SEPs: Space Weather Hazard in Interplanetary Space

Donald V. Reames

NASA Goddard Space Flight Center, Greenbelt MD

In the largest and most hazardous of solar energetic particle (SEP) events, acceleration takes place at shock waves driven out from the Sun by fast CMEs. Multi-spacecraft studies show that the particles from the largest events span more than 180 degrees in solar longitude; the events can last for several days. Protons streaming away from the shock generate waves that trap particles in the acceleration region, limiting outflowing intensities but increasing the efficiency of acceleration to higher energies. Thus, early intensities are bounded, but at the time of shock passage, they can suddenly rise to a peak. These shock peaks extend to >500 MeV in the largest events, creating a serious 'delayed' radiation hazard. At high energies, spectra steepen to form a 'knee.' This spectral knee can vary from ~10 MeV to ~1 GeV depending on shock conditions, greatly affecting the radiation hazard. Elements with different charge-to-mass ratios differentially probe the wave spectra near shocks, producing abundance ratios that vary in space and time. These abundance ratios are a tool that can foretell conditions at an oncoming shock.

1. INTRODUCTION.

As we move beyond the protective shield of the Earth's atmosphere and magnetosphere, we are exposed to sources of radiation that can be a serious hazard to humans and machines. High-energy particles in space include the sudden intense bursts of the solar energetic particle (SEP) events that can last several days. Large 'gradual' SEP events occur at a rate of 10-20 yr^{-1}, but the ones most threatening to human life occur less than once a decade. This makes them especially difficult to study or to predict.

In the preceding article, Kahler described the properties of SEP events [see also *Gosling* 1993; *Kahler* 1994; *Reames* 1997, 1999a, b]. He also discussed the checkered history of the large events that were once mistakenly associated with solar flares rather than CME-driven shock waves. It is impossible to predict SEP events well when you start with the wrong source. Large SEP events with no flares and large flares with no SEP events were among the clues that eventually set us straight. We now know that only the *fastest* CMEs drive the shock waves where acceleration takes place; particle intensity is strongly correlated with CME speed. In fact, CME speed is the best predictor of an intense SEP event.

This article presents our understanding of the underlying physics that controls the energy spectra and element abundances in SEP events and the way that they evolve in space and time. This new understanding has been greatly assisted by the first *dynamic* model of SEP events [*Ng, Reames, and Tylka* 1999].

2. INTENSITY TIME PROFILES.

2.1. Streaming Limited Intensities

Observations of 3-6 MeV proton intensities near 1 AU early in large SEP events showed evidence of an intensity limit of ~100 $(cm^2\ sr\ s\ MeV)^{-1}$, within a factor of ~2 or so [*Reames* 1990]. Later in these same events, near the time of shock passage, intensities can rise by factors of 100 above the early limit. Large events studied during the next solar cycle [*Reames and Ng* 1998] appeared to have limits that decreased with proton energy, as shown in Figure 1. Dashed lines are drawn at the 'streaming limit' for three energy intervals plotted in the figure; the 100-500 MeV protons do not reach the limiting value in the last two events.

It is well known that distributions of particles streaming along magnetic field lines are unstable to the production of resonant Alfvén waves [*Stix* 1962; *Melrose* 1982]. At high particle intensities, sufficient intensities of resonant waves are produced to scatter the particles that come behind and reduce their streaming. This process serves to trap particles near their source and bound the outward flow at the streaming limit.

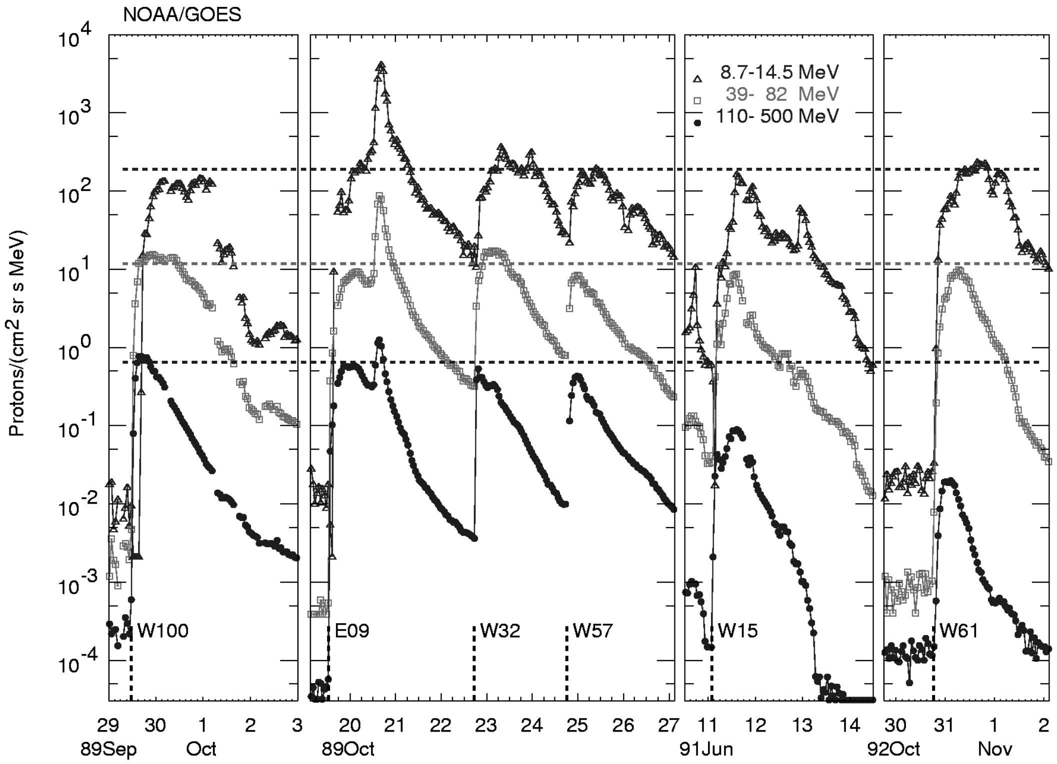

Figure 1. Intensity-time profiles are shown for three energy channels during six large SEP events of the last solar cycle. Streaming-limited intensities for each channel are shown as dashed horizontal lines. CME source longitudes are indicated for each event as dashed vertical lines at the time of onset [*Reames and Ng* 1998].

This limit, of course, depends upon radial distance in the diverging magnetic geometry. *Ng and Reames* [1994] performed a numerical simulation of particle transport out from the Sun through self-generated Alfvén waves. They were able to confirm the value of the low-energy streaming limit. In a subsequent study using Helios data, the radial dependence of the early streaming limit was found to be consistent with the R^{-3} dependence expected theoretically [*Reames and Ng* 1998].

2.2.Longitude Distributions

Kahler [2000] discussed the effect of the solar longitude of the observer relative to the CME on the appearance of the intensity-time profile. Because of the spiral magnetic field, an observer's magnetic connection to the shock swings eastward with time, either approaching or receding from the intense 'nose' of the shock [see Figure 10 of *Kahler* 2000 and *Reames, Barbier, and Ng* 1996].

Source longitudes are shown for the events in Figure 1. Coincidentally, most of these event source longitudes are west of the observer so the shock nose does not reach 1 AU. No strong peaks are seen at times of shock passage for these events, although, the events from W15 and W32 do show shock increases at low energies. However, the event on 1989 October 19 from E09 shows a strong peak in all energy channels when the shock reaches Earth a day later. This shock has an *average* speed of ~1500 km s^{-1}. Shock intensity peaks are produced by CMEs from central meridian that produce sufficiently fast shocks to continue acceleration out to 1 AU. Shock peaks in >100 MeV protons are rare, but can be a serious hazard when they occur.

At times, longitude distributions of a single SEP event can be measured using multiple spacecraft [*Reames, Barbier, and Ng*, 1996; *Reames, Kahler, and Ng*, 1997]. Figure 2 shows intensity-time plots for three spacecraft distributed in longitude about a CME as shown in the inset. Helios 1 passes near the nose of the shock and sees a flat, streaming-limited profile followed by a peak at the shock. Helios 2 and IMP 8 farther around the west flank see increasingly slower rises. This small event has a relatively narrow longitude span; other events have high intensities over a span of more than 90° to the east and west of the central longitude of the CME.

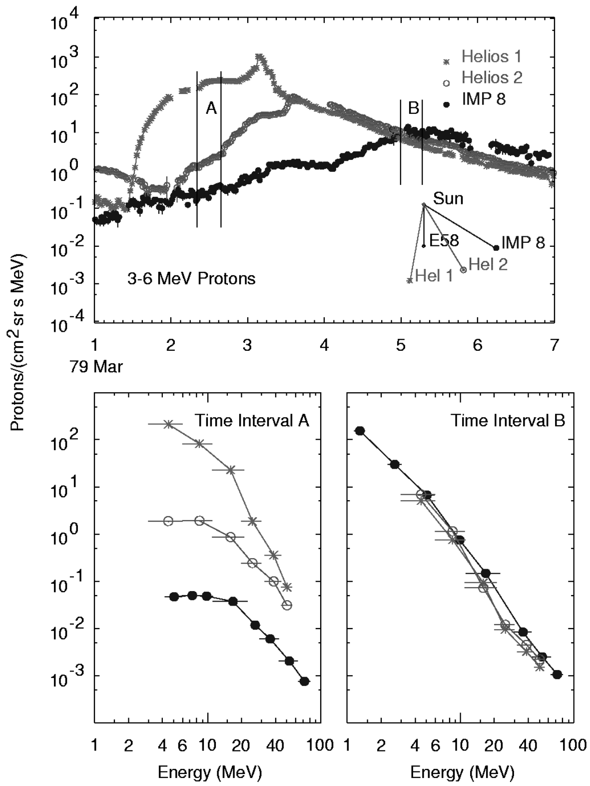

Figure 2. Intensity-time profiles for 3-6 MeV protons for three spacecraft at different longitudes (see inset) are shown in the upper panel. Proton energy spectra at time A are contrasted with invariant spectra at time B in the lower panels.

Figure 2 also shows that the intensities at the three spacecraft merge, within a factor of ~2, late in the event, long after shock passage in this case. This is a region of spatially and temporally invariant spectra [*Reames, Kahler, and Ng*, 1997]. Energy spectra observed early and late in the event are contrasted in the lower panels of the figure. These invariant spectra are produced in regions where particles are trapped or quasi-trapped in magnetic bottles. Adiabatic deceleration of the particles preserves the spectral shape as the volume of the bottle expands. At times, preexisting leaky bottles formed by old CMEs can fill with particles from a new event at the Sun, causing invariant spectra to be seen ahead of the shock [*Reames* 1999a]. Bottles can also be formed when particles are quasi-trapped behind the wave turbulence near a shock, either the shock that accelerated them or one from an earlier event.

3. SHOCK ACCELERATION.

The same proton-generated waves, that limit streaming and trap particles near the source, greatly increase the acceleration efficiency of that source. The importance of self-generated waves has been recognized for shock acceleration in many astrophysical contexts; self-generated waves were first applied to shock acceleration in SEP events by Lee [1983]. Although this is a static, equilibrium model with a planar shock, the Lee model has been seminal in promoting our understanding of the physics of SEP acceleration. SEP acceleration at shocks can only be sustained by proton-generated waves; ambient turbulence is completely inadequate to support acceleration above ~1 MeV. Only a small fraction of the ambient turbulence resonates with energetic ions.

A simple cartoon illustrating shock acceleration is shown in Figure 3. Acceleration actually occurs as particles are scattered back and forth across the shock by waves carried at the different velocities of the upstream and downstream plasma. Injected at low energy, probably from the tail of the thermal plasma

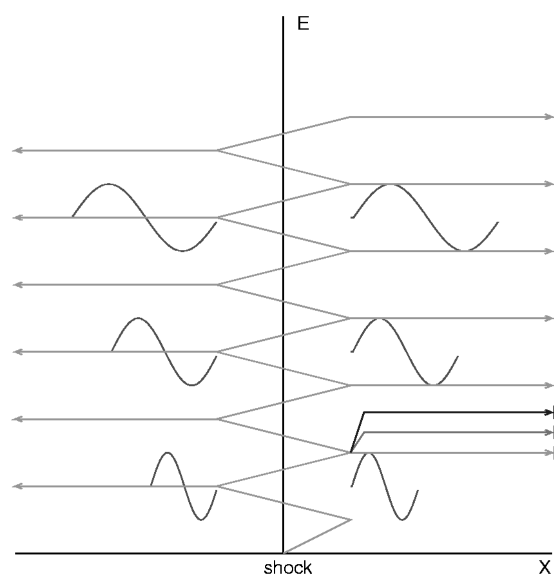

Figure 3. The cartoon illustrates efficient energy gain of particles at a shock because of trapping by self-generated Alfvén waves. Particles of increasing energy resonate with waves of lower wave number, *k*, and greater wavelength.

distribution function, particles begin to scatter, first on ambient turbulence then on resonant waves they generate as they stream away from the shock. Particles of magnetic rigidity (momentum per unit charge) *P*, resonate with waves of wave number *k*, when $k=B/\mu P$, where *B* is the magnetic field strength and μ is the cosine of the particle pitch angle with respect to the field. Most of the waves are produced by the dominant species, protons.

As trapping increases for particles of one rigidity, they are more likely to be accelerated to a higher rigidity, where they again stream out and produce resonant waves, *etc*. As this process continues, a 'wall' of resonant waves grows up the energy axis. Since the streaming of particles away from the shock is limited, the height of the 'wall' depends upon the number of particles injected at the bottom. Thus, increasing the injection increases the maximum energy to which particles can be accelerated.

Given infinite time, acceleration would produce a power-law energy spectrum at the shock. Ions of different elements are accelerated to the same velocity or energy/nucleon at the shock; these spectra differ in proportion to the coronal abundances of the elements [*Reames* 1999a]. However, escape from the shock depends upon the rigidity of an ion and hence upon it's ionization state or charge-to-mass ratio, *Q/A*. Hence, different species, of the same velocity, probe different parts of the wave spectrum as they escape. Element abundance ratios, such as Fe/O, viewed away from the shock, can be enhanced if Fe escapes more easily than O; near the shock Fe/O would be suppressed. The degree of enhancement or suppression depends upon the slope and intensity of the wave spectrum.

The CME-driven shocks that accelerate SEPs are uniquely dynamic when compared with other shock waves in the heliosphere. These shocks are born anew in each event in the plasma of the high corona and they expand in a roughly spherical shell across the magnetic environment. By the time they reach 1 AU, days later, the plasma densities and magnetic fields have decreased by orders of magnitude, and even the fastest shocks have slowed considerably. Simulation of the shock and the particles in this environment requires a numerical model. It is only recently that the first dynamic models of shock acceleration [*Zank, Rice, and Wu* 2000] and of particle transport, solving coupled equations for the transport of both particles and waves [*Ng, Reames, and Tylka* 1999], have become available.

4. SPECTRAL KNEES.

At high particle energies, intensities may become too low to sustain wave growth so that scattering is reduced and the particles begin to leak away from the shock. This causes the energy spectrum to depart from its nominal power-law form and to steepen exponentially, forming a spectral 'knee.' Figure 4 shows examples of spectral knees in SEP events. The left panel shows proton data taken on spacecraft and measured by the ground-level neutron monitor network (NMN, shaded region in figure) in the 1989 September 29 SEP event. The fit to the data is the power-law times exponential form used by *Ellison and Ramaty* [1985]. The e-folding energy E_{knee} = 1 GeV for this event [*Lovell, Duldig, and Humble* 1998]. The right-hand panel in Figure 4 shows spectra of H, He, O, and Fe in the 1998 April 20 event. In this event, E_{knee} =15 MeV for protons and scales as *Q/A* for the other species. In those few other events that can be measured, the e-

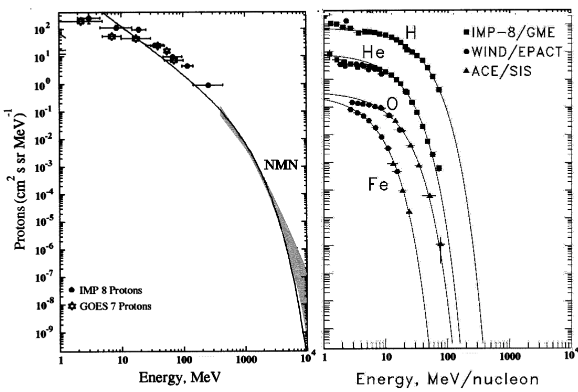

Figure 4. The proton energy spectrum in the 1989 September 29 SEP event (left panel) is measured by spacecraft and the neutron monitor network (NMN) [*Lovell, Duldig, and Humble* 1998]. The right panel shows spectra of ions in the 1998 April 20 event [*Tylka et al.* 2000]. Proton spectral knees occur at much different energies in the two events.

folding energy/nucleon does not always scale linearly with *Q/A* [*Tylka et al.* 2000].

It is difficult to understand the origin of the large difference in E_{knee} for protons in the two events in Figure 4. Both events occur near the west limb of the Sun and the CME speeds are ~1800 and 1600 km s^{-1} in the 1989 and 1998 events, respectively. The detailed physics of shock acceleration that determines the knee energies is not well known. Worse, many of the largest events have knee energies above the region we can observe; the required measurements are simply not available.

However, the practical effect of differing knee energies becomes clear when we directly compare, in Figure 5, fits to the two proton spectra from Figure 4. Also shown in Figure 5 are levels of radiation hazard to astronauts outside the magnetosphere. 'Soft' radiation occurs where protons begin to penetrate space suits or spacecraft walls. ‘Hard’ radiation begins at a proton energy that will penetrate ~5 cm of Al; here, shielding becomes impractical. Even though the two events have similar proton intensities from 10 to 100 MeV, the different values of E_{knee} cause vastly different levels of hazard. The spectrum shown for the 1989 September

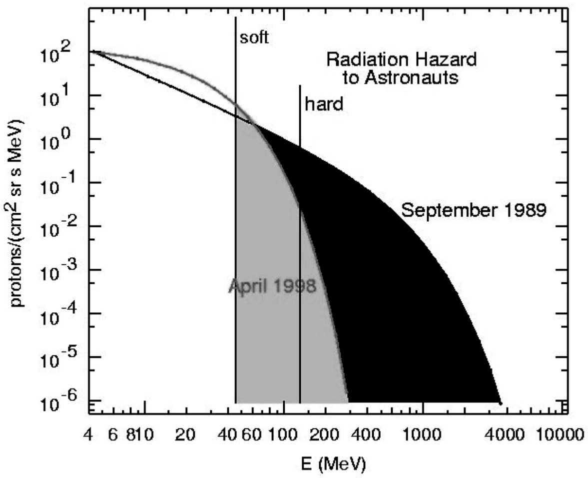

Figure 5. The proton spectra from the two events in Figure 4 are compared to show substantial differences in their radiation hazard inside a spacecraft wall (soft) and inside ~5 cm of Al (hard).

event would produce ~4 rem hr^{-1} behind 10 g cm^{-2} of shielding. The annual allowed dose for astronauts, 50 rem, would be accumulated with exposures of half a day to such intensities. Radiation workers at ground level are only allowed 15 rem yr^{-1}, and reduction of the level for astronauts has been suggested.

A truly serious situation would result if a high-energy knee persisted until the large peak at the time of shock passage. In this case, streaming limits would not apply as they do in the 1989 September event. The event of 1972 August 4 is an example of high intensities of high-energy protons occurring at a shock peak; unfortunately, instrument saturation prevented definitive spectral measurements in that event.

It is generally accepted that radiation levels in the 1972 August 4 event would have been fatal to inadequately shielded astronauts. The issue is the thickness of shielding required for protection. The thickness required to stop protons of given energy goes as the 1.6 power of the energy. Increasing E_{knee} from 50 to 500 MeV would increase the thickness and weight of the required shielding by a factor of 40. Mission costs increase at least linearly with payload weight, and manned missions to Mars, for example, are already expensive. Our present knowledge does not allow us to define a meaningful value of E_{knee} that is appropriate for shielding design.

5. ABUNDANCE VARIATIONS.

The discovery of regular methodical time variations in element abundance ratios in SEP events [*Tylka, Reames, and Ng* 1999] has been a key to our new understanding of the dynamics of acceleration at CME-driven shocks. The theory that evolved to explain these observations [*Ng, Reames, and Tylka* 1999] has also explained other abundance anomalies in He/H that have puzzled observers for 20 years [*Reames, Ng, and Tylka* 2000].

Figure 6 shows dramatic time variations of abundance ratios, normalized to the corresponding coronal abundances, in a large SEP event. The right-hand panel in the figure shows a theoretical simulation of the event. The detailed time behavior of the abundances depends upon the time behavior of shock parameters such as the

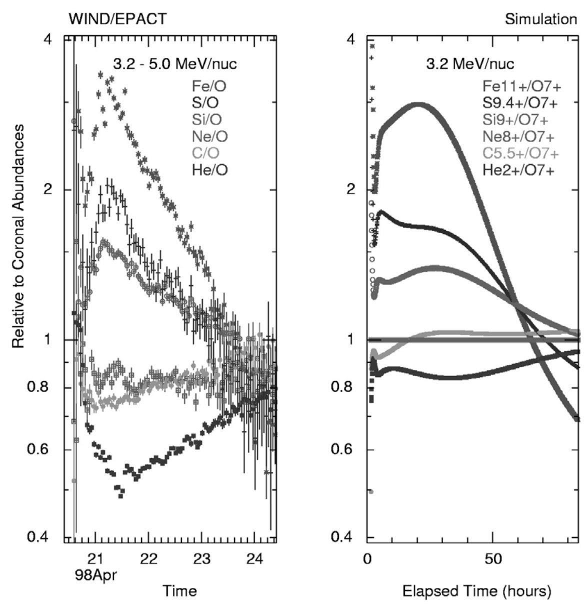

Figure 6. Measured and simulated element abundance ratios vary with time during an SEP event. These variations result from changes in the proton-generated wave field near the shock.

shock compression ratio, which has been assumed to decrease linearly in the simulation. Variations of this kind were essentially unknown a few years ago; abundances were studied only by averaging over entire events.

The variation of abundances with energy and with time results from changes in the spectrum of resonant waves at the shock. Since proton intensities are often streaming-limited early in large events, these abundance variations may be our only probe of conditions at an oncoming shock. For example, He/H ratios that are strongly suppressed and rising early in an event are already a powerful indication of high proton intensities at the oncoming shock [*Reames, Ng, and Tylka* 2000]. Before we can 'calibrate' abundances as a remote-sensing device of proton intensities and spectra at a shock, we must refine our models to include all processes that influence the relationship between protons, resonant waves, and abundance variations. Often we must work with particles from distant shocks whose properties are not independently known. Thus, models of SEP acceleration and transport must eventually be combined with models of the evolution of the shock itself.

6. SUMMARY AND PROSPECTS.

Large SEP events can be a significant hazard to humans and equipment outside the Earth's magneto-sphere. In the largest SEP events, particles are accelerated at CME-driven shock waves. Events where particles are stochastically accelerated in solar flares also occur, but they are small and are not considered in this article [see *Reames* 1999a].

Particle intensities from large SEP events may be streaming-limited, early in the events, by proton-generated waves that throttle the outflow from the shock. This trapping increases the efficiency for acceleration to higher energy. Self-generated waves dominate all aspects of the events, including intensities, element abundances, spectra and angular distributions.

The spatial distribution of accelerated particles around a shock in solar longitude controls the time profile seen by an observer whose magnetic connection swings eastward across the face of the shock with time. Intensities increase (decrease) as the connection point moves toward (away from) the nose of the shock. The shock strength may also decrease with time as the shock expands radially. While flow of particles from the distant shock is streaming-limited, very large intensity peaks can occur when a strong shock from central meridian passes over the spacecraft.

At some high energy, resonant wave generation at the shock can no longer be sustained. At this energy, particles begin to leak from the shock and a spectral knee forms. The position of this knee can vary greatly from event to event and during an event. Events with a high-energy knee are the most threatening to astronauts, especially if that knee occurs during a shock peak where streaming limits do not apply.

Events with high intensities of >100 MeV protons at shock peaks are rare, 1972, 1989, …. However, their occurrence becomes more likely during long-duration missions to the moon or Mars. Furthermore, the rarity of these events itself makes them difficult to study and their probability of occurrence difficult to assess.

Prospects for improving SEP models in the future include the following:

1) Improved theoretical models of shocks and SEP acceleration and transport are likely. Several research groups now work in this new field of dynamic SEP acceleration at shocks [*e.g. Zank, Rice and Wu* 2000].

2) The STEREO mission, scheduled for launch in 2004, will provide stereoscopic images of CMEs permitting three-dimensional modeling of the acceleration region along with multi-spacecraft observation of the SEP events.

3) We have proposed a large-geometry, high-energy experiment, SPARKLE, for the International Space Station that will measure spectra and abundances of particles out to 2 GeV/amu to pursue the study of spectral knees into this new and important energy region that is currently inaccessible. SPARKLE would measure spectral knees at the same time that STEREO is mapping the source region.

A serious problem during the last 10 to 20 years has been the dearth of scientists actively studying the properties of protons in SEP events. Former workers in the field have moved their interests to the outer heliosphere, to abundances and isotopes, or to energies below 1 MeV. Few papers in the refereed literature contribute information of use to space weather. In this context, the renewed theoretical interests in SEP events are especially gratifying.

New models have guided our understanding of SEP acceleration, but we cannot yet make detailed forecasts of SEP properties for a given shock. Nevertheless, recent progress suggests that such forecasts are within our grasp.

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Donald V. Reames, Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771.