKinnon and G. J. Hurford
Space Sci. Rev., 159:167–224, **2011, File** **A Review**
Gamma-rays and neutrons are the only sources of information on energetic ions present during solar flares and on properties of these ions when they interact in the solar atmosphere. The production of γ-rays and neutrons results from convolution of the nuclear cross-sections with the ion distribution functions in the atmosphere. The observed γ-ray and neutron fluxes thus provide useful diagnostics for the properties of energetic ions, yielding strong constraints on acceleration mechanisms as well as properties of the interaction sites. The problem of ion transport between the accelerating and interaction sites must also be addressed to infer as much information as possible on the properties of the primary ion accelerator. In the last couple of decades, both theoretical and observational developments have led to substantial progress in understanding the origin of solar γ-rays and neutrons. This chapter reviews recent developments in the study of solar γ-rays and of solar neutrons at the time of the RHESSI era. The unprecedented quality of the RHESSI data reveals γ-ray line shapes for the first time and provides γ-ray images. Our previous understanding of the properties of energetic ions based on measurements from the former solar cycles is also summarized. The new results—obtained owing both to the gain in spectral resolution (both with RHESSI and with the non solar-dedicated INTEGRAL/SPI instrument) and to the pioneering imaging technique in the γ-ray domain—are presented in the context of this previous knowledge. Still open questions are emphasized in the last section of the chapter and future perspectives on this field are briefly discussed.

The Sun as a particle accelerator: hard X-ray and γ-ray diagnostics of energetic particles

N. **Vilmer**
SF2A-2010: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. Eds.: S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud, p.305, **2010**.
Explosive phenomena of magnetic energy conversion in the solar corona lead to the production of energetic particles at all energies. While some fast particles (electrons and ions) produce high energy radiation when interacting with the solar atmosphere (X-rays,γ-rays), others escape in the corona and interplanetary medium, produce radio emission and may eventually reach the Earth's orbit. I shall illustrate here with some high-energy observations the properties that can be derived on energetic particles. I will concentrate on some of the observations obtained in the last years at high spectral resolution with RHESSI and INTEGRAL/SPI and on the spatially resolved observations provided by RHESSI. I shall present some open questions still being discussed and give a brief overview of future observations in the field of high energy solar physics.

Solar neutrino flux at keV energies

Edoardo **Vitagliano**, Javier Redondo, Georg Raffelt
JCAP **2017**
https://arxiv.org/pdf/1708.02248.pdf
We calculate the solar neutrino and antineutrino flux in the keV energy range. The dominant thermal source processes are photoproduction ($\gamma e \to e\nu\bar{\nu}$), bremsstrahlung ($e+Ze \to Ze+e+\nu\bar{\nu}$), plasmon decay ($\gamma \to \nu\bar{\nu}$), and $\nu\bar{\nu}$ emission in free-bound and bound-bound transitions of partially ionized elements heavier than hydrogen and helium. These latter processes dominate in the energy range of a few keV and thus carry information about the solar metallicity. To calculate their rate we use libraries of monochromatic photon radiative opacities in analogy to a previous calculation of solar axion emission. Our overall flux spectrum and many details differ significantly from previous works. While this low-energy flux is not measurable with present-day technology, it could become a significant background for future direct searches for keV-mass sterile neutrino dark matter.

Neutrino Astrophysics **Review**

Cristina **Volpe**
Lectures presented at "52th Winter School of Theoretical Physics", Ladek Zdroj, 14-21 February 2016.
arXiv admin note: text overlap with arXiv:1503.01355, arXiv:1411.6533 **2016**
http://arxiv.org/pdf/1609.06747v1.pdf
We summarize the progress in neutrino astrophysics and emphasize open issues in our understanding of neutrino flavor conversion in media. We discuss solar neutrinos, core-collapse supernova neutrinos and conclude with ultra-high energy neutrinos.
See Proceedings for "DISCRETE 2014" Symposium http://arxiv.org/pdf/1503.01355v1.pdf

Mars Odyssey/HEND and RHESSI

Vadim **Vybornov** and Michael A. Livshits
RHESSI Science Nugget No. 202, June **2013**
We discuss observations of flares visible from the Earth, as a check on the HEND calibrations, and then show observations from the solar hemisphere (the "backside") invisible from Earth. **27 Oct 2002**

Do All Long-duration Gamma-Ray Bursts Emit GeV Photons?

Yu **Wang**
2021 ApJ 913 86
https://doi.org/10.3847/1538-4357/abf2cb
GRB 190114C extends the focus of gamma-ray burst (GRB) research to the high-energy regime, in which a prime question is "Do all long-duration GRBs emit GeV photons?" Based on the Fermi Large Area Telescope (LAT) 10 yr observations, 54 GRBs initially within the Fermi-LAT field of view and with known redshift are sampled. Within 26 of these GRBs at least one GeV photon has been detected with a probability of >95%, while the other 28 GRBs have no confident GeV photon detection. We hypothesize that all the samples intrinsically emit GeV photons, and the lack of detection is due to the limited capacity of the satellite. We estimate the theoretical number of photons that LAT receives by considering the GRB energy, the distance, and the LAT effective area. Results show, within the uncertainty, that all 26 GRBs with GeV photon detection have a theoretical photon number of >1, and 27 out of 28 GRBs without GeV photon detection have a theoretical photon number of <1. This agreement tends to support our hypothesis and give an answer of "yes" to our initial question.

Physics of ion acceleration in the solar flare on 2005 September 7 determines γ-ray and neutron production

K. **Watanabe**a, , , R.P. Linb, S. Kruckerb, R.J. Murphyc, G.H. Sharedd, M.J. Harrise, M. Grosf, Y. Murakig, T. Sakoh, Y. Matsubarah, T. Sakaii, S. Shibataj, J.F. Valdés-Galiciak, L.X. Gonzálezk, A. Hurtadok, O. Musalemk, P. Mirandal, N. Martinicl, R. Ticonal, A. Velardel, F. Kakimotom, Y. Tsunesadam, H. Tokunon and S. Ogioo
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.**

Highly significant detection of solar neutrons on 2005 September 7

Adv. Space Res. 39(9), *Pages 1464-1468, **2007***
K. **Watanabe**, T. Sako, Y. Muraki, Y. Matsubara, T. Sakai, S. Shibata, J.F. Valdés-Galicia, L.X. González, A. Hurtado, O. Musalem, P. Miranda, N. Martinic, R. Ticona, A. Velarde, F. Kakimoto, S. Ogio, Y. Tsunesada, H. Tokuno, Y.T. Tanaka, I. Yoshikawa, T. Terasawa, Y. Saito, T. Mukai and M. Gros

Solar neutron events in association with large solar flares in November 2003

K. **Watanabe**a, , , Y. Murakia, Y. Matsubaraa, K. Murakamia, T. Sakoa, P. Mirandab, R. Ticonab, A. Velardeb, F. Kakimotoc, S. Ogioc, H. Tokunoc, H. Tsuchiyad, S. Shibatae, T. Sakaif, Y. Mizumotog, R. Ogasawarag, M. Nakagirig, A. Miyashitag and C. Lopateh
Advances in Space Research, Volume 38, Issue 3, **2006**, Pages 425-430
The Sun was intensely active from late October to the beginning of **November 2003**. A series of 11 X class solar flares occurred in NOAA regions 484, 486 and 488. Unique among this series of flares were those occurring on **November 2 and 4** in which solar neutrons were observed by the ground based neutron monitors located at Mt. Chacaltaya, Bolivia and Haleakala, Hawaii, respectively. In these flares, intense emission of hard X-rays and γ-rays have been observed by the satellites. It seems that production of solar neutrons coincided with the production of the hard electromagnetic radiations of these two flares.

A Statistical Study to Determine the Origin of Long-Duration Gamma-ray Flares

Lisa M. **Winter**, Valerie Bernstein, Nicola Omodei, Melissa Pesce-Rollins
ApJ **864** 39 **2018**
https://arxiv.org/pdf/1807.06001.pdf **File**
http://sci-hub.tw/10.3847/1538-4357/aad3c0
https://iopscience.iop.org/article/10.3847/1538-4357/aad3c0/pdf
Two scenarios have been proposed to account for sustained ≥30\,MeV gamma-ray emission in solar flares: (1) prolonged particle acceleration/trapping involving large-scale magnetic loops at the flare site, and (2) precipitation of high-energy (> 300 MeV) protons accelerated at coronal/interplanetary shock waves. To determine which of these scenarios is more likely, we examine the associated soft X-ray flares, coronal mass ejections (CMEs), and solar energetic proton events (SEPs) for: (a) the long-duration gamma-ray flares (LDGRFs) observed by the Large Area Telescope (LAT) on \Fermi, and (b) delayed and/or spatially-extended high-energy gamma-ray flares observed by the Gamma-ray Spectrometer on the Solar Maximum Mission, the Gamma-1 telescope on the Gamma satellite, and the Energetic Gamma-Ray Experiment Telescope on the Compton Gamma-Ray Observatory. For the \Fermi data set of 11 LDGRFs with >100 MeV emission lasting for ≥∼2 hours, we search for associations and reverse associations between LDGRFs, X-ray flares, CMEs, and SEPs, i.e., beginning with the gamma-ray flares and also, in turn, with X-class soft X-ray flares, fast (≥ 1500 km s−1) and wide CMEs, and intense (peak flux ≥2.67×10−3 protons cm−2 s−1 sr−1, with peak to background ratio > 1.38) > 300 MeV SEPs at 1 A.U. While LDGRFs tend to be associated with bright X-class flares, we find that only 1/3 of the X-class flares during the time of \Fermi monitoring coincide with an LDGRF. However, nearly all fast, wide CMEs are associated with an LDGRF. These preliminary association analyses favor the proton precipitation scenario, although there is a prominent counter-example of a potentially magnetically well-connected solar eruption with > 100 MeV emission for ∼10 h for which the near-Earth > 300 MeV proton intensity did not rise above background. **2011.03.07, 2012.01.27, 2012.03.07,**
TABLE 1 *Properties of Fermi LAT Gamma-Ray Flares 2011-2015*
TABLE 2 *Properties of X-class flares without Fermi LAT Gamma-Ray Flares*
TABLE 3 *Properties of Pre-Fermi LAT Gamma-Ray Flares 1982-1991*

On the origin of hard X-ray emissions from the behind-the-limb flare on 2014 September 1

Yihong **Wu**, Alexis P. Rouillard, Athanasios Kouloumvakos, Rami Vainio, Alexandr N. Afanasiev, Illya Plotnikov, Ronald J. Murphy, Gottfried J. Mann, Alexander Warmuth
ApJ **909** 163 **2021**
https://arxiv.org/pdf/2101.05401.pdf
https://doi.org/10.3847/1538-4357/abdc20
The origin of hard X-rays and gamma-rays emitted from the solar atmosphere during occulted solar flares is still debated. The hard X-ray emissions could come from flaring loop tops rising above the limb or Coronal Mass Ejections (CME) shock waves, two by-products of energetic solar storms. For the shock scenario to work, accelerated particles must be released on magnetic field lines rooted on the visible disk and precipitate. We present a new Monte Carlo code that computes particle acceleration at shocks propagating along large coronal magnetic loops. A first implementation of the model is carried out for the **2014 September 1** event and the modeled electron spectra are compared with those inferred from Fermi Gamma-ray Burst Monitor (GBM) measurements. When particle diffusion processes are invoked our model can reproduce the hard electron spectra measured by GBM nearly ten minutes after the estimated on-disk hard X-rays appear to have ceased from the flare site.

Solar neutrino physics **Review**

Xun-Jie **Xu**, Zhe Wang, Shaomin Chen
Progress in Particle and Nuclear **2022**
https://arxiv.org/pdf/2209.14832.pdf
As a free, intensive, rarely interactive and well directional messenger, solar neutrinos have been driving both solar physics and neutrino physics developments for more than half a century. Since more extensive and advanced

neutrino experiments are under construction, being planned or proposed, we are striving toward an era of precise and comprehensive measurement of solar neutrinos in the next decades. In this article, we review recent theoretical and experimental progress achieved in solar neutrino physics. We present not only an introduction to neutrinos from the standard solar model and the standard flavor evolution, but also a compilation of a variety of new physics that could affect and hence be probed by solar neutrinos. After reviewing the latest techniques and issues involved in the measurement of solar neutrino spectra and background reduction, we provide our anticipation on the physics gains from the new generation of neutrino experiments.

High-Energy Emissions Observed in the Impulsive Phase of the 2001 August 25 Eruptive Flare

Boris Y. **Yushkov**, Victoria G. Kurt & Vladimir I. Galkin
Solar Physics volume 298, Article number: 31 (**2023**) **File**
https://doi.org/10.1007/s11207-023-02123-8
We analyze here the impulsive phase of the 2001 August 25 eruptive flare (X5.3, S21, E38) in order to reveal the link of the time evolution of the magnetic-field reconnection rate $\dot{\varphi}(t)$ with the energy-release process, as quantified by electron and proton acceleration to high energies. Hard X-rays and γ-rays from 150 keV to 100 MeV were observed by the SONG (SOlar Neutrons and Gamma) detector onboard the CORONAS-F (Complex ORbital ObservatioNs of the Active Sun) mission. The soft X-ray derivative dISXR/dt was used as a proxy for the flare energy release that revealed itself as a sequence of acceleration pulses.The reconnection rate $\dot{\varphi}(t)$ was calculated previously from flare-ribbon observations in EUV and coaligned magnetic-field maps. The γ-ray emission spectra were obtained from SONG data. All spectra contain both bremsstrahlung and γ-ray lines. The bremsstrahlung spectrum extends to tens of MeV. The pion-decay gamma-ray emission, being a manifestation of proton acceleration to subrelativistic energies, appeared for the first time in the time interval of the $\dot{\varphi}(t)$ maximum. This maximum was ahead of the maxima of dISXR/dt as well as of all other emissions by about one minute. Proton acceleration to subrelativistic energies is confirmed by detection of solar neutrons by SONG and the Chacaltaya neutron monitor

TeV Solar Gamma Rays From Cosmic-Ray Interactions

Bei **Zhou**, Kenny C. Y. Ng, John F. Beacom, Annika H. G. Peter
2016
https://arxiv.org/pdf/1612.02420v1.pdf
The Sun is a bright source of GeV gamma rays, due to cosmic rays interacting with solar matter and photons. Key aspects of the underlying processes remain mysterious. The emission in the TeV range, for which there are neither observational nor theoretical studies, could provide crucial clues. The new experiments HAWC (running) and LHAASO (planned) can look with unprecedented sensitivity. In this paper, we predict the very high energy (up to 1000 TeV) gamma-ray flux from the solar disk and halo, due to cosmic-ray hadrons and electrons, respectively. We neglect solar magnetic effects, which is valid at TeV energies; at lower energies, this gives a theoretical lower bound on the disk flux and a theoretical upper bound on the halo flux. We show that the solar-halo gamma-ray flux allows the first test of the ~ 5--70 TeV cosmic-ray electron spectrum. Further, we show HAWC can immediately make an even stronger test with non-directional observations of electron cosmic rays. Together, these gamma-ray and electron studies will provide new insights about the local density of cosmic rays and their interactions with the Sun and its magnetic environment. These studies will also be an important input to tests of new physics, including dark matter.

Imaging Observations of Quasi-Periodic Pulsatory Nonthermal Emission in Two-Ribbon Solar Flares

I.V. **Zimovets** · A.B. Struminsky
Solar Phys (**2009**) 258: 69–88
Using RHESSI and some auxiliary observations we examine possible connections between the spatial and temporal structure of nonthermal hard X-ray (HXR) emission sources from the two-ribbon flares of **29 May 2003** and **19 January 2005**. In each of these events quasi-periodic pulsations (QPP) with time period of 1 – 3 minutes are evident in both hard X rays and microwaves. The sources of nonthermal HXR emission are situated mainly at the footpoints of the flare arcade loops observed by TRACE and the SOHO/EIT instrument in the EUV range. At least one of the sources moves systematically during and after the QPP phase in each flare. The sources move predominantly parallel to the magnetic inversion line during the 29 May flare and along flare ribbons during the QPP phase of both flares. By contrast, the sources start to show movement perpendicular to the flare ribbons with velocity comparable to that along the ribbons' movement after the QPP phase. The sources of each pulse are localized in distinct parts of the ribbon during the QPP phase. The measured velocity of the sources and the estimated energy release rate do not correlate well with the flux of the HXR emission calculated from these sources. The sources of microwaves and thermal HXRs are situated near the apex of the flare loop arcade and are not stationary either. Almost all of the QPP as well as some pulses of nonthermal HXR emission during the post-QPP phase reveal soft – hard – soft spectral

behavior, indicating separate acts of electron acceleration and injection. In our opinion at least two different flare scenarios based on the Nakariakov *et al.* (2006, *Astron. Astrophys.* **452**, 343) model and on the idea of current-carrying loop coalescence are suitable for interpreting the observations. However, it is currently not possible to choose between them owing to observational limitations.

НЕКОТОРЫЕ ОСОБЕННОСТИ СОЛНЕЧНЫХ ПРОТОННЫХ СОБЫТИЙ И ДЛИТЕЛЬНЫХ ГАММА-ВСПЫШЕК В 24-М ЦИКЛЕ СОЛНЕЧНОЙ АКТИВНОСТИ

Г. А. **Базилевская**1,*, Е. И. Дайбог2, Ю. И. Логачев2, Н. А. Власова2, Е. А. Гинзбург3, В. Н. Ишков4,5, Л. Л. Лазутин2, М. Д. Нгуен2, Г. М. Сурова2, О. С. Яковчук2

Известия РАН **2021**, Vol. 85, No. 8, pp. 1185–1188**. File See English version**

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 πo, 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 корональной вещества двигались не в сторону Земли. Солнечные протоны от таких источников не регистрируются земным наблюдателем.

НАБЛЮДЕНИЯ МОЩНОЙ ВСПЫШКИ 27 ОКТЯБРЯ 2002 Г., ПРОИЗОШЕДШЕЙ НА ОБРАТНОЙ СТОРОНЕ СОЛНЦА

Выборнов В.И., Лившиц М.А., Кашапова Л.К., Митрофанов И.Г., Головин Д.В., Козырев А.С., Литвак М.Л., Санин А.Б., Третьяков В.И., Бойнтон В., Шинохара К., Хамара Д.

АЖ, 89(10), 888, **2012**

Анализируются результаты наблюдений мощной солнечной вспышки 27 октября 2002 г. в жесткой рентгеновской области и микроволновом диапазоне. Вспышка наблюдалась с околомарсианской орбиты аппаратурой HEND, разработанной в ИКИ РАН и установленной на космическом аппарате Mars-Odyssey. Хотя для земного наблюдателя эта мощная вспышка наблюдалась далеко за восточным лимбом Солнца, связанный с ней протяженный источник зарегистрирован RHESSI в области энергий до примерно 60 кэВ. Эруптивное событие наблюдалось в микроволновом диапазоне на обсерватории Nobeyama. По характеристикам рентгеновского излучения находится спектр электронов, ответственных за рассматриваемые излучения в рамках толстой мишени для наблюдений с околомарсианской и тонкой мишени – с околоземной орбиты. Выводы сопоставляются с результатами микроволновых наблюдений. Обсуждаются условия распространения электронов в солнечной короне.

УСКОРЕНИЕ ЭЛЕКТРОНОВ В МАГНИТНЫХ ЛОВУШКАХ СОЛНЕЧНОЙ ВСПЫШКИ: МОДЕЛЬНЫЕ СВОЙСТВА И ИХ НАБЛЮДАТЕЛЬНЫЕ ПОДТВЕРЖДЕНИЯ

ГРИЦЫК П.А.1, СОМОВ Б.В.1

ПАЖ Том: 43Номер: 9 Год: **2017** Страницы: 676

С помощью аналитического решения кинетического уравнения мы исследовали модельные свойства корональных и хромосферного источников жесткого рентгеновского излучения в лимбовой вспышке **19 июля 2012** г. В приближении толстой мишени с обратным током мы рассчитали спектр излучения в основаниях вспышечной петли и показали, что он согласуется с наблюдаемым. Спектр корональных источника, расположенного над вспышечной петлей, рассчитан в приближении тонкой мишени. При этом показатель наклона спектра жесткого рентгеновского излучения воспроизводится очень точно, но интенсивность корональных излучения в несколько раз ниже наблюдаемой. Ранее нами было показано, что это противоречие полностью устраняется, если учесть дополнительное (относительно первичного ускорения в пересоединяющем токовом слое) ускорение электронов в корональной магнитной ловушке, которая сжимается в поперечном направлении и уменьшается по длине во время импульсной фазы вспышки. В настоящей статье мы детально исследуем данный эффект в контексте более реалистичного сценария вспышки, когда за время всплеска в жестком рентгеновском диапазоне существовал целый ансамбль ловушек, каждая из которых находилась на разных этапах своей эволюции: формирование, коллапс, уничтожение. Полученные в работе результаты указывают не только на существование ускорения Ферми первого порядка и бетатронного нагрева электронов в солнечных вспышках, но и на высокую их эффективность. На примере высокоточных наблюдений конкретной вспышки предсказанные ранее теоретические особенности модели находят убедительные подтверждения.

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**

КАТАЛОГ ЖЕСТКИХ РЕНТГЕНОВСКИХ ВСПЫШЕК НА СОЛНЦЕ, ЗАРЕГИСТРИРОВАННЫХ С ОКОЛОМАРСИАНСКОЙ ОРБИТЫ MARS ODYSSEY/HEND В 2001-2016 ГГ

ЛИВШИЦ М.А.1, ЗИМОВЕЦ И.В.2, ГОЛОВИН Д.В.2, НИЗАМОВ Б.А.3,4, ВЫБОРНОВ В.И.2, МИТРОФАНОВ И.Г.2, КОЗЫРЕВ А.С.2, ЛИТВАК М.Л.2, САНИН А.Б.2, ТРЕТЬЯ
АЖ Том: 94Номер: 9 Год: **2017** Страницы: 778-792
Изучение нестационарных процессов на Солнце представляет большой интерес, и в последние годы многоволновые наблюдения излучения и регистрация магнитных полей проводятся как наземными телескопами, так и несколькими специализированными космическими аппаратами на околоземных орбитах. Однако получение новой надежной информации о жестком рентгеновском излучении остается востребованным, особенно, если соответствующие космические аппараты обеспечивают дополнительную информацию, например, при наблюдениях вспышек с иных направлений, отличающихся от направления Солнце-Земля. В статье представлен каталог мощных солнечных вспышек, зарегистрированных прибором High Energy Neutron Detector(HEND), разработанным в Институте космических исследований РАН. Прибор HEND установлен на космическом аппарате "2001 Mars Odyssey", успешно работал при полете к Марсу и в настоящее время функционирует на околомарсианской орбите. Помимо нейтронов, аппаратура HEND чувствительна к жесткому рентгеновскому (до 300 кэВ) и гамма-излучению (выше 300 кэВ). Это излучение регистрируется двумя сцинтилляторами: внешний сцинтиллятор регистрирует фотоны с энергиями выше 40 кэВ, внутренний - свыше 200 кэВ. При создании каталога проведена новая процедура калибровки данных. Кратко обсуждаются методы калибровки внешнего детектора. Для 60 наиболее мощных солнечных вспышек на видимой с Земли и обратной сторонах Солнца приведены временные профили излучения, суммированные по всем каналам рентгеновского, а в некоторых случаях и гамма-диапазонов, спектры и характеристики их степенной аппроксимации. Кратко обсуждаются результаты прежних работ по изучению Солнца с аппаратурой HEND и возможности дальнейшего использования этих данных.

"Рентгеновское и гамма-излучение солнечных вспышек"

Лысенко А Л, Фредерикс Д Д, Флейшман Г Д, Аптекарь Р Л, Алтынцев А Т, Голенецкий С В, Свинкин Д С, Уланов М В, Цветкова А Е, Ридная А В
УФН, принята к публикации **2020**
Приводится краткий обзор современного состояния и актуальных проблем физики солнечных вспышек, которые можно прояснить методами рентгеновской и гамма-астрономии. Подробно рассмотрены несколько вопросов, среди которых – условия и механизмы ускорения электронов во вспышке, распределение вспышечной энергии между тепловой и нетепловой компонентами, гамма-излучение вспышек и его динамика, пространственная структура источников в рентгеновском и гамма-диапазонах. В данном контексте обсуждаются последние результаты российско-американского эксперимента Konus-Wind, отметившего в 2019 г. 25-летие непрерывной работы в космосе.

Особенности развития длительных потоков высокоэнергичного гамма-излучения на разных стадиях солнечных вспышек.

Минасянц Г.С., Минасянц Т.М., Томозов В.М.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том 5. **2019**. № 3. С. 11–20

https://naukaru.ru/ru/storage/view/39748

07.06.2011, 04.08.2011, 9 августа 2011, 6 сентября 2011, 07.09.2011,, 27.01.2012, 17.05.2012, 3 июня 2012, 11.04.2013, 13.05.2013, 11.10.2013, 25.10.2013, 28.10.2013, 25.02.2014, 01.09.2014, 10.09.2017

Рассмотрены характеристики длительных потоков гамма-излучения с энергиями квантов >100 МэВ на разных стадиях вспышечных событий. Для анализа использовались данные наблюдений с временным разрешением 1 мин на космическом аппарате Fermi с помощью Large Area Telescope (LAT). Подтвержден наиболее вероятный процесс возникновения гамма-квантов высоких энергий на импульсной фазе вспышек (6 событий). Ускорение частиц, возникающих в результате вспышечного энерговыделения (при диссипации токового слоя), происходит при взаимодействии с фронтом ударной волны коронального выброса массы (КВМ), который одновременно развивается в той же активной области. Ядерные взаимодействия ускоренных протонов (>500 МэВ) с ионами плазмы приводят в дальнейшем к возникновению высокоэнергичных квантов гамма-излучения. Установлено, что взаимодействие вспышечного потока и высокоскоростного КВМ на импульсной фазе вспышки происходит в довольно ограниченных временных интервалах — от 2 до 16 мин. В рассмотренных событиях зарегистрирована непосредственная связь между максимальными значениями потоков гамма-излучения max γ>100 МэВ F и скоростью КВМ. Для импульсных фаз вспышек характерны высокие максимальные значения потоков гаммаизлучения max γ>100 МэВ F : 3.5·10–4 –1.3·10–2 см–2 с –1 . При этом значение max γ>100 МэВ F =0.013 см–2 с –1 оказалось самым высоким для событий, наблюдавшихся на Fermi/LAT с 2008 по 2017 г. В процессе эволюции КВМ, движущихся со сверхзвуковой скоростью в короне Солнца, образуются ударные волны, которые являются основными энергетическими источниками ускоренных частиц на главной стадии длительных вспышек. Однако в некоторых случаях влияние ударных волн на ускорение частиц оказывается наибольшим на кратковременной импульсной фазе вспышки. С целью выявления параметров, которые могут оказывать наибольшее влияние на генерацию высокоэнергичного гамма-излучения, было проведено их сопоставление для 17 вспышечных событий. Наиболее значимым параметром оказался интервал времени совместного действия вспышечного процесса и ударных волн КВМ. Установлено, что при одновременном развитии вспышечного процесса и сопровождающего вспышку КВМ происходит наиболее эффективное ускорение частиц, приводящее к появлению максимальных потоков высокоэнергичных гамма-квантов.

Солнечные вспышки с продолжительным гамма-излучением и характеристики потоков протонов высоких энергий.

Томозов В.М., Минасянц Г.С., Минасянц Т.М.

СОЛНЕЧНО-ЗЕМНАЯ ФИЗИКА Том 9 № 4 , 2023 С. 38–43.

https://naukaru.ru/ru/storage/viewWindow/138048

Описаны характеристики потоков продолжительного гамма-излучения с энергиями квантов >100 МэВ, полученные по данным космического аппарата Fermi/LAT, на импульсной фазе наиболее энергичных вспышечных явлений. Проведено сравнение данных GOES о потоках протонов с энергиями более 500 МэВ с данными Fermi/LAT о потоках гамма-излучения за 2010-2018 гг. По результатам анализа данных о 32 гамма-вспышках из каталога Fermi/LAT было показано, что вспышечные явления можно отнести к трем различным типам: тип 1 — потоки гамма-излучения сопровождаются потоками энергичных протонов; тип 2 — гамма-излучение регистрируется при отсутствии возрастаний потоков протонов; тип 3 — во время возрастаний потоков энергичных протонов не регистрируются гамма-потоки. Отмечен всплесковый характер выделения энергии в жестком рентгеновском диапазоне у некоторых вспышек. **7 марта 2012, 22 мая 2013, 11 октября 2013, 6 сентября 2017, 10 сентября 2017**

ГАММА-ВСПЫШКИ И КОМПЛЕКСЫ АКТИВНОСТИ НА СОЛНЦЕ

ТОМОЗОВ В.М.[1], ЯЗЕВ С.А.*[1], ИСАЕВА Е.С.[1]

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Проведен анализ мощных вспышечных событий из каталога Share и др. с длительной фазой гамма-излучения с целью объяснения особенностей импульсной и длительных фаз таких вспышек и выявления их связи с комплексами активности и корональными дырами. Показано, что 74% таких событий оказались тесно связанными с комплексами активности. Качественно продемонстрирована связь процессов ускорения частиц в ходе развития вспышки с изменениями магнитной топологии во вспышечной области и с эволюцией коронального выброса массы. Обсуждаются возможная связь корональных дыр с комплексами активности и роль “обменного” пересоединения в этих процессах.

НАБЛЮДЕНИЯ РЕНТГЕНОВСКИХ ВСПЫШЕК 14 ИЮЛЯ 2005 ГОДА С МАРСИАНСКОЙ И ОКОЛОЗЕМНОЙ ОРБИТ

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Пулково, **2009, File**

We analyze the X-ray observations of two limb flares of 14.July 2005 registered on the board of the spacecraft MARS Odyssey with the equipments developed by Space Research Institute of RAS. Besides we obtain spectra and images of these flares from the RHESSI data for a few moments. Both flares are limb-occulted events as they seen from the Earth while from the Mars they observed on the solar disc. We discuss homologic properties of flares, possible stereoscopic effects, features subsequent perturbation in the interplanetary space.