

Solar Energetic Protons

The Sun is an effective particle accelerator. Solar Energetic Particles (SEPs) are an important hazard to spacecraft systems and constrain human activities in space. Primary radiation sources are energetic protons and heavy ions during SEP events, with energies up to few hundreds of MeVs, being protons the most abundant specie. Figure 1 shows a large SEP event observed on December 13, 2006. Proton intensity enhancements during that event reached > 0.5 GeV energies, producing an increase in neutron count rates at ground levels through secondary radiation effects, also known as a Ground Level Event (or GLE).

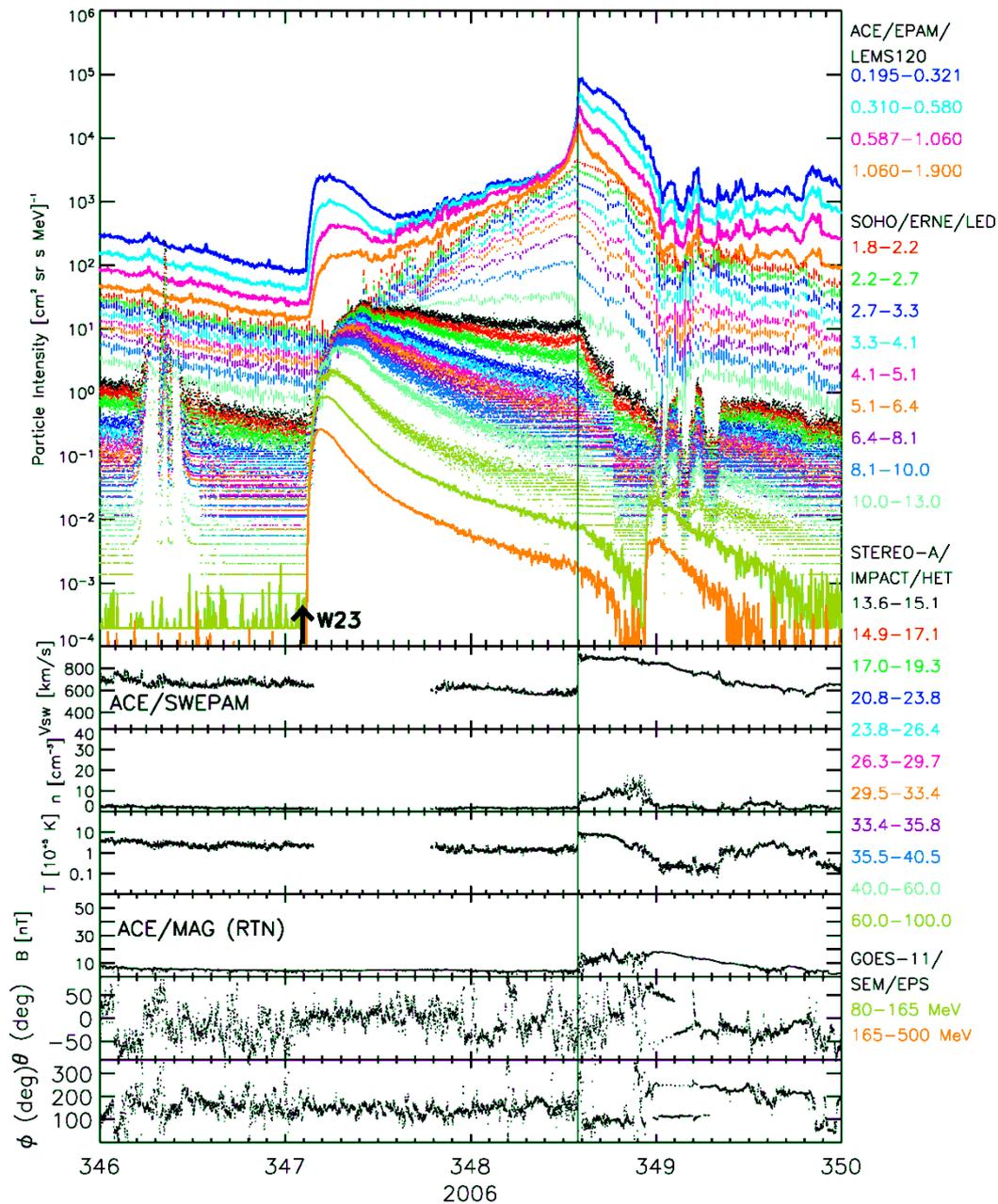


Figure 1. December 13, 2006 SEP event from [1]. Top Panel: 0.3 – 500 MeV proton intensity-time profiles (colour coded) measured by several instruments as indicated in the legend. Bottom panels: Evolution of the solar wind speed (ACE/SWEPAM) and of the interplanetary magnetic field intensity, latitude and longitude (RTN coordinates) measured by ACE/MAG. The vertical solid lines

mark the time of a shock passage by ACE and the dashed lines mark the onset of the 1 – 8 A X-ray flare (GOES). We acknowledge the use of data to the ACE, STEREO and GOES Science Teams.

Such large SEP events, highly random in nature, tend to occur during periods of intense solar activity, although they can also occur around the solar minimum period, as the one shown in Figure 1. These events can lead to high radiation doses in short time intervals. Sporadic increases in the energetic particle fluxes can directly affect human endeavours like aerospace technology or space exploration. For many deleterious effects the relevant parameter of SEPs is the total fluence of particles accumulated during a mission, while for others, it is the maximum particle intensity observed during a single event.

The effect of particle flux or fluence might have severe implications for the lifetime of the satellites and the performance of instruments onboard spacecraft. Intense events can reach fluence values as high as 10^{10} protons cm^{-2} for energies greater than 10 MeV. Figure 2, adapted from [2], summarizes some effects of SEPs at different energies.

Table 1. The Causes of Hazards

Parameter	Effects	Sources
Protons 0.1-1 MeV	surface damage to materials	primarily radiation belt particles
Protons 1-10 MeV	displacement damage in solar cells	radiation belts and shock acceleration in space
Protons >10 MeV	ionization and displacement damage and sensor background	radiation belts, solar energetic particle and galactic cosmic rays
Protons >30 MeV	damage to biological systems	same as above
Protons >50 MeV	single-event effects	same as above
Ions >10 MeV nucleon ⁻¹	single-event effects	solar energetic particle and galactic cosmic rays
GeV particles (ground level events)	single-event effects and hazards to humans in polar flights and deep space	same as above

Figure 2. Space Weather effects of proton events adapted from Table 1 of [2].

Origin

Energetic particles are produced intermittently due to particle acceleration processes in the solar atmosphere associated with solar flares, and in coronal and interplanetary shocks created by the interaction of coronal mass ejections (CMEs) with the solar wind. An evolving CME may generate an interplanetary shock which propagates in space, deforming the interplanetary magnetic field (IMF) lines and draping them around the driver downstream of the shock. Energetic particles may escape from their acceleration sites and propagate along interplanetary magnetic field (IMF) lines into the interplanetary space enabling their detection by spacecraft, as it is sketched in Figure 3.

The intensity-time profiles of SEP events result from the evolution of the particle population in a set of flux tubes that sweep over the observer. The motion of charged energetic particles from their source to the observer is constrained by the Parker spiral pattern of the IMF. This causes an asymmetry in the intensity-time profiles depending upon the observer's longitude (and latitude).

SEP events are conventionally classified into two loosely defined categories: impulsive and gradual [3]. This classification was originally based on the decay time scale of the associated soft X-ray flare, τ_x , but nowadays the naming relates to the duration of the SEP event itself.

Impulsive SEP events have durations from hours to a day and are related to short-duration soft X-ray emission ($\tau_x < 10$ min). These SEP events, often associated with flare acceleration processes, are characterized by small interplanetary ion intensities, a high electron to proton intensity ratio, enhanced abundances of heavy elements, and enhancements of ^3He relative to ^4He by up to a factor of 10^4 . Given the various uncertainties of the IMF including the solar wind speed variations, impulsive SEP events observed at near geospace are generally limited to within a 30° longitude band about the footpoint of the nominal field line magnetically connected to the flaring region, $\sim\text{W}55^\circ$.

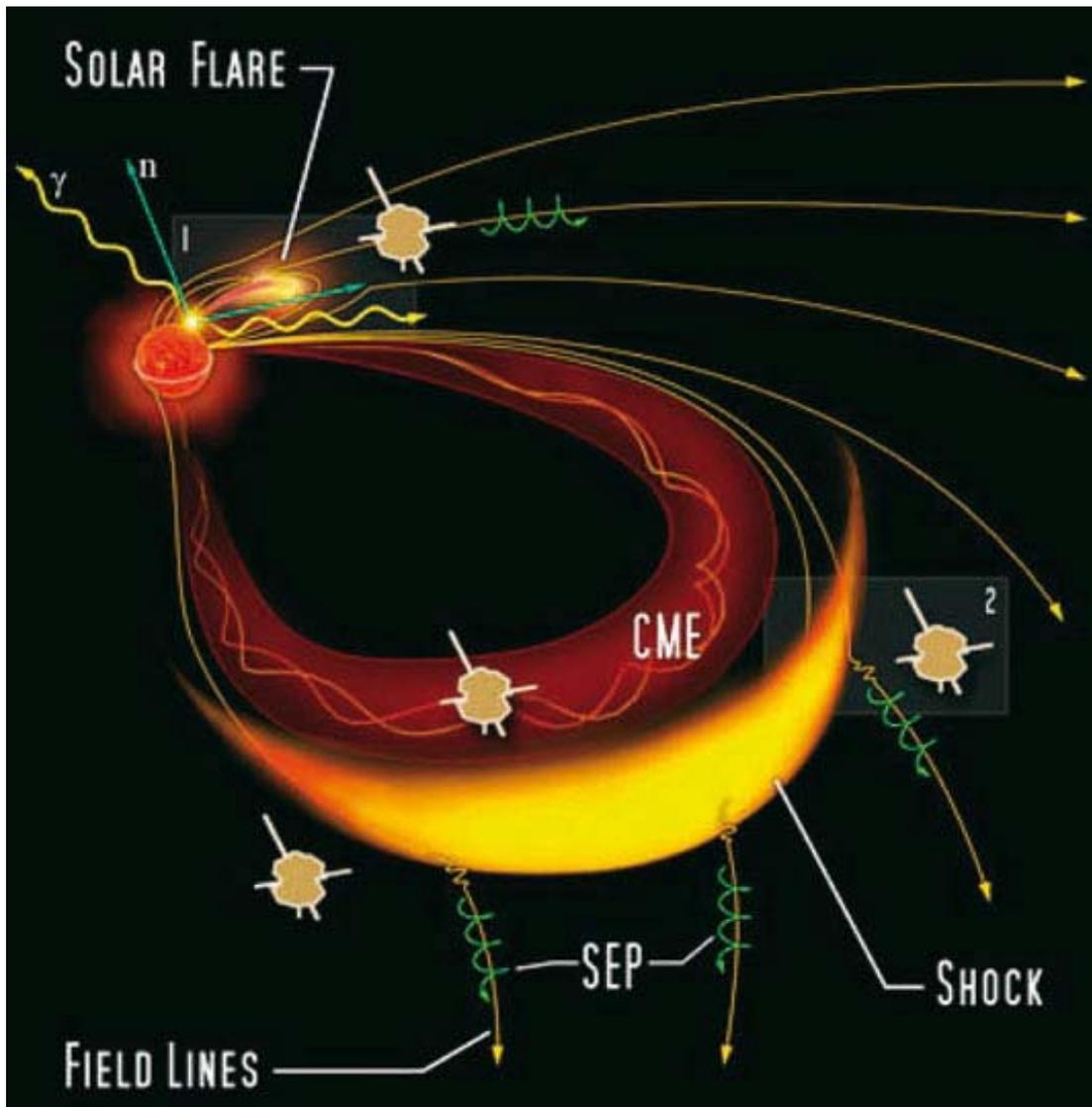


Figure 3. Cartoon showing two sources of particle acceleration: a flare and CME-driven shock wave. Spacecraft located at different vantage points magnetically connect back to different parts of the interplanetary shock or the flare, producing different types of SEP intensity profiles. [NASA/TM-2006-214137. Solar Sentinels: Report of the Science and Technology Definition Team, 2006].

Gradual SEP events have durations of days and are related to long-duration ($\tau_x > 10$ min.) soft X-ray emission and to interplanetary shocks driven by fast CMEs ($v_{\text{CME}} > 750 \text{ km s}^{-1}$). These events are characterized by large interplanetary ion intensities, small electron to proton ratios, average elemental abundances and ionic charge states in consistency with solar coronal abundances and temperatures. Gradual SEP events have a longitude distribution of the associated flare that is much wider than for impulsive events, essentially spread over the whole solar disk. The associated CME-driven shock waves may extend a large range of heliolongitudes—even up to 180° in extreme cases—and latitudes, regardless of the associated solar flare location.

Large SEP events

For a fast CME, particle acceleration begins as the shock forms in the solar corona and continues as the shock moves out into the IP space. The expanding shock crosses other IMF lines, accelerating particles which flow outwards over an extremely wide front. The most efficient acceleration takes place near the nose of the shock, ahead of the CME.

As a consequence, the intensity-time profiles of gradual SEP events (including energetic electrons and ions) show a significant variability from one event to another [e.g., 4, 5, 6]. The variety of spatial and temporal characteristics depends on multiple parameters such as:

- the energy of the particles,
- the existence and characteristics of the shock and its efficiency to accelerate particles,
- the transport processes of the accelerated particles,
- the presence of seed particle populations in IP space to be accelerated,
- the local structure of the ambient solar wind, and
- the heliolongitude of the source region with respect to the spacecraft location.

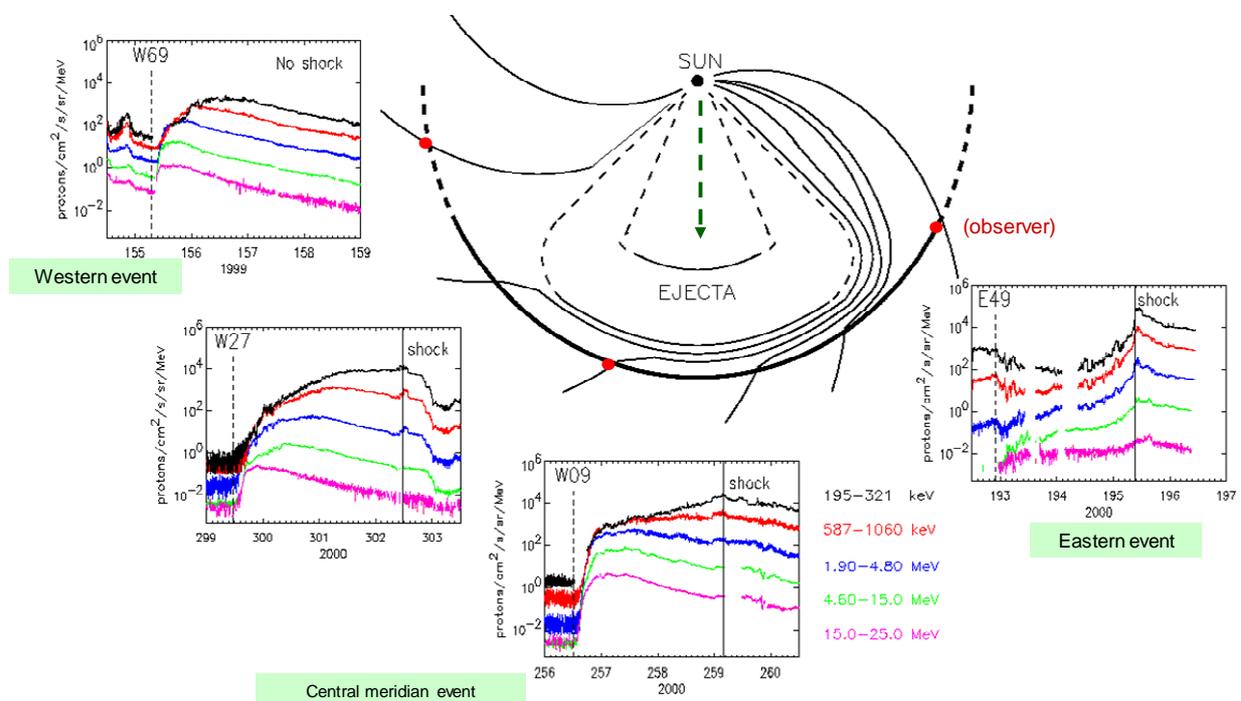


Figure 4. Illustration of the variety of observed SEP events proton intensity-time profiles ($E < 25$ MeV) as seen by observers at 1 AU placed at different longitude with respect to the leading direction of a CME ('ejecta' in the plot) driven shock wave (black bow-line). Note the variation of the intensity profiles with the particle energy. Data shown is from the ACE and IMP-8 spacecraft. Adapted from [4].

The point of the shock front at which successive magnetic field lines connect the observer is usually termed as the cobpoint (Connecting with the Observer POINT) [7]. Various general forms of SEP event intensity profiles can be interpreted by following the clockwise motion of the cobpoint:

Near the earth, particle intensity-time profiles of SEPs originating from the Sun's western hemisphere present rapid rises to their intensity maximum because the cobpoint is close to the nose of the shock near the Sun. Hence the observer is connected to the shock front where and when it is more efficient at accelerating particles. The rapid increment is followed by a gradual decay as the cobpoint moves toward the eastern flank of the shock front where the shock is weaker (see left-hand plot of Figure 4).

In central meridian events, the magnetic connection of the observer with the shock front is also established when the shock is still close to the Sun, and hence the observed rapid increase of the high-energy proton profiles. In these events, the cobpoint moves along the shock's western wing towards its nose as the shock moves away from the Sun and reaches 1 AU. These results in an increase of the low-energy intensity-time profiles up to the shock passage, since the shock is still able to accelerate these particles as it moves in the interplanetary space.

In the case of SEP events originating from the eastern hemisphere, the observer detects an increase of SEP intensity only a few hours prior to the arrival of the shock due to the unfavourable IMF connection between the observer and the shock front (see right-hand plot of Figure 4).

ESP events

Shock-accelerated particles travel along the IMF threading the solar wind, but at low energies (below ~ 10 MeV at 1 AU) a significant fraction can be trapped in front of the propagating shock by wave-particle interactions and form an ion foreshock. This turbulent trapping of particles is of vital importance for the shock acceleration process itself [8]. Once the shock reaches the Earth, the proton flux can increase suddenly by as much as two orders of magnitude, making this latter shock enhancement the most dangerous portion of the solar particle event (see Figure 5). These enhancements are known as Energetic Storm Particle (ESP) events.

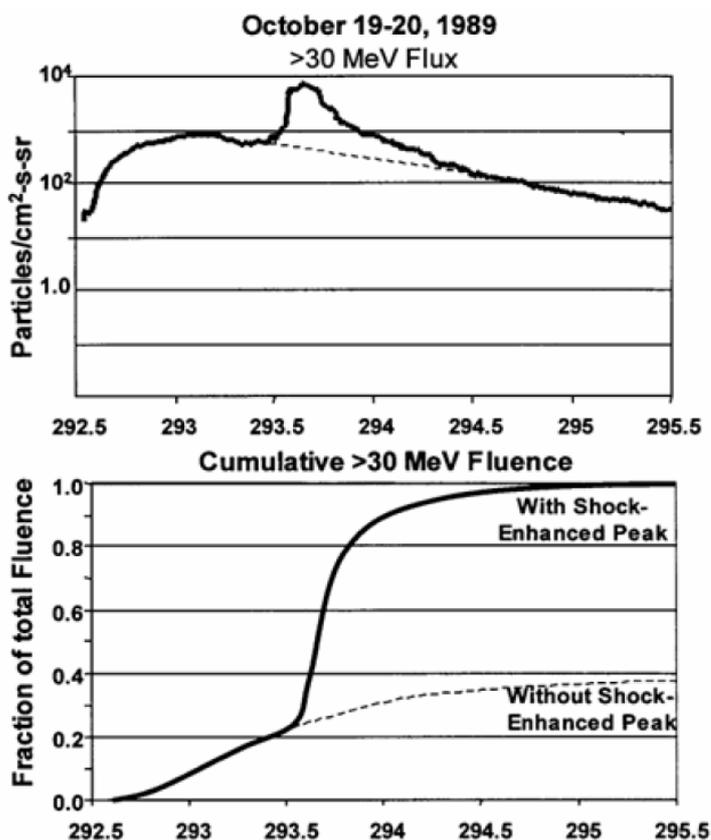


Figure 5. Flux and cumulative fluence of the October 20, 1989 particle event, as measured by the GOES satellite [9].

SEP events and this project in brief

There are multiple processes involved in the development of gradual SEP events. These include the acceleration and transport of particles in a time-dependent system formed by the propagating shock, an evolving magnetic field topology, and the formation of magnetic field fluctuations which, in turn, are affected by the propagating particles. The correct description of these mechanisms by dynamic models is very challenging due to the complexity of the physical processes involved.

For SEP events, existing research models based on magnetohydrodynamics (MHD) and particle acceleration will be developed further to improve the modelling of particle acceleration in interplanetary shocks, and their associated foreshocks (upstream turbulence). The improved models will better predict the peak intensity, fluence, and energy spectrum of SEPs.

References

- [1] Aran, A., N. Agueda, C. Jacobs, D. Lario, B. Sanahuja, S. Poedts and R.G. Marsden, *0.3 - 165 MeV proton and 102 - 312 keV electron injections during the 2006 December 13 SEP event*, American Geophysical Union, Fall Meeting 2010, abstract #SH33A-1824 (2010).
- [2] Feynmann, J. & Gabriel, S.B., *On space weather consequences and predictions*, Journal of Geophysical Research, Volume 105, Issue A5, pp. 10543-10564 (2000)
- [3] Reames, D. V. 1999: Particle acceleration at the Sun and in the heliosphere. Space Sci. Rev., 90, pp. 413-491 (1999).
- [4] Lario, D., and G. M. Simnett, *Solar Energetic Particle Variations, chapter in Solar Variability and Its Effects on Climate*, Geophys. Mon. Series (AGU), 141, pp. 195-216 (2004).
- [5] Vainio, R., L. Desorgher, E. Flückinger, M. Storini, R.B. Horne, G.A. Kovaltsov, K. Kudela, M. Laurenza, S. McKenna-Lawlor, H. Rothkaehl and I.G. Usoskin, *Dynamics of the Earth's Particle Radiation Environment*, Space Sci. Rev., Volume 147, Issue 3-4, pp. 187-231 (2009).
- [6] Watermann J., P. Wintoft, B. Sanahuja, E. Saiz, S. Poedts, M. Palmroth, A. Milillo, F.-A. Metallinou, C. Jacobs, N.Y. Ganushkina, I.A. Daglis, C. Cid, Y. Cerrato, G. Balasis, A.D. Aylward and A. Aran, *Models of Solar Wind Structures and Their Interaction with the Earth's Space Environment*, Space Science Reviews, Volume 147, Issue 3-4, pp. 233-270 (2009).
- [7] A. M. Heras, B. Sanahuja, D. Lario, Smith, Z. K., Detman, T. and Dryer, M., *Three low-energy particle events: Modeling the influence of the parent interplanetary shock*, The Astrophys. J., 445, pp. 497 (1995).
- [8] Lee, M. A., *Coupled Hydromagnetic Wave Excitation and Ion Acceleration at an Evolving Coronal/Interplanetary Shock*, The Astrophys. J. Suppl. Series, 158, pp. 38-67 (2005).
- [9] Turner, R., *What we must know about solar particle events to reduce the risk of astronauts*, Geophys. Monogr. Ser. (AGU), 125, pp. 29-44 (2001).