Report from SHINE 2001 Working Group 3 on Solar Energetic Particles

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The SHINE 2001 WG3 considered three questions relevant to solar energetic particles:

1. Is there evidence for flare-accelerated particles at 1AU in large, gradual SEP events?
2. How can numerical modeling of LASCO images be used to strengthen or test the SEP-CME connection?
3. Are there good predictors of energetic storm particle (ESP) events?

Evidence for flare-accelerated particles at 1AU in large, gradual SEP events

There is absolutely no question that both flares and CME-driven shocks contribute to the energetic particles observed in interplanetary space (Reames 1999a). The existence of at least two distinct acceleration mechanisms has been known for a very long time, based on the existence of 3He-rich events, in which 3He/4He exceeds 10% and thus correspond to >1000x enhancement over solar-wind values. Such very large distortions are thought to be beyond the capabilities of shock acceleration. The reality of these two distinct SEP-acceleration mechanisms has recently been reinforced by the discovery of ultraheavy (atomic number Z > 34) ions by Wind at ~3-10 MeV/nuc (Reames 2000) and subsequent confirmation by ACE at lower energies (Mazur et al. 2001). In the relatively small, so-called "impulsive" events, in which flare-acceleration mechanisms dominate, these ultraheavies are observed at levels exceeding coronal values by factors of 100-1000. On the other hand, in the large so-called "gradual" events, in which the CME-driven shock is generally believed to be the primary accelerator, the ultraheavies are consistent with coronal/meteoritic composition.

The very largest "gradual" SEP events, which typically last for days at ~MeV energies, are always seen in conjunction with fast CMEs and almost always with large flares. This situation naturally leads to questions about the respective roles of these two acceleration sites in producing the interplanetary particle population. The controversy has re-ignited in recent years, due to new observations showing that some gradual events have features previously associated primarily with impulsive events (enhanced Fe/O, 3He/4He enrichment, and relatively high Fe charge states (average charge state QFe > 16)). Some researchers have argued that these features are prima-facie evidence for a larger role for flares in gradual events than generally thought. Other researchers, however, have investigated other factors, such as transport-induced abundance distortions (Ng et al. 1999) and complex source populations (Mason et al. 1999; Tylka et al 2001a), which might mimic a direct flare component. This background of new data, new insights, but as-of-yet-incomplete-understanding sparked some of the liveliest exchanges in the Working Group.

One specific way in which flares and CMEs combine to produce large gradual events has recently been proposed by Mason et al. (1999), in order to explain the measured 3He/4He of a few percent at a few hundred keV/nuc in some large gradual events. Suprathermal particles, with speeds several times that of bulk solar wind, are generally thought to provide the seed population for particles accelerated to high energies by shocks. Mason et al. (1999) suggested that, at least at some times, the ubiquitous solar-wind suprathermals can be augmented by suprathermals from impulsive SEP events. These suprathermals would have been originally accelerated at a flare site, and hence bear distinctive compositional and charge-state characteristics. Since suprathermals take several days to move through the inner heliosphere, they constitute a remnant population, whose magnitude would vary with the rate of preceding flare activity (Desai et al. 2001). A shock would then be expected to accelerate particles from both solar-wind and remnant-flare suprathermals in a more or less unbiased fashion.

Allan Tylka presented some recent work (subsequently published; Tylka et al. 2001a; 2001b) that pursued this notion of remnant flare suprathermals. But instead of focusing on composition at a few hundred keV/nuc, he examined ion spectral characteristics at ~1-100 MeV/nuc, the highest energies measured by Wind and ACE. The spectral analysis made use of the fact that the energy spectra of shock-accelerated particles are expected to show an exponential roll over at high energies, with the e-folding energy proportional to the mass-to-charge (Q/A) ratio of the species (Ellison & Ramaty 1985; Tylka et al 2000). Tylka compared two very large events: 20 April 1998, in which there was no significant flare activity in the four days preceding the event, and the famous 14 July 2000 (Bastille Day) event, which was preceded by 40 C, M, and X-class flares in four days. In the April 1998 event, ionic charge states deduced from the spectra's e-folding energies were consistent with solar-wind values, as well as direct measurements by ACE/SEPICA. But fitting the spectra in the Bastille Day event required a mixture of charge states, comprising 95% solar wind and 5% remnant-flare suprathermals. The mixture was constrained by ACE/SEPICA Fe charge state measurements at a few hundred keV/nuc. The analysis also accounted for the energy-dependence of the mean ionic charge of Fe and Fe/C ratios, two other observations that have featured prominently in the recent flare/CME debate.

Mark Popecki presented further evidence for reacceleration of remnant flare particles, based on SEP charge state measurements from ACE/SEPICA in 3He-enriched energetic storm particle (ESP) events. ESP events are those in which large particle increases occur when an interplanetary shock washes over the spacecraft. Desai et al (2001) identified events with a local shock passage using the ULEIS instrument on ACE. Some of these events showed significant 3He enrichment, which would generally be construed as evidence for a flare-associated source. However, the selected events had no indication of a direct flare observation. Another indicator of flare-related acceleration is a high Fe charge state (≥ 14+). ACE/SEPICA measurements of the SEP Fe charge states during these events showed a trend, in which the fraction of high charge state SEP Fe increased with the 3He enhancement. This was interpreted as further evidence that flare-associated suprathermal ions from earlier flares could be reaccelerated by subsequent shocks. However, there was some evidence that CME-type solar wind, which may contain Fe16+, might also contribute some of the ions reaccelerated by a passing shock.

Hilary Cane presented other observables, in particular radio data and temporal profiles of electrons and protons of the same speed for large proton events (Cane 2001). In events that have fast drift (type III) radio waves extending down to the local plasma frequency, she argued that electrons from a flare source had arrived at the observer's location. She also discussed examples of this type of event in which rise times for electrons and protons of the same speeds were similar. She interpreted these observations as evidence for a single flare source of the energetic protons, electrons and radio waves. Some of the discussion in this section concerned the relation of type III emissions to shocks and their use as unambiguous flare indicators. However, her interpretation of these type III emissions contradicted recent work by Dulk et al. (2000), and the origin of this contradiction was not clear. Gopalswamy pointed out that shock-accelerated particles from the corona could have a complicated time structure as the disturbance moved through changes in the local Alfven speed.

Peggy Shea and Don Smart initiated an interesting discussion of neutron monitor (NM) observations (corresponding to solar protons above 500 MeV) for the 22 October 1989 event. NM rates in this event showed a prompt peak, lasting approximately 6 hours, with highly anisotropic particle angular distributions. This peak was followed by a lower intensity, slowly declining tail lasting for approximately two days, in which the particle distribution was nearly isotropic. Shea & Smart suggested that this structure could be interpreted as a prompt flare-associated component, followed by a shock-accelerated component. The discussion apparently sparked renewed interest in this event, whose features have been known but unexplained for a long time. In particular, two WG participants, John Bieber and Paul Evenson, recently completed a study (presented at the 2001 Fall AGU; Bieber et al. 2001) in which they successfully accounted for the unusual features of this event using a single source combined with magnetic mirroring from a previous CME.

The Working Group's discussion of the relative roles of flares and CMEs in producing SEPs was very spirited at times. But it is perhaps fair to summarize by saying that the two classes of SEP events (impulsive and gradual) may be construed as proxies for two different acceleration mechanisms. The distinction between these two acceleration mechanisms is confirmed by the new observations: shocks accelerate particles from whatever seed population they happen to encounter, albeit with some comparatively modest abundance distortions caused by transport. Acceleration at flares, on the other hand, produces extraordinarily large abundance distortions, as evidenced by 3He/4He and the ultraheavy observations in impulsive events. But the details of how these two mechanisms interact to produce the largest SEP events, which generally occur with *both* a fast CME *and* a large flare, remain a challenge.

Numerical modeling of LASCO images: testing the SEP-CME connection

The CME speed is an important observable for SEP production because the Mach number of a shock, or compression ratio, is one of the critical parameters in determining shock effectiveness (Lee). Correlations between SEP intensities and CME speeds have been previously presented by Kahler and Reames (Kahler 1996; Reames 1999b). There is evidence for at least a weak correlation, even though the CME speeds in previous studies were not even corrected for projection effects. Although no new results were presented on this question, there were numerous suggestions about the issues that must be considered when trying to move beyond the Kahler-Reames correlations, toward more thorough numerical modeling.

It is important to know the CME speed along the Sun-Earth magnetic field line, and how it changes as the CME propagates. It would also be useful to know the local solar wind speed ahead of the CME, because these two speeds determine the Mach number of the shock. Several complications were discussed. The CME speed may change by a factor of two from the published value when it reaches 5 Rs (Mike Andrews). Shock strength may change considerably over the first 10 Rs because of the fast mode speed radial profile. This profile peaks at approximately 3-4 Rs (Gopalswamy, using SOHO/MDI magnetograms to estimate the magnetic field; see also Mann et al. 1999). A CME with an intermediate speed may therefore drive a shock below or above 3-4 Rs, but not necessarily continuously through the altitude range. Additionally, the activity observed at the Sun in association with a CME eruption may be associated with one leg of a two-leg structure. This must be considered when estimating the source location of the CME (Webb).

Several efforts are underway to estimate the CME speed as it propagates toward the Earth. Jim Chen showed considerable success in using flux ropes to model the evolution seen in LASCO images (Krall et al. 2001). He noted that the flux-rope model could calculate the CME speed in three dimensions, resulting in an estimate of the Mach number of the shock. However, calculation of the shock position with respect to the flux rope (standoff distance) may require modeling for each event (Forbes). Gopalswamy reported on a method to estimate CME speeds using LASCO and in-situ observations (Gopalswamy et al. 2000). This method considers the ‘drag force’ on a CME (momentum transfer), which is most important near the Sun. Mike Reiner presented a method in which the CME speed profile might be constrained by radio observations. The transit time of a CME from the Sun to the Earth is combined with radio observations. It is assumed that the CME decelerates to some speed, then propagates at a constant speed after that. The deceleration is assumed to take place over the first 30 hours and 30Rs.

Vic Pizzo presented an overview of models that initiate and propagate CMEs to one AU. In his opinion, these models may be used to test physical concepts, but are not yet ready to model a specific event in detail. One limitation is that energy is treated with a polytrope method, which does not handle the compression ratio, and hence shocks, very well. This limits the models’ capacity to represent shocks deep in the corona. Such a shock is of interest to SEP observers because it may create an energy dependent charge distribution, which has been observed in at least two events. In addition, there is the complication of CMEs propagating into solar-wind structures or slower CMEs ahead. In these cases, the propagation of individual ejecta is not sufficient; the interaction of multiple ejecta must be modeled. Gopalswamy has collected a set of events in which one CME appears to be overtaking another. These cases are associated with distinctive radio signatures in Wind/Waves (Gopalswamy et al. 2001). These events may serve as a basis for a future project involving propagation models and in-situ observations.

Predictors of energetic storm particle (ESP) events

ESP events are particularly important as a space-weather hazard, since they are responsible for the highest proton intensities seen at 1 AU. David Lario presented new results on the 20 October 1989 ESP event, which is perhaps the largest ESP event ever observed. This event was also notable because GOES showed an increase in the proton intensities near the time of shock arrival even at 500 MeV! Lario used high-time-resolution IMP8 data to reveal magnetic structures. He suggested that these structures confined high-energy protons accelerated at an earlier time, when the shock was near the Sun, and that these structures, rather than the shock itself, were responsible for the extraordinarily large intensities at high energies.

Marty Lee and David Lario also discussed a closely related issue, the so-called streaming limit on shock-accelerated SEP intensities. This limit is the maximum intensity for SEPs that have escaped ahead of the shock (Reames and Ng 1998). It is believed to be caused by wave-particle interactions at the shock, in which proton-excited waves scatter ions and trap them near the shock. The injection of more protons would produce more waves, trapping particles more effectively, thus limiting the leakage of SEPs ahead of the shock. In analysis of data from Cycles 21 and 22, Reames & Ng suggested that the streaming limit for ~1 MeV protons was about a few hundred protons/cm2-s-sr-MeV. But Lario presented several events from Cycle 23 that significantly exceeded that value. No explanation for this difference from previous solar cycles was presented. Marty Lee suggested that in the streaming-limited regime, there should also be a characteristic shape for the energy spectrum. This form has not yet been determined, but it would potentially valuable for space-weather and space-system design.

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