AN INTRODUCTION TO CMES AND ENERGETIC PARTICLES

H. V. CANE[1,*] and D. LARIO[2]
[1]*School of Mathematics and Physics, University of Tasmania, Tasmania, Australia*
[2]*Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA*
*(*Author for correspondence: E-mail: hilary.cane@utas.edu.au)*

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Abstract. Energetic particle observations in the interplanetary medium provide fundamental information about the origin, development and structure of coronal mass ejections. This paper reviews the status of our understanding of the ways in which particles are energised at the Sun in association with CMEs. This understanding will remain incomplete until the relationship between CMEs and flares is determined and we know the topology of the associated magnetic fields. The paper also discusses the characteristics of interplanetary CMEs that may be probed using particle observations.

1. Introduction

From the occurrence of a coronal mass ejection (CME) on the Sun until even after its passage over a spacecraft, energetic particle observations in the interplanetary medium help us to discern the development and structure of CMEs both close to the Sun and in the interplanetary (IP) medium. Solar energetic particles (SEPs) originate in at least two different ways both of which are likely related to CMEs. The shocks that CMEs create are accelerators of energetic particles as are the reconnection processes that must occur because of the CME–associated solar magnetic field topology changes. Crucial questions remain about both processes. With respect to shock acceleration the major question concerns the distance from the solar surface that CME shocks form. The major question in the case of reconnection regions is the connectivity of such regions to the IP medium, that is the accessibility to, and extent of, open field lines. Composition and charge state measurements indicate that some solar particles have their origin in heated and/or dense plasma. These observations place limits on the height in the solar corona where particles are accelerated and injected into the IP medium. Once the source regions of particles are understood the particles themselves may provide answers to other questions about CMEs. Because particles tend to follow field lines they can be used to trace field line topologies. Indeed, decreases in the intensity of galactic cosmic rays can indicate the presence of a CME in the IP medium (known as an ICME). Particle flows and intensity changes track magnetic structures within ICMEs. Also, shock accelerated populations provide information about the sizes of CME shocks as they travel from the Sun to the observer.

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2. CMEs at the Sun

Solar activity associated with the onset of an SEP event involves many related phenomena of which the most prominent, for all but the weakest events, is a CME. However, prompt events originating on the disk are also associated with flares. In almost all of the largest events the flare emissions are intense and long-lasting, suggesting that there is possibly a relationship between these emissions and the earliest energetic particles.

2.1. CMEs AND FLARES: CLASSES OF SEP EVENTS

The division of SEP events into two classes goes back to the early work of Lin (1970) in which he found that some electron increases were accompanied by proton increases and some were not. The 'pure' electron events were found to be associated with small flares that produced type III bursts and impulsive microwave and hard X-ray bursts. It was suggested that the 10–100 keV electrons were responsible for the electromagnetic emissions and were an integral part of the initial rapid, bright expansion phase of flares. Observations in the 1980's and 1990's showed that the acceleration mechanism could also produce high energy electrons (up to $\sim$100 MeV) and ions to about 1 GeV as evidenced primarily by gamma ray observations but also by more sensitive in-situ observations.

Proton events were found by Lin (1970) to be associated with large flares and with type II and type IV radio bursts. The associated microwave bursts had complex structure. Previously it had been suggested that, since proton events were associated with type II bursts (taken as evidence of a coronal shock) protons are likely to be shock accelerated. In the late 1970's it was determined that large proton events also occurred at the times of CMEs (Kahler *et al.*, 1978) and it was assumed that type II bursts are a signature of the bow shocks of CMEs. But the picture is more complicated because proton events are actually best associated with long lasting type III emissions (Cane *et al.*, 2002). The importance of late low frequency radio emissions was previously stressed by Klein *et al.* (1999). Also it is unlikely that type II bursts observed from the ground are the high frequency component of the CME shock (Wagner and MacQueen, 1983; Cane, 1983). Nevertheless proton events are well associated with CMEs that do drive shocks, but it is not clear at what coronal height these shocks form and at what height accelerated energetic particles escape the shock. Furthermore, it seems likely that particles accelerated during the flare process contribute in large SEP events (Klein *et al.*, 1999; Torsti *et al.*, 2001; Cane *et al.*, 2002). This possibility is supported by charge state and abundance measurements.

Another complication is that the more intense electron events are also associated with CMEs, albeit ones that affect a smaller region of the corona. However, in the paradigm espoused by Reames (1999) the presence of a CME is what distinguishes two classes of particle events. Taken together the associations suggest that there are two ways in which particles are accelerated and, in the largest events, both occur to some extent dependent on energy. Thus it is unlikely that there is a sharp division separating SEP events into two classes.

2.2. CHARGE STATES AND COMPOSITION

SEP charge states provide crucial clues as to the particle acceleration site, the acceleration process and their transportation out of the low corona. Whereas prior work, in cycle 21, was limited to long averaging and determinations of mean charge states in a small, low energy range, the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) instrumentation can examine the average charge state over a wide energy range from 0.3 to 70 MeV/nuc (Oetliker *et al.*, 1997; and references therein). Furthermore, the Solar Energetic Particle Ionic Charge Analyzer (SEPICA) instrument on the Advanced Composition Explorer (ACE) can measure charge state distributions and their energy dependence. These new data show that the idea based on the work of Luhn *et al.* (1985) that there are two classes of SEP events distinguished by very different charge states is no longer tenable. Of particular interest are the high energy measurements (Leske *et al.*, 2001) that show that many large western events have high charge states ($\sim+20$ for Fe), just like in the smaller events. The origin of these high charge states is not yet clear. It has also been found that the charge states in all events are strongly dependent on energy (Möbius *et al.*, 2003; Popecki *et al.*, 2000). This means that acceleration at heights above 2 solar radii, as is thought to be the case in large events (Reames, 1999), is unlikely (Kochorov *et al.*, 2000). The new results imply that for small events the temperature of the ambient plasma is lower than previously deduced. The average $\sim$0.5 MeV/nuc Fe charge state of near $+21$ found in cycle 21 must reflect additional stripping during and after acceleration (Möbius *et al.*, 2003).

Abundance variations are another important diagnostic tool. As noted above it was a comparison of electron and protons that first indicated that there were possibly two classes of SEP events. Later two classes were also indicated by measurements on the isotopes of He (viz ^{3}He/^{4}He) and of ratios of heavy ions. Most of these earlier measurements were made at low energies ($<\sim$25 MeV) where the largest events are those in which there is strong IP shock acceleration. Thus in cycle 21 it was determined that large proton events had abundances comparable to that of the solar wind and very different from that seen in small, Fe–rich, ^{3}He–rich events (Reames, 1999). In cycle 23 with the large geometry factor instruments on ACE and on the Solar Heliospheric Observatory (SOHO) it has been found that smaller ‘proton’ events and larger ones at high energies, are also Fe–rich (Cohen *et al.*, 1999) and ^{3}He–rich (Torsti *et al.*, 2003) although not to the extent of the small ‘electron’ events. Thus abundance variations no longer indicate a clear separation into two classes. The observations suggest that abundance variations may be related to flare duration (Kocharov *et al.*, 1986; Cane *et al.*, 1986).

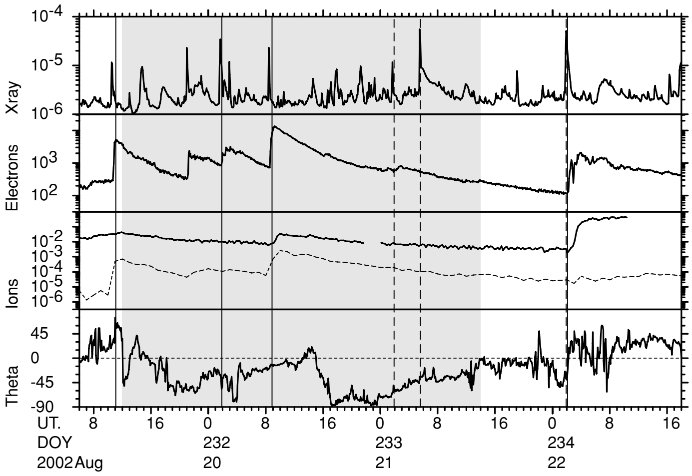

Figure 1. Observations during ~3 days in August 2002. There are (at least) four electron–rich events and one proton–rich event. Several electron events, including the largest at ~0800 UT on August 20, occurred inside an ICME (indicated by the gray shading). The proton event on August 22 occurred in association with the largest, but not the fastest, CME. Large CMEs are indicated by vertical solid lines and type II bursts by dashed lines.

The difficulty in untangling the relevant physics of solar particle acceleration is illustrated by the time period shown in Figure 1. The figure shows (from top to bottom) 1–8 Å soft X-ray intensity, ~200 keV electron, ~25 MeV proton and ~10 MeV/nuc Fe intensities. The bottom panel shows the elevation angle of the ambient interplanetary magnetic field. The particle events were some of the many events arising from the same active region in August 2002. All of them were associated with CMEs. The solid lines in the figure indicate the four CMEs with angular widths >100°. These CMEs had sky–plane speeds of 549, 961, 1099 and 1005 km/s. One would expect the second, third and fourth of these to drive shocks yet only for the last was a type II burst reported. The last SEP event has high proton to electron ratio and a relatively low Fe intensity making it a 'proton' event. The other SEP events are 'electron' events. Although only the proton event has a type II burst it was not observed beyond a few solar radii from the Sun. The presence of a fast CME does not differentiate the proton event from the electron events. The clearest difference is in the behavior of the metric type III radio emissions. These lasted much longer and started at lower frequencies for the proton event indicating the occurrence of extended particle acceleration in the middle corona. The magnetic field angle in the bottom panel shows that the electron event near 0800 UT on August 20 occurred inside an ICME as indicated by the field rotation and relatively smooth field. The extremely short flare suggests a short solar injection that was only seen at 1 AU because of interplanetary conditions appropriate for weak particle scattering.

2.3. TIMING

Deductions about when particles left the Sun are crucially dependent on what assumptions are made about particle propagation. The term “scatter–free” is often applied to events where the injection time is calculated by determining how long it takes particles of a particular energy to travel along an Archimedean spiral of length 1.2 AU (corresponding to a solar wind speed of 400 km/s). A more detailed analysis involves plotting the arrival time of particles as a function of their inverse speed. Such a plot is expected to produce a straight line having a slope corresponding to the path length and the intercept on the time axis indicating the injection time. Indeed, it is commonly assumed that the straight line that is usually found with a slope implying a path length of $\approx$1.2 AU is proof that the particles travel scatter free. Recent analyses using the new experiments with good counting statistics have indicated that the onset times are nearly always delayed relative to the flare emissions. This is true even in small electron events in which the electrons are believed to have caused the flare emissions. This delay has been interpreted by some reserachers to indicate that the $>$25 keV electrons that they observe are not related to the flare emissions but rather are probably shock accelerated at the leading edge of a CME (Haggerty and Roelof, 2002). Alternatively, Cane (2003) has proposed that interplanetary scattering must be occurring based on an analysis of the radio emissions. Delayed injections are also deduced for ions (see Posner and Kunow 2003). Clearly propagation effects require further investigation. It is possible that mean free paths vary with rigidity in such a way that the straight lines obtained in “1/beta plots” are fortuitous and not indicative of a lack of transport effects. Also suggestive that scattering is likely occurring is the fact that the particle events with the shortest inferred delays also have intensity–time profiles indicative of little scattering.

3. Propagation of CMEs

A fast CME driven shock will accelerate particles out of the bulk solar wind and its suprathermal tail, and/or out of the suprathermal remnants left over from prior SEP events or injected during the flare process (Desai *et al.*, 2003). The way in which these energetic particles are observed depends on (1) how they are accelerated and injected into the IP medium by the traveling CME-driven shock, and (2) how they are transported along the interplanetary magnetic field (IMF). These two factors implicitly depend on the energy of the particles, the particle species and mass per charge, the characteristics of the CME-driven shock (i.e., its speed, size, shape, strength and efficiency in particle acceleration), and the IMF topology that determines the magnetic connection between the observer and the expanding CME-driven shock. A great effort to model all these processes has been undertaken (e.g., Lario *et al.*, 1998; Kallenrode, 2001; Ng *et al.*, 2003; Rice *et al.*, 2003 and references therein). These efforts, however, are still in their infancy since none of them treats particle acceleration and transport, as well as CME-driven shock propagation, in their entirety. Models simplify the variety of processes involved in the particle shock-acceleration by assuming either arbitrary injection functions or quasi-steady diffusive shock-acceleration mechanisms. None of the models has yet treated the injection process self-consistently, or the complete evolution of the shocks from their formation close to the Sun to their propagation towards the outer heliosphere (see review of these models in Lario, 2005).

Energetic particle observations from IP spacecraft can be used to infer the properties of the traveling CME. For example, the time-intensity profiles of the SEP events observed in the ecliptic plane at 1 AU are organized in terms of the longitude of the observer with respect to the traveling CME-driven shock (Cane *et al.*, 1988). Figure 2 shows proton intensity profiles of several SEP events observed by the IMP-8 spacecraft as a function of the longitude of the parent solar event. (Note that

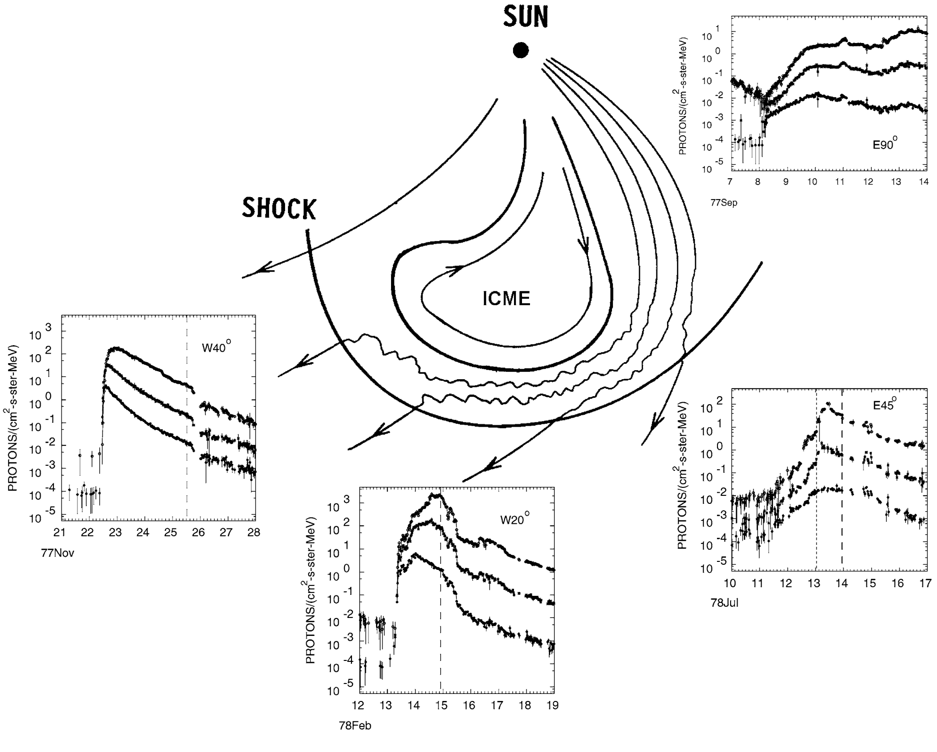

Figure 2. Cartoon showing the shape of an ICME and surrounding IP field structure including the presence of a shock. A strong shock will accelerate particles to an extent dependent on energy and the location of the observer. Thus particle intensity profiles are organised by the longitude of the associated solar event. Proton intensities in three energy ranges (~5, ~15 and ~30 MeV) are shown. Dashed lines indicate the passage of shocks. Figure adapted from Cane *et al.* (1988).

the events illustrated are typical, but event to event variations can be quite large in particular when there are additional CMEs either at the Sun or in the IP medium). Whereas events generated from the western longitudes have rapid rises followed by gradual decreasing intensities, events generated from eastern longitudes show slowly rising intensity enhancements structured around the arrival of the CME-driven shocks. This longitudinal dependence of the time-intensity profiles together with the rate at which the particle intensities increase or decrease have been used to predict the arrival of CME-driven shocks at 1 AU (Smith *et al.*, 2004; Vandegriff *et al.*, 2005). At large heliocentric distances and at high heliolatitudes, however, the relation between the origin of the event and the time-intensity profiles is less clear (e.g., McKibben *et al.*, 2001).

Simultaneous observations by widely separated spacecraft show that in large events particles reach widespread regions of the heliosphere, up to 300° in longitude (Cliver *et al.*, 1995); and up to at least 80° in latitude (Lario *et al.*, 2003). This widespread observation of SEP events suggests that there are magnetic connections to broad sources of particles that are able to both accelerate and inject particles into wide regions of the heliosphere. Alternatively, or in addition, the transport of particles across magnetic field lines might be very efficient as suggested by a number of authors (McKibben *et al.*, 2001; Cane and Erickson, 2003; Dalla *et al.*, 2003). However, particle anisotropies observed at the onset of large SEP events (at both low and high latitudes) are field-aligned with small or zero flow transverse to the magnetic field (Sanderson *et al.*, 2003). This suggests that perpendicular transport is inefficient. If there is widespread shock acceleration of particles close to the Sun then the shocks must decrease in latitudinal and longitudinal extent as they move away from the Sun since the necessary low coronal sizes are much more extended than implied from in situ observations (Cane, 1996). Only when the CME-driven shock arrives at the observer, is it possible to study, in situ, both the shock properties and the mechanisms working on particle acceleration (e.g., Tsurutani and Lin, 1985; and references therein). Whereas the study of specific events helps us to understand the underlying physics of the mechanisms involved in the generation of particular events, it is necessary to extend these studies to a comprehensive analysis of diverse events and thus, determine the multitude of processes involved in the generation of energetic particles by traveling CME-driven shocks.

4. Structure of ICMEs

Observations of energetic particles during the passage of an ICME over the observer provide valuable information about the structure of the ICME and its magnetic field topology (Richardson, 1997 and references therein). Energetic particle signatures associated with the passage of ICMEs in the ecliptic plane at 1 AU include (1) energetic particle intensity depressions (Forbush decreases) (Cane, 2000 and references

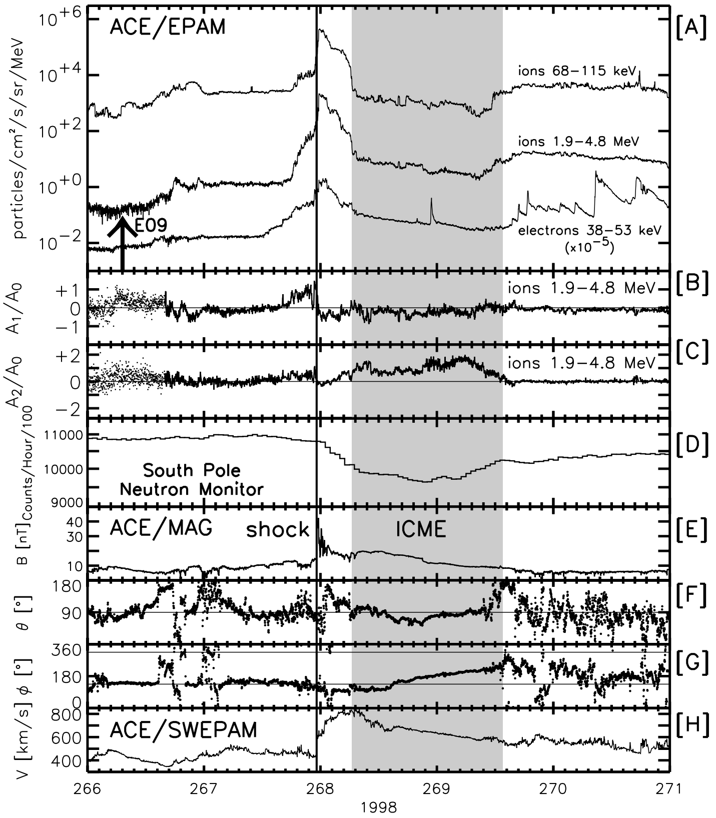

Figure 3. From top to bottom. [A] 96-s averages of the ion and electron intensities as measured by the ACE spacecraft. [B] 1.9–4.8 MeV ion first-order parallel anisotropy coefficient in the solar wind frame. [C] 1.9–4.8 MeV ion second-order anisotropy coefficient in the solar wind frame. [D] Count rates measured by the South Pole cosmic ray monitor. [E-G] Magnetic field magnitude and directions (in the GSE coordinate system) as measured by the ACE spacecraft. [H] Solar wind speed as measured by the ACE spacecraft.

therein); (2) bidirectional ∼1 MeV ion flows (Marsden *et al.*, 1987); (3) bidirectional cosmic ray flows (Richardson *et al.*, 2000); and (4) occasionally, unusual SEP flow directions due to the fresh injection of SEPs by unrelated solar events (Richardson and Cane, 1996). In contrast to in the ecliptic plane, observations of ICMEs in high-speed streams at high heliographic latitudes show enhanced particle intensities instead of depressions (Bothmer *et al.*, 1995; Lario *et al.*, 2004).

Figure 3 shows the energetic particle response to the passage of an ICME through the near-earth solar wind observed by the ACE spacecraft in September 1998. (Note that this ICME was atypical in having well-defined boundaries; Cane and Richardson, 2003). This fast ICME was able to drive a strong IP shock (solid vertical line) that locally accelerated ions to at least ∼60 MeV and electrons to at least ∼50 keV at its arrival at 1 AU. The panels [B] and [C] show the 1.9–4.8 MeV first-order parallel (A_1) and second-order (A_2) anisotropy coefficients, respectively, computed in the solar wind frame following the method described in Lario *et al.* (2004). Note that A_1 changed its sign at the passage of the shock indicating that these particles were flowing away from the shock in the solar wind frame of reference. The entry of the spacecraft into the ICME showed an abrupt decrease in the low-energy ion intensities. Panels [B] and [C] show that $A_2 > A_1$ throughout the passage of the ICME indicating the presence of bidirectional ion flows (BIFs). A small impulsive electron event was observed at the end of day 268 when ACE was within the ICME, showing that the spacecraft was still magnetically connected to the Sun. Panel [D] shows that the particle intensity depressions extended to high energies indicating that the access of galactic cosmic rays into the ICME was limited. After exit from the ICME, low-energy ion intensities recovered to values similar to those observed prior to the passage of the ICME (after allowing for their gradual fall off with distance from the shock). The recovery of cosmic ray intensities, however, was more gradual and extended for several days after the ICME passage. This is because at these energies the post-shock turbulence causes an additional longer lasting decrease.

The presence of BIFs and the rapid onset of the electron event inside the ICME, are usually interpreted as evidence for the presence of looped magnetic field lines with the legs rooted at the Sun. The sharp decrease of the low-energy ion intensities observed upon entry into ICMEs at 1 AU show that the penetration of shock-accelerated particles into the ICME is restricted. Other particles inside ICMEs could come from particles accelerated at the time when the CME leaves the Sun (which implies the existence of a particle acceleration mechanism different from the CME-driven shock), and/or particles injected into the ICME by unrelated solar events. Although Figure 3 shows only a particular event, the study of energetic particle observations around and within ICMEs can be used not only to determine the magnetic topology of ICMEs but also the origin of intra-ICME particles and the transport conditions of these particles within and around the ICME (Lario *et al.*, 2004; and references therein).

5. Summary

Although energetic particle observations help us to study CMEs from their origin close to the Sun up to their arrival at the spacecraft, there are still many unknowns. Theoretical models of CME initiation at the Sun, three-dimensional simulations of the interplanetary transport of the CMEs and energetic particles, combined with multi-spacecraft observations of both ICMEs and SEPs (including composition measurements, ionic charge-state distributions and anisotropy analyses) will help us to understand the underlying physical mechanisms involved in the origin, acceleration and transport of energetic particles.

In order to discern the origin of the SEPs it is essential to determine both the relationship between flares and CMEs as well as the coronal magnetic topology during the eruption of the CMEs. In particular, challenges for future theoretical models of CME initiation include the following questions:

- Where are the flaring regions relative to the CME?
- Are there open field lines in the reconnection region behind a CME along which the energetic particles may propagate and escape to the IP medium? Is there evidence for progressive field line opening away from CMEs?
- Where, when and how do the CME-driven shocks form?
- What is the relationship between coronal shock waves and interplanetary shocks?
- When, where and how does particle injection start?
- What are the values of the physical parameters that are required to reproduce the abundance measurements, the energy dependence of the ionic charge states, and the maximum achievable energy of the particles?

Energetic particle observations by spacecraft are modulated by transport effects. Future and present models of energetic particle propagation and acceleration in the IP medium should include:

- Three-dimensional simulation of shock propagation from their formation to beyond the spacecraft location.
- Realistic seed particle populations for the time-dependent mechanisms of shock-acceleration including possible contributions from suprathermal remnants and particles accelerated during the flare processes.
- Evolution of the shock characteristics and its efficiency in accelerating and injecting particles into the IP medium.
- The influence of the IMF structure on the particle transport, i.e., on determining the onset times, spectra, anisotropy flows and time-intensity profiles of the SEP events at different regions of the heliosphere.

Finally, energetic particle observations within and around ICMEs should help us to determine both the origin of the intra-CME particle populations and the magnetic topology of the ICMEs. Energetic particle measurements should be used to improve both the methods of ICME identification and the models used to infer the three-dimensional structure of the ICMEs. Multi-spacecraft observations are essential to achieve these purposes. Most of the topics mentioned above are discussed in more detail in Klecker *et al.* (2006, this volume) or in Forbes *et al.* (2006, this volume).

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