Solar Energetic Particles Observed by the STEREO Spacecraft During Solar Cycle 24

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Solar energetic particle (SEP) events are temporary enhancements in the proton, heavy ion and electron intensity resulting from the acceleration of particles by solar flares and/or shocks driven by coronal mass ejections and their subsequent release and transport through the heliosphere.

Range in energy from ~10s of keVs to GeVs.

A significant hazard to space-based assets, in particular outside the shield of Earth’s magnetosphere, and to aircraft at high latitudes (e.g., polar routes).

Occur ~randomly and with little warning – the fastest particles can arrive at Earth’s orbit within minutes of the solar event.

Richardson et al., 2003

GeV ions arrive ~10 minutes after X-ray peak
SEP acceleration mechanisms are still the topic of heated debate!

Acceleration in solar flares by magnetic reconnection, wave-particle interactions.

Acceleration at the CME-driven shock

Temmer et al., 2010
Particle Acceleration by Bouncing Between Converging Scattering Centers Upstream and Downstream of a (Quasi-Parallel) Shock

Richardson, Nature Physics, 2013
- Short durations of a few hours to ~1 day;
- Associated with impulsive (brief) solar flares. Hence, are usually termed \textit{“impulsive” events};
- Usually attributed to flare acceleration;
- Electron rich;
- Enhanced in $^3$He (rare in the photosphere/solar wind);
- Fe-rich; higher Fe/O than the photosphere, solar wind;
- Flare-accelerated electrons $\Rightarrow$ Type III (fast-drift) radio emission.
- Durations of several days;
- Associated with longer duration flares, hence "gradual" events;
- May have intensity peak at passage of CME-driven shock ("Energetic Storm Particle (ESP) Event");
- Electron poor;
- ~Photospheric/solar wind abundances + re-accelerated minor ions e.g. $^3$He;
- Fe/O ~ solar wind;
- Type II (slow drift) radio emission associated with shock;
- Type III radio emissions, stronger for larger SEP events;

Not two distinct classes of events, many show "mixed" properties
Differences in SEP (~5, 15, 30 MeV Proton) Intensity-Time Profiles for Western, Central and Eastern Solar Events (Cane and Lario, 2006, adapted from Cane et al. 1988)

Well connected to W event; prompt onset

Poorly connected to E event; slow rise

Central event may be dominated by shock-accelerated particles
Longitudinal-dependence of Fe/O Ratio at 25-80 MeV/n (Cane et al., 2006)
STEREO – Two Spacecraft in Heliocentric Orbits at ~1 AU, Launched October, 2006

Study SEPs using observations from the High Energy Telescopes (HETs) on STEREO A and B together with similar observations from near-Earth spacecraft (e.g., from ERNE and EPHIN on SOHO).
Why I Don’t Use GOES For Near-Earth Proton Data (If I Have a Choice)!

Comparison of GOES and SOHO/EPHIN shows the high background in GOES.

Many more features, including small SEP events, are visible in the EPHIN (and ERNE, not shown) data.
We focus on solar particle events that include 25 MeV protons. Why?
- The intensity-time profile at 25 MeV is less frequently dominated by ions associated with local interplanetary shocks than e.g., the “standard” GOES >10 MeV proton flux;
- It is relatively easy to identify event onsets and the related solar event;
- Energy range of interest for radiation hazards;
- Associated with relatively energetic solar events (e.g., nearly all have CMEs);
- Events since 1967 have been recorded in several studies.

Example of an SEP event onset that is harder to identify at lower energies where an ongoing shock-associated event dominates.

M1 Flare at W24°, 0351 UT, February 12, 2000. LASCO CME: 0431 UT, 1107 km/s (Cane et al., 2010). Particle data from ACE/EPAM, ACE/ULEIS, SOHO/ERNE; ACE plasma and field observations.

Richardson et al. (2017)
Overview of 14-24 MeV Proton Intensities at STEREO A, B and at Earth (SOHO/ERNE) From STEREO Launch (October, 2006) to November 2018

Updated from Richardson et al., 2014; ~400 individual SEP events
It was fortuitous that the large December 2006 SEP events occurred soon after launch when the STEREO spacecraft were still close to Earth:

• Allowed the HET calibration to be checked relative to instruments on near-Earth spacecraft over a large dynamic range.

• Identified an unexpected (and still unexplained) factor of ~14 reduction in the HET electron intensity relative to other instruments.

• If not identified, this would have led to errors in the longitudinal distribution of electrons based on combined STEREO and near Earth observations, errors in electron/proton ratios, etc.

Richardson et al. (2014)
Example of a Solar Particle Event Detected at Both STEREO Spacecraft and at Earth ("3-Spacecraft Event")

August 31 (DOY 244), 2012

STEREO A

STEREO B

EARTH/SOHO

CME: 2000 UT, 360°, 1442 km/s (CDAW)
X-rays: C8.4

Flare location wrt: STEREO B: W74° Earth: E42° STEREO A: E165°

STEREO-SWAVES/WIND-WAVES

STA

Occulted Type III

Type III, Type II, 2000 UT @ WIND, STB

Earth

STB

Type III, Type II, 2000 UT
August 18 (DOY 230), 2010

STEREO A 0.7-4 MeV e−, 14-24 MeV, 24-41 MeV protons

SOHO EPHIN 0.7-3 MeV e−; ERNE 14-24 MeV, 24-41 MeV protons

STEREO B 0.7-4 MeV e−, 14-24 MeV, 24-41 MeV protons

CME: 0548 UT, 184°, 1471 km/s (CDAW)

Flare location wrt:
STEREO B: W172°  Earth: W100°  STEREO A: W20°

Type III-ľ
Occulted Type III-ľ
Type II, all S/C, 0605 UT
Weak, occulted Type III

COR1: 2010/08/18 06:05:00  EUVI: 06:05:30
Nov. 3, 2011: Rapid onset at Earth and both STEREOs following a solar event behind the east limb.
Most Recent 25 MeV Proton Event, on May 3, 2018, at STEREO A

Flaring (~E136°) and erupting filament (STA EUVI)

CME observed by STA COR 2; CACTUS width= 102°, 581 km/s

CME ("halo") observed by LASCO; CACTUS width= 128°, 374 km/s

ENLIL+CONE simulation of CME (DONKI database) E155°, 650 km/s

Type III radio emission observed at STA (top) and WIND (bottom).
Two Other Recent 25 MeV Proton Events, January 22 and February 12, 2018, at Earth

W55°, B9.5 flare
SOHO/ERNE
14-24 MeV
24-41 MeV

AIA 193Å

LASCO/CACTUS 64°, 625 km/s

ENLIL+CONE (from DONKI):
W66°, 560 km/s
Type III @ WIND

W14°, C1.5 flare
SOHO/ERNE
14-24 MeV
24-41 MeV

LASCO/CACTUS 104°, 425 km/s

ENLIL+CONE (from DONKI):
W22°, 554 km/s
Type III @ STA, WIND
Peak 25 MeV Proton Intensity vs. Solar Event Longitude Relative to the Observing Spacecraft

SEPs can arrive from anywhere on the Sun!

Richardson et al., 2014
Three viewpoints (two STEREOs and another, e.g. Earth) are insufficient to characterize the longitudinal dependence of SEP events, especially when well separated. Assume a simple longitudinal dependence, such as a Gaussian fit to peak intensities mapped to the magnetic field line footpoint longitude relative to the solar event (“connection angle”, CA).

Examples of Gaussian fits to 3-spacecraft proton and electron intensities for several events

Distribution of connection angles of 14-24 MeV proton peaks for a sample of three spacecraft events. While the Gaussian peak is most frequently near the field line connecting to the solar event, there are also events that appear to be significantly asymmetric.

Richardson et al., 2014
SEP Proton Intensity Formula (Richardson et al., 2014)

14-24 MeV Proton Intensity Gaussian fit vs. $\varphi$ for 3 spacecraft (STEREOs + near Earth) events

$$I(\varphi) \ (\text{MeV s cm}^2 \text{ sr})^{-1} \approx 0.013 \exp(0.0036V - \varphi^2 / 2\sigma^2), \ \sigma = 43^\circ,$$

where:

- $\varphi$ is the angle (longitude) between the solar event and the solar footpoint of the spiral magnetic field line passing the observing spacecraft, and
- $\sigma$ is the Gaussian width; 43° is the average value.

Gaussian peak intensity vs. LASCO CME speed

$\Rightarrow$

$\Rightarrow$
Gaussian Peak 25 MeV proton intensity vs. Gaussian Full Width at Half Maximum (=2.355σ).

Most events lie in the FWHM=70-120° range (σ=30-51°).

Maybe an increase in FWHM for decreasing event size. This could be a selection effect since, for an intrinsically small event to be detectable as a 3 S/C event, a larger FWHM (wider Gaussian) is advantageous.

FWHM vs. CME speed

There is no correlation.

However, combined with the tendency for the proton intensity to be correlated with the CME speed, the proton intensity will tend to exceed a particular threshold over a wider longitude range as the CME speed increases.

von Rosenvinge et al., 2015
SEP Prediction for NASA’s Lunar Outpost to Extend Human Presence in Deep Space, and Missions to Moon/Mars

- Greater radiation hazard from Galactic Cosmic Rays and SEPs than for the ISS in LEO (less shielding from vehicle and geomagnetic cut off).
SEPs

- Only an occasional concern and lower energies than GCRs but little warning.
- Astronauts can reduce radiation exposure by building a shelter from supplies already on the vehicle in ~15 minutes.
- The Space Radiation Analysis Group (SRAG) at Johnson SFC is charged with issuing timely SEP warnings to astronauts with a low false alarm rate.
- SRAG are working with CCMC to select several SEP forecast models to develop an operational “scoreboard” to issue an SEP alert or “all-clear”.
- One of these is “SEPSTER” (SEP prediction based on STEReo observations) (Richardson et al., Space Weather, 16, 1862, 2018)
Problem: Most CMEs (~85%) are NOT accompanied by an SEP event.

Hence, there are many cases when a predicted event is not observed.
Major problem: Only \(~15\%\) of CMEs are actually associated with 25 MeV proton events.

Filter using e.g., the presence of type II or type III radio emissions, or the CME speed and width, to reduce “false alarms”

**Filtering by DONKI CME Speed x Width**

Currently running in real time at the CCMC, GSFC
How are energetic particles transported in longitude in extended events?


• Particle transport to remote longitudes by large scale magnetic loops?  X  ? No clear evidence but not ruled out.

• Diffusion near/at the Sun, e.g. Coronal propagation?  ? Particles appear to spread rapidly in longitude near the Sun, but does diffusion play a role?

• Acceleration by coronal waves?  ? Particles are observed beyond the range of coronal waves; waves may be the “skirts” of CMEs.

• Connection to an expanding 3-dimensional CME shock?  ✓ ? Could explain the rapid transport of particles near the Sun, but some events extend beyond the connected region.

• Cross-field transport/diffusion in the Solar Wind?  ✓ ? Used to model some events. (Are the assumed parameters realistic?)

• Acceleration by expansive interplanetary shocks?  ✓ Clearly observed in the heliosphere.

• Guidance by non-Parker spiral interplanetary magnetic fields, e.g. in ICMEs?  ✓ Clearly observed, but only operates at individual spacecraft in certain events.
Different Longitudinal Source Speeds For Protons and Electrons

Electron and Proton Onset Delays are Correlated

Electron and Proton Times to Peak Intensity are Correlated
Different estimates of onset times using different methods: Blue lines=uncertainty “by eye”; green dots=Poisson-CUSUM; orange dots=Fixed onset level method.

Evolving magnetic connection to an expanding ellipsoidal model shock front assuming a PFSS+GONG coronal field

A particle transport model including cross field diffusion may also account for the particle profiles, in particular the onset at STEREO A which does not connect to a fast section of the shock.
The first 25 MeV proton event detected at both STEREOs and at Earth occurred on December 22, 2009, when the STEREO A and B spacecraft were ~65° ahead or behind the Earth in longitude, respectively. This event occurred in one of several brief intervals of enhanced SEP occurrence (indicated by vertical lines) separated by similar several (~6)-month periods with relatively few SEP events. These intermittent intervals with SEPs characterize the rise of Cycle 24.
~Six Month Periodicity in the Hemispheric SEP (25 MeV Proton) Event Rate in 2008-2014

Monthly rate of 25 MeV proton events (blue) plotted with the monthly-averaged sunspot area (from David Hathaway) multiplied by 0.006, for the whole Sun, and Northern and Southern hemisphere separately.

Note the excellent correlation except in late 2014, when a large southern sunspot region was associated with non-erupting flares.

(Richardson et al., 2016)
Evidence for periodicities in SEPs in Cycle 23 were discussed by Richardson and Cane (2005).

19-28 MeV proton intensity (from IMP 8) in 1996-2004 and rotation/monthly averages of several parameters. The vertical lines are separated by 166 days, the prominent period found in the ICME rate at Earth around solar maximum, where they approximately align with local minima in the ICME rate. During the early phase of the cycle, the SEP events were clustered with a similar period, as was the case in Cycle 24 where the period was also comparable (~6 months).
And in Cycle 21 SEPs and IMF by *Cane et al.* (1998):

Vertical lines are separated by 153 days

*Figure 1.* The lower panel shows daily-averages of the magnetic field strength at 1 AU in nT for July, 1977 to June, 1983, running averaged over a 27-day (∼solar rotation) period. The upper panel shows 8-hour averages of the intensity of 63-82 MeV protons at 1 AU.

The periodicities are related to variations in other solar and interplanetary parameters during cycle 24 (Richardson et al., 2016).

Green (purple) vertical lines are times of North (South) SEP rate maxima.

Photospheric magnetic field (McIntosh et al., 2015)

**Project:** Survey the global energetics of solar flares and CMEs observed with SDO, including data from AIA, HMI, EVE, STEREO/EUVI, RHESSI, GOES, etc.

**Data set:** 2010-2014, first 5 years of SDO mission; 398 GOES flares (28 X- and 370 M-class); 177 flares near disk center (<45° longitude)

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**Solar Energetic Particle (SEP) Component:**

**Dick Mewaldt (leader):** Scattering correction, total energy calculation

**Christina Cohen:** He, heavier ions

**Mihir Desai:** H, heavy ion spectra

**Glenn Mason, George Ho:** Low energy H, heavy ions.

**David Lario:** Electrons

**Ian Richardson:** SEP/flare/CME associations, identify usable events, spectral fitting.
SEP Observations During a 7-day Period in July, 2012 With 33 M/X Flares
Results for Three-Spacecraft Events as Reported in Aschwanden et al. (2017)

The SEP energy is typically only a few percent of the CME energy.
How is the Event-Integrated SEP Energy Distributed in Energy?

The top left figure shows the percentage of the total integrated proton energy that lies below a given energy, for the Oct 22 (day 295), 2011 flare. 60% of the total energy in this event is contributed by 0.32-3.5 MeV protons. The intensity at these energies is greatest in the local enhancement associated with passage of the flank of the interplanetary shock (10/24, 18 UT) related to this W77° M1.3 flare. Hence, this local shock-associated particle increase dominates the SEP energetics in this event.
The STEREO mission has made significant contributions to understanding SEPs.

Observations confirm that SEPs can be detected from anywhere on the Sun (as strongly suspected from previous observations at Earth), though they are most intense on field lines well connected to the solar event.

The rapid spread of SEPs over large longitudinal extents places significant constraints on mechanisms of particle transport near the Sun and/or in the solar wind.

Field line connection to expanding shocks is the simplest explanation, but cross-field transport may be required to explain cases where connection appears to be unlikely.

Because of its launch at solar minimum, STEREO could not satisfactorily address the variations in SEP properties with longitude anticipated from previous statistical studies. However, STEREO A is approaching the Earth again, and may be favorably placed for such studies as the next solar cycle ramps up.

The > factor of 2 increase in SEP event statistics available with the STEREO observations improves studies of for example, variations in the SEP rate, showing quasi-periodicities that are probably a manifestation of the evolution of solar magnetic fields during the solar cycle. Observing and understanding this evolution may be a significant advance in space weather forecasting, including the longer-term (several months) prediction of SEPs.