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Solar energetic particles: A paradigm shift

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Introduction

The first evidence of high-energy particles from the Sun was obtained 50 years ago when *Forbush* [1946] used sea-level ion chambers to study the large solar events of February and March of 1942. Over the next 20 years, observation of these solar energetic particle (SEP) events using neutron monitors and riometers (that measure radio opacity of the ionosphere) and, later, with detectors on balloons and satellites, led to an extensive body of knowledge on the time profiles, spectra and particle abundance in the large events. Meanwhile, there was already a rich history of the study of solar flares spanning 100 years since the first observations reported by *Carrington* [1860]. With no knowledge of the existence of coronal mass ejections (CMEs) [*Kahler* 1992], it was tempting to assume that the particle acceleration somehow occurred in spatial and temporal conjunction with the solar flare itself. Thus the "solar flare myth" [*Gosling* 1993] of particle acceleration began nearly 30 years ago.

However, it was not so easy to explain the SEP observations in terms of a flare source. Flare activity at the Sun lasts, at most, for hours while SEP events can persist for many days. Particles could be seen from events anywhere on, and sometimes behind, the visible disk, yet it was well known that particles could not cross the interplanetary magnetic field lines over such large distances. The proposed explanation, which dominated the study of energetic particles, was the Reid-Axford model [*Reid* 1964; *Axford* 1965]. The key to this model was a solar corona that stored the particles, somehow allowing them to diffuse easily in longitude, then slowly diffuse outward once the particles leaked from the corona into interplanetary space. No mechanism for the "coronal diffusion" was ever identified, however, the model offered enough adjustable parameters to fit some of the more well-behaved time profiles of the particle intensities in large SEP events.

At about the same time, *Wild, Smerd and Weiss* [1963] proposed a much different picture to explain their radio observations. They observed type III bursts, in which fast frequency drifts were produced as electrons streamed outward from the Sun through plasma of decreasing density, and type II bursts, where drift rates corresponded to the lower speed (~1000 km/s) of an outbound shock. This led to the idea of two-phase acceleration, with electron acceleration early in the flare followed by proton acceleration at the expanding shock. While we now know that protons and electrons are accelerated in both "phases", these authors emphasized the presence of two acceleration mechanisms and prophetically suggested that particle abundances might distinguish them. Of course, interplanetary (IP) shocks had also been observed directly near Earth by this time, but the idea that shocks could dominate the acceleration of particles over a long time periods at longitudes far from the flare was not appreciated. We now know from Voyager and Pioneer observations that multiple mass ejections merge to drive shocks that continue to accelerate particles far beyond the orbit of Earth, perhaps all the way to the heliospheric boundary.

An essential ingredient of our current picture of both SEP events and large non-recurrent geomagnetic storms [see *e.g.*, *Webb* 1994] is the coronal mass ejection (CME). Observations on the Skylab mission [*Gosling et al.*, 1974] (a decade after the "coronal diffusion" models) showed that CMEs can eject up to 10^{16} g of material at speeds above 1000 km/s (an energy of $\sim 10^{32}$ ergs). These sudden, violent ejections probably drive all of the traveling interplanetary shocks and are associated with gradual or long-duration (>1 hr) soft X-ray production associated with field reconnection as the large filament and surrounding magnetic structure of the CME tears away from the restraining fields. CMEs are poorly associated with flares [see review by *Kahler* 1992] but, in very large events, CMEs and flares do occur together.

Particles from impulsive and gradual events

For a number of reasons, nearly all of the early SEP observations were made in events we now call gradual events or simply "proton" events. Element abundances of the MeV particles in these events were found to be simply related to those of the solar corona [see *e.g., Meyer* 1985; *Reames* 1992]. In 1970, however, *Hsieh and Simpson* [1970] first reported ^{3}He-rich events. Such events would be found to have ^{3}He/^{4}He ratios in the range of 0.1 to 10, while the corresponding ratio in the corona and solar wind is 5×10^{-4}. Order of magnitude enhancements in heavy element abundances (e.g. Fe/O) were also seen [see reviews by *Reames* 1990a, 1993, 1994]. As more and more ^{3}He-rich events were seen, it became clear that they had a different behavior from the proton events.

Figure 1a shows the time history of a typical large gradual proton event. Protons dominate electrons in these events. Low energy (~1 MeV) protons reach a plateau in intensity at the same value in many large events, although their intensity may rise again several days later as the shock passes. Profiles of electrons and higher-energy protons decline slowly with time. Figure 1b shows a series of ^{3}He-rich events at the same scale. These events are often dominated by electrons and the intensities of all species decay rapidly with time. If the time profiles were controlled by pre-existing interplanetary scattering, why would particles of the same species and energy always have different profiles for ^{3}He-rich and proton events?

When ^{3}He-rich events have high intensities of nearly relativistic electrons, which arrive within minutes of the photons, it is relatively easy to associate the events with impulsive X-ray and Hα flares and the with type III radio bursts [see *Reames et al.* 1988, 1990]. The longitude dependence of the associated flares fall within a longitude band of <30° width about the footpoint of

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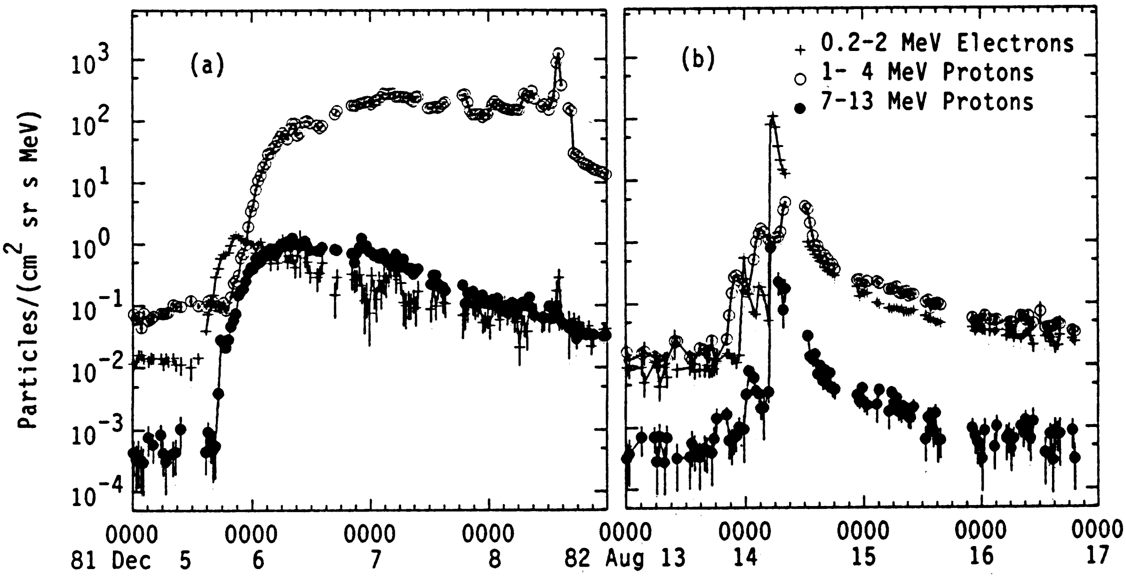

Figure 1. Time profiles of protons and electrons in (a) gradual (proton) and in (b) impulsive (^{3}He-rich) events.

the nominal spiral field line, as seen in Figure 2. Gradual proton events [from *Cane et al.* 1988] show a more uniform longitude pattern. Why would particles from the ^{3}He-rich events be unable to share the "coronal diffusion" of their brethren in the gradual events? Shocks cross field lines much more easily than particles and thus can accelerate particles over a wide longitude interval.

A completely different sort of information comes from the ionization state of the energetic Fe ions. In the gradual events, Fe has a mean ionization state of 14.1 ± 0.2 [*Luhn et al.* 1987], similar to that of Fe ions in the solar wind, and indicative of ambient (unheated) coronal material at a temperature of ~2 MK. Even at energies above 200 MeV/amu Fe ions were found to have charge Q_{Fe}~12.5 [*Adams et al.* 1993] in three large gradual events. If this Fe had been processed at a temperature of 20-30 MK, typical of a large flare, it would have Q_{Fe}>24 and lighter elements would be fully ionized. Meanwhile, Fe ions in ^{3}He-rich events have an average ionization state of 20.5 ± 0.2 [*Luhn et al.* 1987], indicating either heating to ~10 MK, or, more probably, stripping of the ions in the intense electron beams in impulsive flares [*Miller and Viñas* 1993]. Fully ionized Fe has Q_{Fe}=26.

A final indication that the particle acceleration in the large proton events is related to CMEs rather than flares comes from event associations. According to *Kahler et al.* [1984], 96% of the large proton events have CMEs associated with them. Some of the proton events are associated with "disappearing filament" events on the Sun. In these events a filament and surrounding magnetic structure rises from the Sun to form a CME, but there is no associated impulsive flare event [see *Kahler et al.* 1986]. In fact, the "typical" large proton event I have shown in Figure 1a comes from a disappearing filament event.

Impulsive-flare (^{3}He-rich) events were once thought to be rare, however, it is now clear [*Reames*, 1993; *Reames et al.* 1994] that the events are observed at 1 AU at a rate of about 100 events/yr during solar maximum. Since they come from a restricted longitude interval as seen in Figure 2, ~20° or less when we allow for field-line motion with solar wind speed, the total number of events on the solar disk must be ~1000/yr at solar maximum. The number of hard X-ray bursts, Hα flares and type III bursts vary from ~4000/yr to ~10000/yr [see *Reames* 1993]. Even at the present level of instrument sensitivity, the ^{3}He-rich events account for a significant fraction of solar flares; this fraction might increase when instruments with 100 times this sensitivity are flown aboard the WIND spacecraft. Meanwhile, *Cane et al.* [1988] found a total of 235 proton events in 20 years, or ~20/yr at solar maximum. In this case there is no correction for longitude since the events come from the visible disk and even from far behind the west limb. The rate of CMEs is ~500/yr,

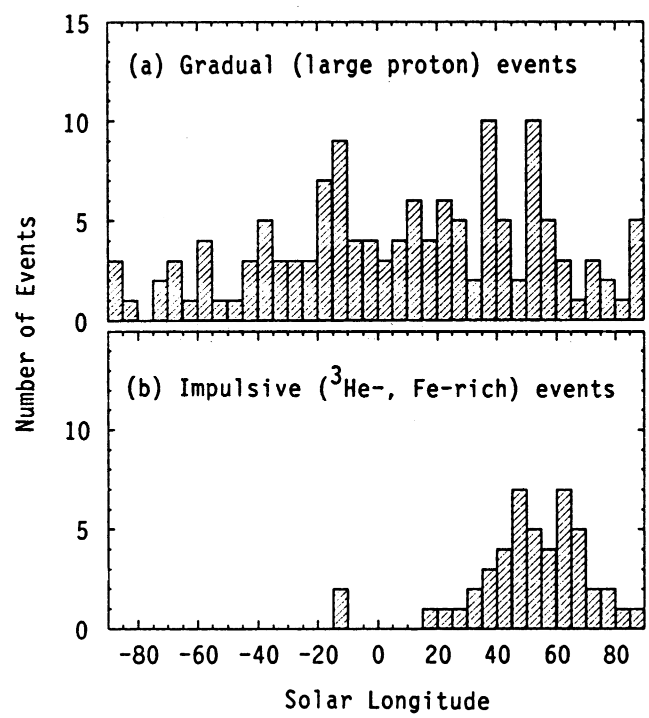

Figure 2. Longitude distributions of gradual and impulsive events.

Table 1. Properties of Impulsive and Gradual Events

	Impulsive	Gradual
Particles:	Electron-rich	Proton-rich
$^3He/^4He$	~ 1	~ 0.0005
Fe/O	~ 1	~ 0.1
H/He	~ 10	~ 100
Q_{Fe}	~ 20	~ 14
Duration	Hours	Days
Longitude Cone	<30 deg	~180 deg
Radio Type	III, V (II)	II, IV
X-rays	Impulsive	Gradual
Coronagraph	-	CME (96%)
Solar Wind	-	IP Shock
Flares/year	~1000	~10

however, many are too slow to form the strong shock that is necessary for particle acceleration.

A summary of the properties of gradual and impulsive events is given in Table 1. These observations have led to a new paradigm: in most of the large proton events a CME-driven shock wave accelerates the particles from the ambient plasma of the corona and solar wind as it propagates over a large region of space and time. The particles that *are* actually accelerated in impulsive flares have unusual ^{3}He-rich, Fe-rich, and electron-rich abundances that were probably produced by wave-particle interactions induced by the streaming electrons in the flare plasma [*Temerin and Roth* 1992; *Miller and Viñas* 1993].

Proton events and CME-driven shocks

The flat time profile seen in many large proton events as in Figure 1a is a signature of continuous acceleration. Suppose a shock wave accelerates some fraction of the local solar wind plasma to the energy of interest and the particles then expand like R^{-2} as they come out to the observer. If the source solar wind density also varies like R^{-2}, the intensity seen by an observer at distance R from the Sun will not vary with time. In the diffusive shock acceleration picture [*Lee* 1983], particles near the shock are scattered back and forth across the shock by self-generated waves, gaining energy on each transit. The intensity of particles and waves decreases with distance from the shock to a point where there are not enough particles to produce sufficient waves; thence the particles stream freely away. This determines the maximum intensity that particles can have early in the event, a few x 100 protons/(cm^2 sr s MeV) on the saturation plateau at a few MeV [*Reames* 1990b, 1993, 1994; *Ng and Reames* 1994] as seen in Figure 1a and the lower panel in Figure 3. The intensity peak near the shock has historically been called the "energetic storm particle" (ESP) event. Note, however, that all the particles actually can come from the shock, those that arrive early as well as those in the ESP event.

At higher energies, where the particles are less numerous, fewer resonant waves are produced and the trapping structure (ESP event) weakens as the shock front expands like R^{-2}. The decreased trapping results in less efficient acceleration and the intensity of the higher energy particles decreases with time. At sufficiently high energies the ESP structure does not survive all the way out to 1 AU and is not seen. Thus the highest energy particles are accelerated closest to the Sun. Generally the highest energy particles (~100 MeV to >20 GeV) reach peak intensity when the CME is at 5-15 solar radii [*Kahler* 1994]. The 1989 September 29 event at 105°W has a CME speed of 1828 km/s and the 21 GeV particle intensity peaks at 5 solar radii [*Kahler* 1994]. This is an event where *Adams et al.* [1993] find Q_{Fe}=12.5 above 200 MeV/amu. Clearly this suggests that this "ground-level event" is caused by a CME-driven shock propagating across the high corona to accelerate ambient, unheated plasma on the field line connected the Earth.

However, the story of the profiles of intensity *vs.* time is somewhat more complex, because of the variation of the profiles with the CME longitude. This variation, described by *Cane et al.* [1988], is shown for protons of different energy in Figure 3. Events near central meridian produce the intense flat profiles. Behind the shock is a second plateau region that is characterized by bi-directional streaming events [*Marsden et al.* 1987; *Richardson and Reames* 1993] and magnetic clouds where the spacecraft is probably passing through the CME itself. For western events, the peak intensity occurs early when the nose of the shock is best connected to the observer. By the time the shock reaches 1 AU, the observer is connected far around on the eastern flank of the event where the shock is weak, if it is seen at all. For eastern events, the intensity may begin to rise when the coronal shock reaches the base of the observer's field line, but the peak intensity may occur late, after the weak local shock has passed and the observer reaches field lines that connect to the strong acceleration region near the nose of the shock which is now far out beyond him. *Reames* [1994] shows large events that are viewed from 3 widely separated spacecraft.

Impulsive flare events

In impulsive flares, the streaming 10-100 keV electrons, that are seen by the type III radio bursts and hard X-rays they produce, form velocity distributions that are unstable for production of hydrogen electromagnetic ion cyclotron (EMIC) waves [*Temerin and Roth* 1992]. The frequencies of these waves lie between the gyrofrequencies of H and of ^{4}He. The rare isotope ^{3}He is the only species whose gyrofrequency lies in this range to resonantly absorb these waves. The waves are only produced in a regions of high magnetic field near the base of the corona where the Alfvén speed is >2000 km/s. The acceleration is extremely efficient, in fact, the observed number of ^{3}He ions in space requires the acceleration of >10% of the ^{3}He in a typical flare volume near the base of the corona [*Reames* 1993].

Heavy ions probably interact with other wave modes produced below the ^{3}He gyrofrequency [*Miller and Viñas* 1993], and their enhancements are more modest [see *Mason et al* 1986; *Reames et al.* 1994]. The similar enhancements of Ne, Mg and Si suggest that those species have similar gyrofrequencies. This only occurs if acceleration begins at a plasma temperature of ~3 MK [*Reames et al* 1994].

Acceleration of the ions we observe at 1 AU probably occurs on open magnetic field lines, but there is gamma-ray evidence that the ions are accelerated on closed loops by the same mechanism. The broad gamma-ray lines, produced by ions in the energetic beam, show the same pattern of heavy-element enhancements and the low proton/^{4}He ratio (~1.0) that is seen in the ^{3}He-rich events at 1 AU [*Murphy et al* 1991]. Unfortunately,

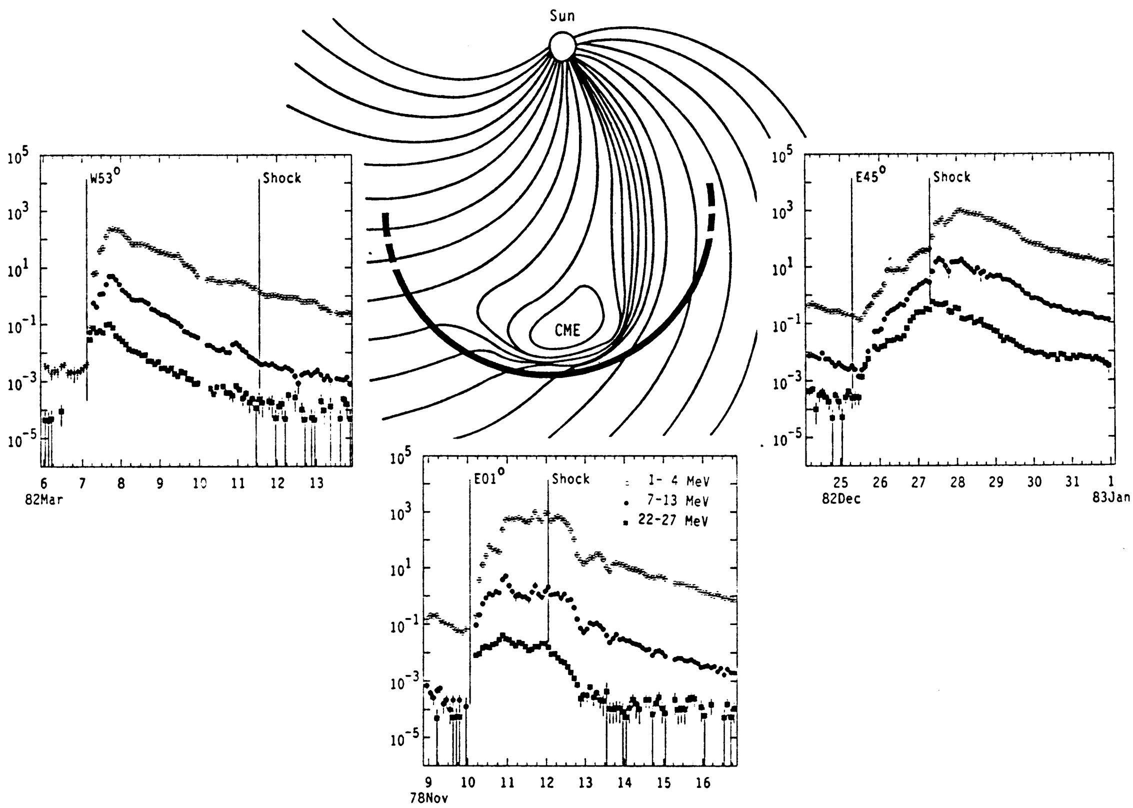

Figure 3. Intensity profiles for protons of different energy for observers viewing a CME from the three different longitudes indicated in the panels.

the $^3He/^4He$ ratio itself cannot be measured with gamma-ray line spectroscopy.

The particles accelerated in gamma-ray events at the Sun can produce intense particle events with hard spectra near Earth [*Van Hollebeke, McDonald and Meyer* 1990]. Partly because of the small longitude cone, however, they are relatively rare. Some well-connected events also show the presence of both impulsive and gradual components, with Fe/O~1 early in the event falling to Fe/O~0.1 later in the gradual phase of the event [*Reames* 1990b].

Conclusions

During the last few years there has been a shift in the paradigm of solar particle acceleration based on improved measurements of particles and their correlation with solar phenomena. We now recognize that the particles in most of the largest events are accelerated over a large spatial region by the shock wave ahead of a CME, ***not*** in a solar flare. The particles that ***are*** accelerated in association with impulsive flares have unusual ^3He-rich, Fe-rich abundances resulting from electron-beam induced resonant wave-particle interactions in the flare. In fact, particle abundances and ionization states have become a tool that can distinguish the two mechanisms of acceleration, even in some events where both mechanisms are present [*Reames* 1990b].

The identification of the particle sources has changed our ideas of particle transport. With extended shock acceleration, we no longer need ***ad hoc*** concepts like "coronal diffusion" to explain the longitude distribution or time profiles, and the particles stream outward from any source with only moderate scattering. In large events the time profiles tell us mostly about the evolution of the source and our connection to it, and almost nothing about particle transport from it.

Having the correct acceleration paradigm is of great practical importance if one is to predict particle events at Earth. The highest intensities and longest durations of 1-10 MeV protons are likely to come from CMEs launched near central meridian. The highest energy protons, accelerated fairly near the Sun in all cases, will come from events near ~50° west. Highly-ionizing Fe ions will be especially abundant at 1 AU when large impulsive flares occur at ~40°-70° west. As a large, magnetically-complex active region traverses the solar disk, the intensity, abundances, spectra and time profile of the particles that might be expected from events in the region will change with time.

We have only begun to understand the physics of particle acceleration in solar events and many questions remain. In the impulsive events the mechanism of acceleration of the intense electron beams is not clear, both electric-field and stochastic mechanisms seem possible. We cannot yet predict the abundances of all the elements in these events and the role of wave cascading is not clear. In the gradual events we do not know the structure, strength and time evolution of the shock far around on the flanks and especially in the corona. We are especially uncertain about the connectivity and topology of the magnetic field lines close behind the shock within the "ejecta" and still farther behind where field lines may be "drawn out" by the CME [see *Reames* 1994]. We cannot even predict the abundance variations that occur in different gradual events. Recognizing the approximate site of the acceleration is only the beginning.

It is now clear that the errors of the previous paradigm came about partly because of an excessive focus on protons. This made proton-poor events seem small and inconsequential so they were overlooked while great effort was lavished on fitting proton time profiles and anisotropies in large events. Much of our new understanding has come from the study of the abundances of elements and isotopes and of their ionization states. Not only do these ions tell us about the conditions in the source plasma but they have opened a new window on the complex plasma physics of particle acceleration. The existence of resonant wave interactions that enhance ^{3}He by many orders of magnitude can not be inferred from photon observations of flares. Similar processes may be important in distant sources of astrophysical interest where direct particle observations are not possible.

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