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

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Observations of Energetic-Particle Population Enhancements along Intermittent Structures near the Sun from Parker Solar Probe

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Observations at 1 au have confirmed that enhancements in measured energetic particle fluxes are statistically associated with "rough" magnetic fields, i.e., fields having atypically large spatial derivatives or increments, as measured by the Partial Variance of Increments (PVI) method. One way to interpret this observation is as an association of the energetic particles with trapping or channeling within magnetic flux tubes, possibly near their boundaries. However, it remains unclear whether this association is a transport or local effect; i.e., the particles might have been energized at a distant location, perhaps by shocks or reconnection, or they might experience local energization or re-acceleration. The Parker Solar Probe (PSP), even in its first two orbits, offers a unique opportunity to study this statistical correlation closer to the corona. As a first step, we analyze the separate correlation properties of the energetic particles measured by the \isois instruments during the first solar encounter. The distribution of time intervals between a specific type of event, i.e., the waiting time, can indicate the nature of the underlying process. We find that the \isois observations show a power-law distribution of waiting times, indicating a correlated (non-Poisson) distribution. Analysis of low-energy \isois data suggests that the results are consistent with the 1 au studies, although we find hints of some unexpected behavior. A more complete understanding of these statistical distributions will provide valuable insights into the origin and propagation of solar energetic particles, a picture that should become clear with future PSP orbits.

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

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Astronomy & Astrophysics , Lett.   **2021**
https://www.aanda.org/articles/aa/pdf/forth/aa41009-21.pdf
https://arxiv.org/pdf/2109.05570.pdf

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

Radial dependence of solar energetic particle peak fluxes and fluences
Multispacecraft observations based on Parker Solar Probe, Solar Orbiter, and near-Earth particle detectors

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Context. We present a list of solar energetic particle (SEP) events detected by instruments on board the Solar and Heliospheric Observatory (SOHO), Parker Solar Probe (PSP), and Solar Orbiter between 2021 and 2023. The investigation focuses on identifying the peak flux and the fluence of SEP events in four energy ranges from 10.5 to 40 MeV, as observed by PSP or Solar Orbiter at heliospheric distances shorter than 1 AU and by SOHO at the Sun-Earth L1 Lagrangian point.
Aims. Based on the data from these events, we conduct a statistical analysis to study the radial dependence of the SEP proton peak flux and fluence at different energies.
Methods. We identified 42 SEP events with enhanced proton flux that were observed simultaneously by at least two out of three spacecraft (SOHO, PSP, and Solar Orbiter). These events were further selected based on a criterion of a difference smaller than a 30° difference in longitudinal separation between the magnetic footpoints of the two spacecraft. For the selected events, we used a linear interpolation method to compute the proton peak flux and fluence in four energy ranges and quantified their radial dependence as a function of Rα, where R is the radial distance of the observer from the Sun.
Results. The peak flux and fluence of the SEP events display the following radial dependence: The average values of α across all energies range between about −3.7 and −2 for the peak fluxes and between −2.7 and −1.4 for the fluences. We also obtained the energy dependence of |α|, which decreases with increasing energy. Additionally, based on theoretical functions, we find that the SEP source and transport parameters may have a significant impact on α(E), and the measurement-derived |α(E)| values and their distribution fall within the range of theoretical predictions.
Conclusions. (1) Despite the uncertainties arising from the low statistics and the longitudinal influence, the radial dependence of the peak flux agrees with the upper limit R−3 predicted by previous studies. (2) The radial dependence on the fluence R−2 tends to be weaker than the radial decay of the peak flux. (3) As the proton energy increases, the proton mean free path increases, and the adiabatic cooling effect modifies the proton energy. As a result, the peak flux and fluence decay more significantly with increasing radial distance for lower-energy particles.
March 21, 2022
Solar Orbiter Nugget #55 2025 **https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-radial-dependence-of-solar-energetic-particle-peak-fluxes-and-fluences**

Evidence of Time-Dependent Diffusive Shock Acceleration in the 2022 September 5 Solar Energetic Particle Event

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https://arxiv.org/pdf/2506.20322
https://iopscience.iop.org/article/10.3847/1538-4357/ae1227/pdf
On **2022 September 5,** a large solar energetic particle (SEP) event was detected by Parker Solar Probe (PSP) and Solar Orbiter (SolO), at heliocentric distances of 0.07 and 0.71 au, respectively. PSP observed an unusual velocity-dispersion signature: particles below ~1 MeV exhibited a normal velocity dispersion, while higher-energy particles displayed an inverse velocity arrival feature, with the most energetic particles arriving later than those at lower energies. The maximum energy increased from about 20-30 MeV upstream to over 60 MeV downstream of the shock. The arrival of SEPs at PSP was significantly delayed relative to the expected onset of the eruption. In contrast, SolO detected a typical large SEP event characterized by a regular velocity dispersion at all energies up to 100 MeV. To understand these features, we simulate particle acceleration and transport from the shock to the observers with our newly developed SEP model - Particle ARizona and MIchigan Solver on Advected Nodes (PARMISAN). Our results reveal that the inverse velocity arrival and delayed particle onset detected by PSP originate from the time-dependent diffusive shock acceleration processes. After shock passage, PSP's magnetic connectivity gradually shifted due to its high velocity near perihelion, detecting high-energy SEPs streaming sunward. Conversely, SolO maintained a stable magnetic connection to the strong shock region where efficient acceleration was achieved. These results underscore the importance of spatial and temporal dependence in SEP acceleration at interplanetary shocks, and provide new insights to understand SEP variations in the inner heliosphere.

Three-stage Acceleration of Solar Energetic Particles Detected by Parker Solar Probe

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https://iopscience.iop.org/article/10.3847/2041-8213/ad4a79/pdf

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

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

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A&A **2020**
https://arxiv.org/pdf/2011.08329.pdf

Context:In 2020 May-June, six solar energetic ion events were observed by the Parker Solar Probe/ISoIS instrument suite at 0.35 AU from the Sun. From standard velocity-dispersion analysis, the apparent ion path length is 0.625 AU at the onset of each event. Aims:We develop a formalism for estimating the path length of random-walking magnetic field lines, to explain why the apparent ion pathlength at event onset greatly exceeds the radial distance from the Sun for these events. Methods:We developed analytical estimates of the average increase in pathlength of random-walking magnetic field lines, relative to the unperturbed mean field. Monte Carlo simulations of fieldline and particle trajectories in a model of solar wind turbulence are used to validate the formalism and study the path lengths of particle guiding-center and full-orbital trajectories. The formalism is implemented in a global solar wind model, and results are compared with ion pathlengths inferred from ISoIS observations. Results:Both a simple estimate and a rigorous theoretical formulation are obtained for fieldlines' pathlength increase as a function of pathlength along the large-scale field. From simulated fieldline and particle trajectories, we find that particle guiding centers can have pathlengths somewhat shorter than the average fieldline pathlength, while particle orbits can have substantially larger pathlengths due to their gyromotion with a nonzero effective pitch angle. Conclusions:The long apparent path length during these solar energetic ion events can be explained by 1) a magnetic field line path length increase due to the field line random walk, and 2) particle transport about the guiding center with a nonzero effective pitch angle. Our formalism for computing the magnetic field line path length, accounting for turbulent fluctuations, may be useful for application to solar particle transport in general. **2020 May 21-June 3**

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

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Aims. The Parker Solar Probe (PSP) orbit provides an opportunity to study the inner heliosphere at distances closer to the Sun than previously possible. Due to the solar minimum conditions, the initial orbits of PSP yielded only a few solar energetic particle (SEP) events for study. Recently during the fifth orbit, at distances from 0.45 to 0.3 au, the energetic particle suite on PSP, Integrated Science Investigation of the Sun (IS⊙IS), observed a series of six SEP events, adding to the limited number of SEP events studied inside of 0.5 au. Variations in the H and He spectra and the He/H abundance ratio are examined and discussed in relation to the identified solar source regions and activity.

Methods. IS⊙IS measures the energetic particle environment from ~20 keV to >100 MeV/nuc. Six events were selected using the ~1 MeV proton intensities, and while small, they were sufficient to calculate proton and helium spectra from ~1 to ~10 MeV/nuc. For the three larger events, the He/H ratio as a function of energy was determined. Using the timing of the associated radio bursts, solar sources were identified for each event and the eruptions were examined in extreme ultraviolet emission.

Results. The largest of the selected events has peak ~1 MeV proton intensities of 3.75 (cm2 sr s MeV)−1. Within uncertainties, the He and H spectra have similar power law forms with indices ranging from −2.3 to −3.3. For the three largest events, the He/H ratios are found to be relatively energy independent; however, the ratios differ substantially with values of 0.0033 ± 0.0013, 0.177 ± 0.047, and 0.016 ± 0.009. An additional compositional variation is evident in both the 3He and electron signatures. These variations are particularly interesting as the three larger events are likely a result of similar eruptions from the same active region.

Energetic Particle Increases Associated with Stream Interaction Regions

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https://iopscience.iop.org/article/10.3847/1538-4365/ab4c38/pdf

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

Investigation of Inverse Velocity Dispersion in a Solar Energetic Particle Event Observed by Solar Orbiter

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Inverse velocity dispersion (IVD) events, characterized by higher-energy particles arriving later than lower-energy particles, challenge the classical understanding of SEP events and are increasingly observed by spacecraft, such as Parker Solar Probe (PSP) and Solar Orbiter (SolO). However, the mechanisms underlying IVD events remain poorly understood. This study aims to investigate the physical processes responsible for long-duration IVD events by analyzing the SEP event observed by SolO on **2022 June 7**. We explore the role of evolving shock connectivity, particle acceleration at interplanetary (IP) shocks, and cross-field transport in shaping the observed particle this http URL utilize data from Energetic Particle Detector (EPD) suite onboard SolO to analyze the characteristics of the IVD, and model the event using the Heliospheric Energetic Particle Acceleration and Transport (HEPAT) model. The IVD event exhibited a distinct and long-duration IVD signature, across proton energies from 1 to 20 MeV and lasting for approximately 10 hours. Simulations suggest that evolving shock connectivity and the evolution of shock play a primary role in the IVD signature, with SolO transitioning from shock flank to nose over time, resulting in a gradual increase in maximum particle energy along the field line. Furthermore, model results show that limited cross-field diffusion can influence both the nose energy and the duration of the IVD event. This study demonstrates that long-duration IVD events are primarily driven by evolving magnetic connectivity along a non-uniform shock that evolves over time, where the connection moves to more efficient acceleration sites as the shock propagates farther from the Sun. Other mechanisms, such as acceleration time at the shock, may also contribute to the observed IVD features.

Solar Orbiter Science Nuggets #68 **2025** https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-inverse-velocity-dispersion-in-solar-energetic-particle-events

Modelling two Energetic Storm Particle Events Observed by Solar Orbiter Using the Combined EUHFORIA and iPATH Models

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By coupling the EUropean Heliospheric FORcasting Information Asset (EUHFORIA) and the improved Particle Acceleration and Transport in the Heliosphere (iPATH) model, two energetic storm particle (ESP) events, originating from the same active region (AR 13088) and observed by Solar Orbiter (SolO) on **August 31 2022 and September 05 2022**, are modelled. While both events originated from the same active region, they exhibited notable differences, including: 1) the August ESP event lasted for 7 hours, while the September event persisted for 16 hours; 2) The time intensity profiles for the September event showed a clear cross-over upstream of the shock where the intensity of higher energy protons exceeds those of lower energy protons, leading to positive (``reverse") spectral indices prior to the shock passage. For both events, our simulations replicate the observed duration of the shock sheath, depending on the deceleration history of the CME. Imposing different choices of escaping length scale, which is related to the decay of upstream turbulence, the modelled time intensity profiles prior to the shock arrival also agree with observations. In particular, the cross-over of this time profile in the September event is well reproduced. We show that a ``reverse" upstream spectrum is the result of the interplay between two length scales. One characterizes the decay of upstream shock accelerated particles, which are controlled by the energy-dependent diffusion coefficient, and the other characterizes the decay of upstream turbulence power, which is related to the process of how streaming protons upstream of the shock excite Alfvén waves. Simulations taking into account real-time background solar wind, the dynamics of the CME propagation, and upstream turbulence at the shock front are necessary to thoroughly understand the ESP phase of large SEP events.

Solar Orbiter Science Nuggets #25 Jan **2024** https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-modelling-two-consecutive-energetic-storm-particle-events-observed-by-solar-orbiter

Solar Energetic Particles Produced by a Slow Coronal Mass Ejection at ~0.25 au

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We present an analysis of **Parker Solar Probe (PSP)** IS⊙IS observations of ~30–300 keV n−1 ions on **2018 November 11** when PSP was about 0.25 au from the Sun. Five hours before the onset of a solar energetic particle (SEP) event, a coronal mass ejection (CME) was observed by STEREO-A/COR2, which crossed PSP about a day later. No shock was observed locally at PSP, but the CME may have driven a weak shock earlier. The SEP event was dispersive, with higher energy ions arriving before the lower energy ones. Timing suggests the particles originated at the CME when it was at ~7.4R ⊙. SEP intensities increased gradually from their onset over a few hours, reaching a peak, and then decreased gradually before the CME arrived at PSP. The event was weak, having a very soft energy spectrum (−4 to −5 spectral index). The earliest arriving particles were anisotropic, moving outward from the Sun, but later, the distribution was observed to be more isotropic. We present numerical solutions of the Parker transport equation for the transport of 30–300 keV n−1 ions assuming a source comoving with the CME. Our model agrees well with the observations. The SEP event is consistent with ion acceleration at a weak shock driven briefly by the CME close to the Sun, which later dissipated before arriving at PSP, followed by the transport of ions in the interplanetary magnetic field.

Small, Low-energy, Dispersive Solar Energetic Particle Events Observed by Parker Solar Probe

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The Energetic Particle Instrument–Low Energy (EPI-Lo) experiment has detected several weak, low-energy (~30–300 keV nucleon–1) solar energetic particle (SEP) events during its first two closest approaches to the Sun, providing a unique opportunity to explore the sources of low-energy particle acceleration. As part of the Parker Solar Probe (PSP) Integrated Science Investigation of the Sun (IS⊙IS) suite, EPI-Lo was designed to investigate the physics of energetic particles; however, in the special lowest-energy "time-of-flight only" product used in this study, it also responds to solar photons in a subset of approximately sunward-looking apertures lacking special light-attenuating foils. During the first three perihelia, in a frame rotating with the Sun, PSP undergoes retrograde motion, covering a 17° heliographic longitudinal range three times during the course of the ~11-day perihelion passes, permitting a unique spatial and temporal study into the location, correlation, and persistence of previously unmeasurable SEPs. We examine the signatures of these SEPs (during the first PSP perihelion pass only) and the connection to possible solar sources using remote observations from the Solar Dynamics Observatory (SDO), the Solar TErrestrial RElations Observatory (STEREO), and the ground-based Global Oscillation Network Group (GONG). The orientation of the Sun relative to STEREO, SDO, and GONG makes such identifications challenging, but we do have several candidates, including an equatorial coronal hole at a Carrington longitude of ~335°. To analyze observations from EPI-Lo, which is a new type of particle instrument, we examine instrumental effects and provide a preliminary separation of the ion signal from the photon background.

Energetic Particle Measurements with Solar Orbiter

George C. **Ho**
Fleishman's webinar 19 June **2020**
https://youtu.be/zyuMlQh6_Sw

Energetic Particle Observations from the Parker Solar Probe Using Combined Energy Spectra from the IS⊙IS Instrument Suite

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The **Integrated Science Investigations of the Sun (IS⊙IS)** instrument suite includes two Energetic Particle instruments: EPI-Hi, designed to measure ions from ~1 to 200 MeV nuc−1, and EPI-Lo, designed to measure ions from ~20 to ~15 MeV nuc−1. We present an analysis of eight energetic proton events observed across the energy range of both instruments during Parker Solar Probe's (PSP) first two orbits in order to examine their combined energy spectra. Background corrections are applied to help resolve spectral breaks between the two instruments and are shown to be effective. In doing so we demonstrate that even in the early stages of calibration, IS⊙IS is capable of producing reliable spectral observations across broad energy ranges. In addition to making groundbreaking measurements very near the Sun, IS⊙IS also characterizes energetic particle populations over a range of heliocentric distances inside 1 au. During the first two orbits, IS⊙IS observed energetic particle events from a single corotating interaction region (CIR) at three different distances from the Sun. The events are separated by two Carrington rotations and just 0.11 au in distance; however, the relationship shown between proton intensities and proximity of the spacecraft to the source region shows evidence of the importance of transport effects on observations of energetic particles from CIRs. Future IS⊙IS observations of similar events over larger distances will help disentangle the effects of CIR-related acceleration and transport. We apply similar spectral analyses to the remaining five events, including four that are likely related to stream interaction regions (SIRs) and one solar energetic particle (SEP) event.

The Solar Origin of Particle Events Measured by Parker Solar Probe

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During the second solar encounter phase of Parker Solar Probe (PSP), two small solar energetic particle (SEP) events were observed by the Integrated Science Investigation of the Sun, on **2019 April 2 and 4**. At the time, PSP was approaching its second perihelion at a distance of ~24.8 million kilometers from the solar center, it was in near-radial alignment with STEREO-A and in quadrature with Earth. During the two SEP events multiple narrow ejections and a streamer-blowout coronal mass ejection (SBO-CME) originated from a solar region situated eastward of PSP. We analyze remote-sensing observations of the solar corona, and model the different eruptions and how PSP was connected magnetically to the solar atmosphere to determine the possible origin of the two SEP events. We find that the SEP event on April 2 was associated with the two homologous ejections from active region 12738 that included two surges and EUV waves occurring in quick succession. The EUV waves appear to merge and were fast enough to form a shock in the low corona. We show that the April 4 SEP event originates in the SBO-CME. Our modeling work suggests that formation of a weak shock is likely for this CME.

Magnetic reconnection as a mechanism to produce multiple proton populations and beams locally in the solar wind

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Context. Spacecraft observations early revealed frequent multiple proton populations in the solar wind. Decades of research on their origin have focused on processes such as magnetic reconnection in the low corona and wave-particle interactions in the corona and locally in the solar wind.
Aims.This study aims to highlight that multiple proton populations and beams are also produced by magnetic reconnection occurring locally in the solar wind.
Methods. We use high resolution **Solar Orbiter** proton velocity distribution function measurements, complemented by electron and magnetic field data, to analyze the association of multiple proton populations and beams with magnetic reconnection during a period of slow Alfvénic solar wind on **16 July 2020**.
Results. At least 6 reconnecting current sheets with associated multiple proton populations and beams, including a case of magnetic reconnection at a switchback boundary, are found during this day. This represents 2% of the measured distribution functions. We discuss how this proportion may be underestimated, and how it may depend on solar wind type and distance from the Sun. Conclusions. Although suggesting a likely small contribution, but which remains to be quantitatively assessed, Solar Orbiter observations show that magnetic reconnection must be considered as one of the mechanisms that produce multiple proton populations and beams locally in the solar wind.

Observations of the 2019 April 4 Solar Energetic Particle Event at the Parker Solar Probe

R. A. **Leske**, E. R. Christian, C. M. S. Cohen, A. C. Cummings, A. J. Davis, M. I. Desai, J. Giacalone, M. E. Hill, C. J. Joyce, S. M. Krimigis, A. W. Labrador, O. Malandraki, W. H. Matthaeus, D. J. McComas, R. L. McNutt Jr., R. A. Mewaldt, D. G. Mitchell, A. Posner, J. S. Rankin, E. C. Roelof, N. A. Schwadron, E. C. Stone, J. R. Szalay, M. E. Wiedenbeck, A. Vourlidas, S. D. Bale, R. J. MacDowall, M. Pulupa, J. C. Kasper, R. C. Allen, A. W. Case, K. E. Korreck, R. Livi, M. L. Stevens, P. Whittlesey, B. Poduval

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https://iopscience.iop.org/article/10.3847/1538-4365/ab5712/pdf

A solar energetic particle event was detected by the Integrated Science Investigation of the Sun (ISOIS) instrument suite on Parker Solar Probe (PSP) on **2019 April 4** when the spacecraft was inside of 0.17 au and less than 1 day before its second perihelion, providing an opportunity to study solar particle acceleration and transport unprecedentedly close to the source. The event was very small, with peak 1 MeV proton intensities of ~0.3 particles (cm^2 sr s MeV)^-1, and was undetectable above background levels at energies above 10 MeV or in particle detectors at 1 au. It was strongly anisotropic, with intensities flowing outward from the Sun up to 30 times greater than those flowing inward persisting throughout the event. Temporal association between particle increases and small brightness surges in the extreme-ultraviolet observed by the Solar TErrestrial RElations Observatory, which were also accompanied by type III radio emission seen by the Electromagnetic Fields Investigation on PSP, indicates that the source of this event was an active region nearly 80 degrees east of the nominal PSP magnetic footpoint. This suggests that the field lines expanded over a wide longitudinal range between the active region in the photosphere and the corona.

Energetic Electron Observations by Parker Solar Probe/IS⊙IS during the First Widespread SEP Event of Solar Cycle 25 on 2020 November 29

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At the end of 2020 November, two coronal mass ejections (CMEs) erupted from the Sun and propagated through the interplanetary medium in the direction of Parker Solar Probe while the spacecraft was located at ∼0.81 au. The passage of these interplanetary CMEs (ICMEs) starting on November 29 (DOY 334) produced the largest enhancement of energetic ions and electrons observed by the Integrated Science Investigation of the Sun (IS⊙IS) energetic particle instrument suite on board Parker Solar Probe during the mission's first eight orbits. This was also the first spatially widespread solar energetic particle event observed in solar cycle 25. We investigate several key characteristics of the energetic electron event including the time profile and anisotropy distribution of near-relativistic electrons as measured by IS⊙IS's low-energy Energetic Particle Instrument (EPI-Lo) and compare these observations with contextual data from the Parker Solar Probe Fields Experiment magnetometer. These are the first electron anisotropy measurements from IS⊙IS/EPI-Lo, demonstrating that the instrument can successfully produce these measurements. We find that the electron count rate peaks at the time of the shock driven by the faster of the two ICMEs, implying that the shock parameters of this ICME are conducive to the acceleration of electrons.

Additionally, the angular distribution of the electrons during the passage of the magnetic clouds associated with the ICMEs shows significant anisotropy, with electrons moving primarily parallel and antiparallel to the local magnetic field as well as bidirectionally, providing an indication of the ICME's magnetic topology and connectivity to the Sun or magnetic structures in the inner heliosphere.

The Energetic Particle Detector (EPD)

Energetic particle instrument suite for the Solar Orbiter mission

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A&A 642, A7 (**2020**)
https://www.aanda.org/articles/aa/pdf/forth/aa35287-19.pdf
https://doi.org/10.1051/0004-6361/201935287
https://www.aanda.org/articles/aa/pdf/2020/10/aa35287-19.pdf

After decades of observations of solar energetic particles (SEP) from space-based observatories, relevant questions on particle injection, transport, and acceleration remain open. To address these scientific topics, accurate measurements of the particle properties in the inner heliosphere are needed. In this paper we describe the Energetic Particle Detector (EPD), an instrument suite that is part of the scientific payload aboard the Solar Orbiter mission. Solar Orbiter will approach the Sun as close as 0.28 au and will provide extra-ecliptic measurements beyond ∼ 30◦ heliographic latitude during the later stages of the mission. The EPD will measure electrons, protons, and heavy ions with high temporal resolution over a wide energy range, from suprathermal energies up to several hundreds of megaelectronvolts/nucleons. For this purpose, EPD is composed of four units: the SupraThermal Electrons and Protons (STEP), the Electron Proton Telescope (EPT), the Suprathermal Ion Spectrograph (SIS), and the High-Energy Telescope (HET) plus the Instrument Control Unit (ICU) that serves as power and data interface with the spacecraft. The low-energy population of electrons and ions will be covered by STEP and EPT, while the high-energy range will be measured by HET. Elemental and isotopic ion composition measurements will be performed by SIS and HET, allowing full particle identification from a few kiloelectronvolts up to several hundreds of megaelectronvolts/nucleons. Angular information will be provided by the separate look directions from different sensor heads, on the ecliptic plane along the Parker spiral magnetic field both forward and backwards, and out of the ecliptic plane observing both northern and southern hemispheres. The unparalleled observations of EPD will provide key insights into long-open and crucial questions about the processes that govern energetic particles in the inner heliosphere.

2. Science objectives of the Energetic Particle Detector (Injection, Acceleration mechanisms, Transport, Additional science targets)

Seed Population Pre-Conditioning and Acceleration Observed by Parker Solar Probe

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https://arxiv.org/pdf/1912.02888.pdf
https://iopscience.iop.org/article/10.3847/1538-4365/ab5527/pdf

A series of solar energetic particle (SEP) events were observed at Parker Solar Probe (PSP) by the Integrated Science Investigation of the Sun (\ISOIS) during the period from **April 18, 2019 through April 24, 2019**. The PSP spacecraft was located near 0.48 au from the Sun on Parker spiral field lines that projected out to 1 au within ∼25◦ of near Earth spacecraft. These SEP events, though small compared to historically large SEP events, were amongst the largest observed thus far in the PSP mission and provide critical information about the space environment inside 1 au during SEP events. During this period the Sun released multiple coronal mass ejections (CMEs). One of these CMEs observed was initiated on **April 20, 2019** at 01:25 UTC, and the interplanetary CME (ICME) propagated out and passed over the PSP spacecraft. Observations by the Electromagnetic Fields Investigation (FIELDS) show that the magnetic field structure was mostly radial throughout the passage of the compression region and the plasma that followed, indicating that PSP did not directly observe a flux rope internal to the ICME, consistent with the location of PSP on the ICME flank. Analysis using relativistic electrons observed near Earth by the Electron, Proton and Alpha Monitor (EPAM) on the Advanced Composition Explorer (ACE) demonstrates the presence of electron seed populations (40--300 keV) during the events observed. The energy spectrum of the \ISOIS~ observed proton seed population below 1 MeV is close to the limit of possible stationary state plasma distributions out of equilibrium. \ISOIS~ observations reveal the \revise{enhancement} of seed populations during the passage of the ICME, which \revise{likely indicates a key part} of the pre-acceleration process that occurs close to the Sun.

3He-rich Solar Energetic Particle Observations at the Parker Solar Probe and near Earth

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2020 ApJS 246 42
https://iopscience.iop.org/article/10.3847/1538-4365/ab5963/pdf
The Integrated Science Investigation of the Sun (IS⊙IS) instrument suite on the Parker Solar Probe (PSP) spacecraft is making in situ observations of energetic ions and electrons closer to the Sun than any previous mission. Using data collected during its first two orbits, which reached perihelion distances of 0.17 au, we have searched for ^{3}He-rich solar energetic particle (SEP) events under very quiet solar minimum conditions. On **2019**-110–111 (**April 20–21**), ^{3}He-rich SEPs were observed at energies near 1 MeV nucleon–1 in association with energetic protons, heavy ions, and electrons. This activity was also detected by the Ultra-Low-Energy Isotope Spectrometer and the Electron, Proton, and Alpha Monitor instruments on the Advanced Composition Explorer (ACE) spacecraft located near Earth, 0.99 au from the Sun. At that time, PSP and ACE were both magnetically connected to locations near the west limb of the Sun. Remote sensing measurements showed the presence of type III radio bursts and also helical jets from this region of the Sun. This combination of observations is commonly associated with ^{3}He-rich SEP acceleration on the Sun. AR 12738, which was located at Carrington coordinates from which numerous X-ray flares were observed over a period of more than 6 months, was identified as the source of the ^{3}He-rich events. This region was also the source of several other SEP events detected at PSP or ACE. Aside from the period in 2019 April, IS⊙IS did not observe any other ^{3}He-rich SEPs during orbits 1 and 2.

First year of energetic particle measurements in the inner heliosphere with Solar Orbiter's Energetic Particle Detector

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A&A **2021**
https://arxiv.org/pdf/2108.02020.pdf
Solar Orbiter strives to unveil how the Sun controls and shapes the heliosphere and fills it with energetic particle radiation. To this end, its Energetic Particle Detector (EPD) has now been in operation, providing excellent data, for just over a year. EPD measures suprathermal and energetic particles in the energy range from a few keV up to (near-) relativistic energies (few MeV for electrons and about 500 MeV/nuc for ions). We present an overview of the initial results from the first year of operations and we provide a first assessment of issues and limitations. During this first year of operations of the Solar Orbiter mission, EPD has recorded several particle events at distances between 0.5 and 1 au from the Sun. We present dynamic and time-averaged energy spectra for ions that were measured with a combination of all four EPD sensors, namely: the SupraThermal Electron and Proton sensor (STEP), the Electron Proton Telescope (EPT), the Suprathermal Ion Spectrograph (SIS), and the High-Energy Telescope (HET) as well as the associated energy spectra for electrons measured with STEP and EPT. We illustrate the capabilities of the EPD suite using the **10-11 December 2020** solar particle event. This event showed an enrichment of heavy ions as well as 3He, for which we also present dynamic spectra measured with SIS. The high anisotropy of electrons at the onset of the event and its temporal evolution is also shown using data from these sensors. We discuss the ongoing in-flight calibration and a few open instrumental issues using data from the **21 July and the 10-11 December 2020** events and give guidelines and examples for the usage of the EPD data. We explain how spacecraft operations may affect EPD data and we present a list of such time periods in the appendix. A list of the most significant particle enhancements as observed by EPT during this first year is also provided.
Table A.1. List of electron intensity enhancements observed by EPT during the first year of observations.
Table A.2. List of ion intensity enhancements observed by EPT during the first year of observations.

Energetic storm particles (near shock) ESP

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

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

M. **Battarbee**, J. Guo, S. Dalla, R. Wimmer-Schweingruber, B. Swalwell, D. J. Lawrence
A&A 612, A116 **2017**
https://arxiv.org/pdf/1706.08458.pdf
http://sci-hub.tw/https://www.aanda.org/articles/aa/abs/2018/04/aa31451-17/aa31451-17.html
. We distinguish different time profile shapes for well-connected and weakly connected observers, and find our onset time analysis to agree with this distinction. At select observers, we identify an additional low-energy component of **Energetic Storm Particles** (ESPs).

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

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

MULTI-SPACECRAFT ANALYSIS OF ENERGETIC HEAVY ION AND INTERPLANETARY SHOCK PROPERTIES IN ENERGETIC STORM PARTICLE EVENTS NEAR 1 au

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2016 *ApJ* **831** 153
We examine the longitude distribution of and relationship between interplanetary (IP) shock properties and ~0.1–20 MeV nucleon^{-1} O and Fe ions during **seven multi-spacecraft energetic storm particle (ESP)** events at 1 au. These ESP events were observed at two spacecraft and were primarily associated with low Mach number, quasi-perpendicular shocks. Key observations include the following: (i) the Alfvén Mach number increased from east to west of the coronal mass ejection source longitude, while the shock speed, compression ratios, and obliquity showed no clear dependence; (ii) the O and Fe time intensity profiles and peak intensities varied significantly between longitudinally separated spacecraft observing the same event, the peak intensities being larger near the nose and smaller along the flank of the IP shock; (iii) the O and Fe peak intensities had weak to no correlations with the shock parameters; (iv) the Fe/O time profiles showed intra-event variations upstream of the shock that disappeared downstream of the shock, where values plateaued to those comparable to the mean Fe/O of solar cycle 23; (v) the O and Fe spectral index ranged from ~1.0 to 3.4, the Fe spectra being softer in most events; and (vi) the observed spectral index was softer than the value predicted from the shock compression ratio in most events. We conclude that while the variations in IP shock properties may account for some variations in O and Fe properties within these multi-spacecraft events, detailed examination of the upstream seed population and IP turbulence, along with modeling, are required to fully characterize these observations.

The 2012 July 23 Backside Eruption: An Extreme Energetic Particle Event?

Nat **Gopalswamy**, Seiji Yashiro, Neeharika Thakur, Pertti Mäkelä, Hong Xie, Sachiko Akiyama
ApJ 833 216 **2016**
https://arxiv.org/pdf/1610.05790v1.pdf **File**
https://iopscience.iop.org/article/10.3847/1538-4357/833/2/216/pdf
The backside coronal mass ejection (CME) of **2012 July 23** had a short Sun to Earth shock transit time (18.5 hours). The associated solar energetic particle (SEP) event had a >10 MeV proton flux peaking at ~5000 pfu, and the

energetic storm particle (ESP) event was an order of magnitude larger, making it the most intense event in the space era at these energies. By a detailed analysis of the CME, shock, and SEP characteristics, we find that the July 23 event is consistent with a high-energy SEP event (accelerating particles to GeV energies). The time of maximum and fluence spectra in the range 10-100 MeV were very hard, similar to those of ground level enhancement (GLE) events. ***We found a hierarchical relationship between the CME initial speeds and the fluence spectral indices: CMEs with low initial speeds had SEP events with the softest spectra, while those with highest initial speeds had SEP events with the hardest spectra***. CMEs attaining intermediate speeds result in moderately hard spectra. The July 23 event was in the group of hard-spectrum events. During the July 23 event, the shock speed (>2000 km s-1), the initial acceleration (~1.70 km s-2), and the shock formation height (~1.5 solar radii) were all typical of GLE events. The associated type II burst had emission components from metric to kilometric wavelengths suggesting a strong shock. These observation confirm that the 2012 July 23 event is likely to be an extreme event in terms of the energetic particles it accelerated.

Table 1: Intense ESP and GLE events since 1976

Table 2. List of SEP events, the fluence spectral indices, and the CME information (1997-2016)

. ESP events are typically associated with eruptions close to the disk center and show significant east–west hemispheric asymmetry (e.g., Sarris et al. 1984; Reames 1999; Mäkelä et al. 2011). In the eastern hemisphere, ESPs occur in events originating all the way to the east limb. When we examined the source regions of ESP events listed in the CDAW catalog (http://cdaw.gsfc.nasa.gov/CME_list/sepe/),

Major solar energetic particle events of solar cycles 22 and 23: Intensities above the streaming limit

D. **Lario**, A. Aran, R. B. Decker

SPACE WEATHER, VOL. 6, S12001, doi:10.1029/2008SW000403, **2008**

Large solar energetic particle (SEP) events constitute a serious radiation hazard to astronauts and spacecraft systems. It is essential to determine the highest particle intensities reached in SEP events, especially at the energies that pose serious risks to human health and spacecraft performance. It has been argued that the highest particle intensities measured during large SEP events occur in association with the passage of shocks driven by coronal mass ejections known as the energetic storm particle (ESP) component. Furthermore, it has been argued that the intensities measured early in the SEP events (known as the prompt component) are bounded by a maximum intensity plateau that results from wave-particle interactions that restrict the free streaming of particles (also called the “streaming limit”). We analyze proton intensities measured by the GOES spacecraft at the energy channels P5 (~39–82 MeV) and P7 (~110–500 MeV) during solar cycles 22 and 23 and examine whether the highest intensities were measured during the prompt or the ESP components of the SEP events. We find three (one) SEP events in which the highest proton intensities measured during the prompt component at the energy channel P5 (P7) exceeded by a factor of 4 or more the previously determined “streaming limit”. Arguments to explain intensities during the prompt components exceeding this limit invoke interplanetary conditions that inhibit the amplification of waves resonating with the streaming particles and/or the presence of interplanetary structures able to confine and/or mirror energetic particles. We analyze these possibilities for each one of these events.

Shock Acceleration of Ions in the Heliosphere **Review**

Martin A. **Lee** · R.A. Mewaldt · J. Giacalone

Space Sci. Rev., 173, Issue 1-4, pp 247-281, **2012, File**

https://link.springer.com/content/pdf/10.1007/s11214-012-9932-y.pdf

Energetic particles constitute an important component of the heliospheric plasma environment. They range from solar energetic particles in the inner heliosphere to the anomalous cosmic rays accelerated at the interface of the heliosphere with the local interstellar medium. Although stochastic acceleration by fluctuating electric fields and processes associated with magnetic reconnection may account for some of the particle populations, the majority are accelerated by the variety of shock waves present in the solar wind. This review focuses on “gradual” solar energetic particle (SEP) events including their **energetic storm particle (ESP) phase**, which is observed if and when an associated shock wave passes Earth. Gradual SEP events are the intense long-duration events responsible for most space weather disturbances of Earth’s magnetosphere and upper atmosphere. The major characteristics of gradual SEP events are first described including their association with shocks and coronal mass ejections (CMEs), their ion composition, and their energy spectra. In the context of acceleration mechanisms in general, the acceleration mechanism responsible for SEP events, diffusive shock acceleration, is then described in some detail including its predictions for a planar stationary shock, shock modification by the energetic particles, and wave excitation by the accelerating ions. Finally, some complexities of shock acceleration are addressed, which affect the predictive ability of the theory. These include the role of temporal and spatial variations, the distinction between the plasma and wave compression ratios at the shock, the injection of thermal plasma at the shock into the process of shock acceleration, and the nonlinear evolution of ion-excited waves in the vicinity of the shock.

Energetic storm particle events in coronal mass ejection-driven shocks

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J. Geophys. Res., Vol. 116, No. A8, A08101, **2011, File**

http://cdaw.gsfc.nasa.gov/publications/makela/makela2011JGR.pdf

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2011JA016683

We investigate the variability in the occurrence of energetic storm particle (ESP) events associated with shocks driven by coronal mass ejections (CMEs). The interplanetary shocks were detected during the period from 1996 to 2006. First, we analyze the CME properties near the Sun. The CMEs with an ESP-producing shock are faster (VCME = 1088 km/s) than those driving shocks without an ESP event (VCME = 771 km/s) and have a larger fraction of halo CMEs (67% versus 38%). The Alfvénic Mach numbers of shocks with an ESP event are on average 1.6 times higher than those of shocks without. We also contrast the ESP event properties and frequency in shocks with and without a type II radio burst by dividing the shocks into radio-loud (RL) and radio-quiet (RQ) shocks, respectively. The shocks seem to be organized into a decreasing sequence by the energy content of the CMEs: RL shocks with an ESP event are driven by the most energetic CMEs, followed by RL shocks without an ESP event, then RQ shocks with and without an ESP event. The ESP events occur more often in RL shocks than in RQ shocks: 52% of RL shocks and only ∼33% of RQ shocks produced an ESP event at proton energies above 1.8 MeV; in the keV energy range the ESP frequencies are 80% and 65%, respectively. Electron ESP events were detected in 19% of RQ shocks and 39% of RL shocks. In addition, we find that (1) ESP events in RQ shocks are less intense than those in RL shocks; (2) RQ shocks with ESP events are predominately quasi-perpendicular shocks; (3) their solar sources are located slightly to the east of the central meridian; and (4) ESP event sizes show a modest positive correlation with the CME and shock speeds. The observation that RL shocks tend to produce more frequently ESP events with larger particle flux increases than RQ shocks emphasizes the importance of type II bursts in identifying solar events prone to producing high particle fluxes in the near-Earth space. However, the trend is not definitive. If there is no type II emission, an ESP event is less likely but not absent. The variability in the probability and size of ESP events most likely reflects differences in the shock formation in the low corona and changes in the properties of the shocks as they propagate through interplanetary space and the escape efficiency of accelerated particles from the shock front.

The Large Energetic Storm Particle Event of September 18, 2017 Observed by STEREO-A

R. **Mewaldt**, C. Cohen, G. Li, J. Hu, D. Lario and E. Christian

PoS(ICRC2019) id. 1120 **2019**

https://pos.sissa.it/358/1120/pdf

Solar Cycle 24 solar activity ended during September 2017 with a series of ”bangs” that included four X-Class flares, a record-breaking 3000 km/s CME, and a large ground-level event, all recorded by Earth-based observers. Less well known is the eruption of a far-side CME from the same active region on September 17, which resulted in a spectacular energetic storm particle (ESP) event observed on September 18-19 at STEREOWe report the time history, energy spectra, and composition of ~0.1 to 100 MeV/nucleon ions and 0.1 to 4 MeV electrons measured during this period by the SEPT, LET and HET instruments on STEREO-A. We also compare this event with the intense **July 23, 2012** ESP event also observed by STEREO-A. The composition of ESP ions will be compared with possible seed-particle sources. Finally, these observations will serve as a basis for a modeling effort to be reported by Hu et al. at this conference.

Species-dependent Variability in the Energy Spectra of Intense Solar Energetic Particle Events Observed by PSP/ISΘIS/EPI-Hi/LET

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2025 ApJS 281 21

https://iopscience.iop.org/article/10.3847/1538-4365/ae07d5/pdf

Solar energetic particle (SEP) events, comprising electrons, protons, and heavy ions with energies ranging from tens of keV nuc−1 to several GeV nuc−1, offer critical insights into solar particle acceleration and transport mechanisms. The Parker Solar Probe Integrated Science Investigation of the Sun High Energy Energetic Particle Instrument (EPI-Hi) has enabled in situ measurements of 16 ion species in the near-Sun environment, including both commonly studied ions (H, He, O, and Fe) and less frequently analyzed species (C, N, Ne, Na, Mg, Al, Si, S, Ar, Ca, Cr, and Ni) at multi–MeV nuc−1 energies. This study presents a comprehensive spectral and compositional analysis of intense SEP events observed by EPI-Hi's Low Energy Telescope (LET), incorporating newly derived species-specific geometric factors and instrument response variations. Energy spectra are characterized using Band function fits across different intensity phases of each event, accounting for changes in instrument mode, energy coverage, and detection efficiency. Relative contributions of each ion species during the SEP events are also examined. The results reveal a trend of increasing spectral indices with intensity during the 11 studied events, indicating that low-energy particle enhancements dominate during the high-intensity phase. By extending the analysis beyond the commonly studied ion species, this work provides a more complete picture of SEP composition and contributes to a deeper understanding of their source conditions and transport dynamics in the inner heliosphere. Finally, this paper and its appendices document new instrument response functions used for the EPI-Hi/LET public data release going forward. **2023-05-16**

Table 1 Intense SEP Events that Triggered EPI-Hi/LET1 Dynamic Threshold Modes during PSP Orbits 1–23 2020-2024

Acceleration of Solar Wind Particles by Traveling Interplanetary Shocks

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2019 ApJ 878 144

https://iopscience.iop.org/article/10.3847/1538-4357/ab211b/pdf

The acceleration of thermal solar wind (SW) protons at spherical interplanetary shocks driven by coronal mass ejections is investigated. The SW velocity distribution is represented using κ-functions, which are transformed in response to simulated shock transitions in the fixed-frame flow speed, plasma number density, and temperature. These heated SW distributions are specified as source spectra at the shock from which particles with sufficient energy can be injected into the diffusive shock acceleration process. It is shown that for shock-accelerated spectra to display the classically expected power-law indices associated with the compression ratio, diffusion length scales must exceed the width of the compression region. The maximum attainable energies of shock-accelerated spectra are found to be limited by the transit times of interplanetary shocks, while spectra may be accelerated to higher energies in the presence of higher levels of magnetic turbulence or at faster-moving shocks. Indeed, simulations suggest that fast-moving shocks are more likely to produce very high energy particles, while strong shocks, associated with harder shock-accelerated spectra, are linked to higher intensities of energetic particles. The prior heating of the SW distribution is found to complement shock acceleration in reproducing the intensities of typical **energetic storm particle (ESP)** events, especially where injection energies are high. Moreover, simulations of ~0.2–1 MeV proton intensities are presented that naturally reproduce the observed flat energy spectra prior to shock passages. Energetic particles accelerated from the SW, aided by its prior heating, are shown to contribute substantially to intensities during ESP events. **2003 October 29**

A semi-analytical foreshock model for energetic storm particle events inside 1 AU

Rami **Vainio**1,2*, Arttu Pönni1, Markus Battarbee2, Hannu E. J. Koskinen1,3, Alexandr Afanasiev1 and Timo Laitinen

J. Space Weather Space Clim. 4 (**2014**) A08

http://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130035.pdf

We have constructed a semi-analytical model of the energetic-ion foreshock of a CME-driven coronal/interplanetary shock wave responsible for the acceleration of large solar energetic particle (SEP) events. The model is based on the analytical model of diffusive shock acceleration of Bell (1978), appended with a temporal dependence of the cut-off momentum of the energetic particles accelerated at the shock, derived from the theory. Parameters of the model are re-calibrated using a fully time-dependent self-consistent simulation model of the coupled particle acceleration and Alfvén-wave generation upstream of the shock. Our results show that analytical estimates of the cut-off energy resulting from the simplified theory and frequently used in SEP modelling are overestimating the cut-off momentum at the shock by one order magnitude. We show also that the cut-off momentum observed remotely far upstream of the shock (e.g., at 1 AU) can be used to infer the properties of the foreshock and the resulting energetic storm particle (ESP) event, when the shock is still at small distances from the Sun, unaccessible to the in-situ observations. Our results can be used in ESP event modelling for future missions to the inner heliosphere, like the Solar Orbiter and Solar Probe Plus as well as in developing acceleration models for SEP events in the solar corona.

Composition variation of the May 16 2023 Solar Energetic Particle Event observed by Solar Orbiter and Parker Solar Probe

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https://iopscience.iop.org/article/10.3847/2041-8213/ad8b18/pdf

In this study, we employ the combined charged particle measurements from Integrated Science Investigation of the Sun (\ISOIS) onboard the Parker Solar Probe (PSP) and Energetic Particle Detector (EPD) onboard the Solar Orbiter (SolO) to study the composition variation of the solar energetic particle (SEP) event occurring on **May 16, 2023**. During the event, SolO and PSP were located at a similar radial distance of ~0.7 au and were separated by ∼60∘ in longitude. The footpoints of both PSP and SolO were west of the flare region but the former was much closer (18∘ vs 80∘). Such a distribution of observers is ideal for studying the longitudinal dependence of the ion composition with the minimum transport effects of particles along the radial direction. We focus on H, He, O, and Fe measured by both spacecraft in sunward and anti-sunward directions. Their spectra are in a double power-law shape, which is fitted best by the Band function. Notably, the event was Fe-rich at PSP, where the mean Fe/O ratio at energies of 0.1 - 10 Mev/nuc was 0.48, higher than the average Fe/O ratio in previous large SEP events. In contrast, the mean Fe/O ratio at SolO over the same energy range was considerable lower at 0.08. The Fe/O ratio between 0.5 and 10 MeV/nuc at both spacecraft is nearly constant. Although the He/H ratio shows energy dependence, decreasing with increasing energy, the He/H ratio at PSP is still about twice as high as that at SolO. Such a strong longitudinal dependence of element abundances and the Fe-rich component in the PSP data could be attributed to the direct flare contribution. Moreover, the temporal profiles indicate that differences in the Fe/O and He/H ratios between PSP and SolO persisted throughout the entire event rather than only at the start.

Acceleration and Release of Solar Energetic Particles Associated with a Coronal Shock on 2021 September 28 Observed by Four Spacecraft

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https://arxiv.org/pdf/2401.10388.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ad1e57/pdf

Extreme ultraviolet (EUV) waves are thought to be the propagating footprint of the shock on the solar surface. One of the key questions in SEP research is the timing of the SEP release with respect to the time when the EUV wave magnetically connects with an observer. Taking advantage of close-to-the-Sun measurements by Parker Solar Probe (PSP) and Solar Orbiter (SolO), we investigate an SEP event that occurred on **2021 September 28** and was observed at different locations by SolO, PSP, STEREO-A, and near-Earth spacecraft. During this time, SolO, PSP and STEREO-A shared similar nominal magnetic footpoints relative to the SEP source region but were at different heliocentric distances. We find that the SEP release times estimated at these four locations were delayed compared to the times when the EUV wave intercepted the footpoints of the nominal magnetic fields connecting to each spacecraft by around 30 to 60 minutes. Combining observations in multiple wavelengths of radio, white-light, and EUV, with a geometrical shock model, we analyze the associated shock properties, and discuss the acceleration and delayed release processes of SEPs in this event as well as the accuracy and limitations of using EUV waves to determine the SEP acceleration and release times.

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