

ENERGETIC PARTICLE OBSERVATIONS

Report of Working Group C

B. KLECKER^{1,*}, H. KUNOW², H. V. CANE³, S. DALLA⁴, B. HEBER²,
K. KECSKEMETY⁵, K.-L. KLEIN⁶, J. KOTA⁷, H. KUCHAREK⁸, D. LARIO⁹,
M. A. LEE⁸, M. A. POPECKI⁸, A. POSNER¹⁰, J. RODRIGUEZ-PACHECO¹¹,
T. SANDERSON¹², G. M. SIMNETT¹³, and E. C. ROELOF⁹

¹ *Max-Planck-Institut für extraterrestrische Physik, 85740 Garching, Germany*

² *Institut für Experimentelle und Angewandte Physik, University of Kiel, 24118 Kiel, Germany*

³ *School of Mathematics and Physics, University of Tasmania, Tasmania, Australia*

⁴ *School of Physics and Astronomy, University of Manchester, Manchester M60 1QD, UK*

⁵ *Hungarian Academy of Sciences, Central Research Institute for Physics, Budapest, Hungary*

⁶ *Observatoire de Paris, LESIA-CNRS UMR 8109, Bat. 14, F-92195 Meudon, France*

⁷ *Department of Physics, University of Arizona, Tucson, AZ 85721, USA*

⁸ *University of New Hampshire, Durham, NH 03824, USA*

⁹ *Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA*

¹⁰ *Southwest Research Institute, Space Science and Engineering Division, 6220 Culebra Rd.,
San Antonio, TX 78228, USA*

¹¹ *Space Research Group, Departamento de Física, Universidad de Alcalá, Ctra. Madrid-Barcelona,
28871 Alcalá de Henares, Espana*

¹² *Space Science Dept. of ESA, Postbus 299, 2200 AG Noordwijk, The Netherlands*

¹³ *School of Physics and Space Research, University of Birmingham, B15 2TT, UK*

(*Author for correspondence: E-mail: berndt.klecker@mpe.mpg.de)

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Abstract. The characteristics of solar energetic particles (SEP) as observed in interplanetary space provide fundamental information about the origin of these particles, and the acceleration and propagation processes at the Sun and in interplanetary space. Furthermore, energetic particles provide information on the development and structure of coronal mass ejections as they propagate from the solar corona into the interplanetary medium. In this paper we review the measurements of energetic particles in interplanetary space and discuss their implication for our understanding of the sources, and of acceleration and propagation processes.

Keywords: solar energetic particles, energetic particle propagation, energetic particle acceleration, energetic particle composition, energetic particle ionic charge states, solar electrons, shock acceleration, interplanetary coronal mass ejections

1. Introduction

B. KLECKER, H.V. CANE, AND K.-L. KLEIN

Solar energetic particles (SEP), in their intensity-time profiles, energy spectra, elemental, isotopic, and ionic charge composition carry fundamental information on

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the source region and their acceleration and propagation processes. High-energy particles originating at the Sun were first reported by Forbush (1946). At that time there was little doubt that these high energy particles were closely related to contemporary solar flares. Later it became clear that acceleration at interplanetary shocks is also an efficient mechanism for particle acceleration (e.g. Bryant *et al.*, 1962). As anticipated (e.g. Gold, 1962), and confirmed by coronagraphic observations of CMEs, such shock waves are not blast waves from flares, but are driven by magnetic structures ejected from the Sun.

In the early seventies a new type of event was discovered (Cane and Lario, 2006, this volume) that showed enhanced ^3He abundances (Hsieh and Simpson, 1970) with $^3\text{He}/^4\text{He}$ -ratios > 1 (Balasubrahmanyam and Serlemitsos, 1974), while the corresponding ratio in the solar corona and solar wind is 5×10^{-4} . Such events were later found to exhibit enhancements of heavy ions by about an order of magnitude (e.g. Hurford *et al.*, 1975; Mason *et al.*, 1986) relative to coronal abundances. These small events also showed high ionic charge states of Si (~ 14) and Fe (~ 20) that were interpreted as indicative of high coronal temperatures ($\sim 10^7$ K), compared to charge states compatible with $\sim 1.5 - 2 \times 10^6$ K in interplanetary (IP) shock related events. Based on these and other observations SEPs were classified as ‘impulsive’ and ‘gradual’, following a classification of flares based on the duration of soft X-rays (Pallavicini *et al.*, 1977). In this picture the ‘impulsive’ SEP events were related to flares and the ‘gradual’ SEP events were related to coronal mass ejection (CME) driven coronal and interplanetary shocks (see e.g. review by Reames, 1999).

However, new results from instruments with improved collecting power and resolution onboard several spacecraft (e.g. WIND, SAMPEX, SOHO, ACE) have shown that this two-class picture was oversimplified. The new composition and ionic charge measurements show that some solar particles have their origin in a dense plasma low in the corona, even in events classified as ‘gradual’, that enrichments in ^3He are also common in IP shock accelerated populations (Desai *et al.*, 2001), and that enrichments in heavy ions are often observed in large events at high energies. Whether these new findings are best explained by a suprathermal population from previous ‘impulsive’ events (Mason *et al.*, 1999), by the interplay of shock geometry and different seed populations (solar wind and flare suprathermals, Tylka *et al.*, 2005), or by direct injection from the flare acceleration process (e.g. Klein and Trotter, 2001, and references therein; Cane *et al.*, 2003), with or without further acceleration by a coronal shock, is now heavily debated.

In this chapter we will focus on SEP observations in gradual events. We provide in Section 2 an example of typical intensity versus time profiles, summarise the dependence of event characteristics on longitude and latitude, review SEP elemental, isotopic, and ionic charge composition, and summarise electron observations. In Section 3 we discuss acceleration and propagation processes and their relation to the observations. Section 4 relates energetic particles observed in interplanetary space to the electromagnetic signature of plasma and energetic particles in the solar atmosphere. In Section 5 we discuss energetic particle signatures associated with

the passage of interplanetary CMEs (ICMEs) and the use of SEPs as a tool to infer the magnetic topology of these structures.

2. Solar Energetic Particle Observations

2.1. SPATIAL AND TEMPORAL VARIATIONS

S. DALLA, D. LARIO, H. V. CANE, AND T. R. SANDERSON

The intensities of SEP events show a wide variety of spatial and temporal variations. They are the result of many factors, including the efficiency and time dependence of the acceleration, the particle transport conditions, the local plasma properties at the observing spacecraft (such as the presence of ICMEs, shocks and magnetic discontinuities), and the spacecraft location with respect to the associated flare and CME at the Sun. In this section we first present ‘typical’ observations of SEP intensity-time profiles and anisotropies at 1 AU from the Sun and in the ecliptic plane (Section 2.1.1). We then focus on a description of how event characteristics are influenced by the relative position of the observing spacecraft and the solar events source of the SEP (Section 2.1.2).

2.1.1. *Intensity-Time Profiles and Anisotropies at one Location*

ISEE-3, launched in 1978, was one of the first missions to study in detail the particle and field characteristics of ICMEs, as a consequence of its sophisticated set of instruments.

Figure 1 shows particle, magnetic field and solar wind data from ISEE-3 for an ICME event on 11 December, 1980 studied by Sanderson *et al.* (1983). The event of Figure 1 has typical intensity profiles and anisotropies at 1AU from the Sun and in the ecliptic plane, although it did not extend to high energies, i.e. above ~ 20 MeV.

There was a strong shock, a magnetic cloud with field rotation, and shock-accelerated energetic particles. It is important to realize that there is a great deal of variation in the characteristics of ICME events at 1 AU, and that not all events exhibit these characteristics. Other examples observed by ISEE-3 were studied by Klecker *et al.* (1981), van Nes *et al.* (1984) and Sanderson *et al.* (1985a).

The event shown in Figure 1 begins with a rapid onset in the intensity-time profiles, with the highest energy particles arriving first. These particles were accelerated close to the Sun and arrived within several hours of the start of the associated flare on December 9. At the onset there was a large first order field-aligned anisotropy. Similar events were discussed by Heras *et al.* (1994).

For around a day following onset, the intensities continued to rise at energies < 1.6 MeV. The shape of this part of the intensity-time profile depends upon many parameters, such as the injection at the flare site, acceleration at the CME shock (Heras *et al.*, 1994), the position of the observer relative to the site (Sanahuja and

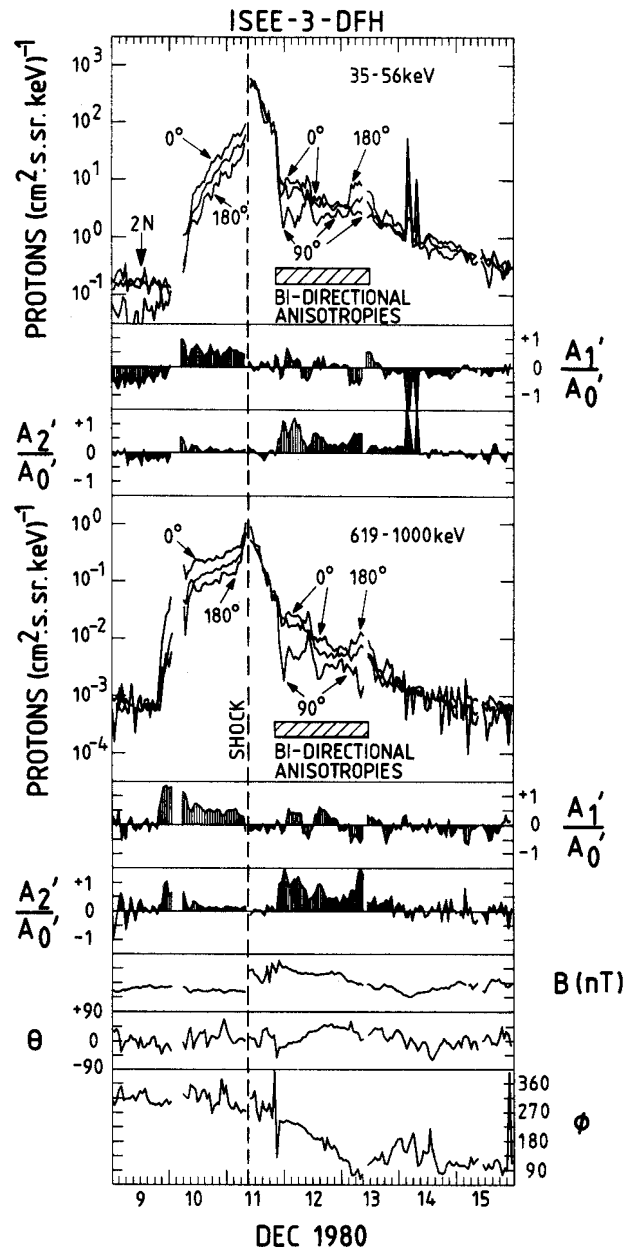


Figure 1. Intensity-time profiles together with anisotropy parameters, solar wind and magnetic field data for the 11 December, 1980 ICME event (from Sanderson *et al.*, 1983).

Domingo, 1987; Domingo *et al.*, 1989; Cane *et al.*, 1988) and the characteristics of the interplanetary medium (Klecker *et al.*, 1981; van Nes *et al.*, 1985; Beeck *et al.*, 1990).

The shock in front of this ICME arrived approximately two days after the solar event, together with a rapid increase in the lower energy particle intensity, the intensity rising around an order of magnitude in about an hour before the shock. In the model of Lee (1983), the later rise of the intensity is ascribed to the acceleration of particles by the interaction with upstream turbulence at quasi-parallel shocks.

At some shocks waves with frequencies <0.1 Hz were observed just upstream of the shock, i.e. in the frequency range where protons can be in cyclotron resonance with the waves (Kennel *et al.*, 1986; Sanderson *et al.*, 1985b), as predicted by Lee (1983). Needless to say, not all events follow this pattern. Some were preceded by complicated magnetic field structures such as planar magnetic structures (van Nes *et al.*, 1985), and others by magnetic loops (Balogh and Erdos, 1983), which may either assist or prevent the growth of these waves.

Traveling behind the 11 December, 1980 shock was a turbulent region lasting several hours, containing particles accelerated by the shock, with the maximum intensity occurring one or two hours after the shock and not at the shock. This is quite a common feature (e.g. Lario *et al.*, 2003a) that suggests that trapping of particles plays a role. This turbulent region is often responsible for a depression in particle intensity at very high energies, which is the first step of a two-step Forbush decrease (Sanderson *et al.*, 1992; Cane *et al.*, 1994).

In this event, the arrival of the ICME itself was heralded by a rapid drop in the low energy ion intensity coincident with the arrival of a discontinuity. A discontinuity, or multiple discontinuities (Sanderson *et al.*, 1990), are usually at the leading edge of ICMEs, which is also the start of the second step of the Forbush decrease.

Within the ICME, strong bidirectional ion anisotropy signatures were observed. In a similar event (Tranquille *et al.*, 1987) derived a large mean free path of ~ 3 AU from the low magnetic field variance. Both low magnetic field variance and bidirectional ion anisotropies are typical signatures of this type of events (Marsden *et al.*, 1987).

2.1.2. *Dependence of Event Characteristics on Longitude and Latitude*

Several characteristics of an SEP event at 1 AU in the ecliptic plane are influenced by the relative separation in heliolongitude between the location of the associated flare and the magnetic footpoint of the observing spacecraft.

Looking at a large sample of near-Earth SEP data, it was recognised that peak intensities are reached earlier in SEP events following flares at western longitudes, than in those following eastern flares (Burlaga, 1967; van Hollebeke *et al.*, 1975). The onset time of SEP events was also shown to be ordered by heliolongitude (Barouch *et al.*, 1971).

The organisation of event profiles by longitudinal separation between flare location and spacecraft is most obvious by looking at the same event from several

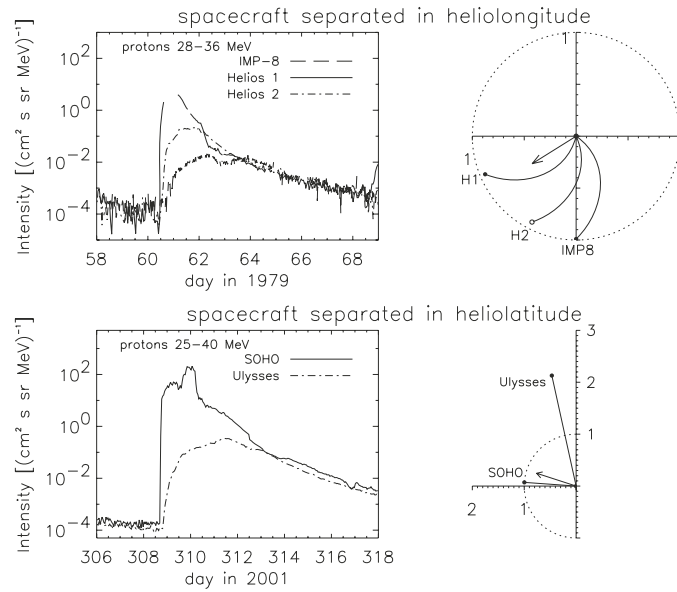


Figure 2. Upper panels: Left: SEP intensity-time profiles at spacecraft widely separated in heliolongitude: 1 March 1979 event as observed by Helios 1 and 2 and IMP-8. Right: A projection of the spacecraft locations onto the solar equatorial plane, with solid lines indicating Parker magnetic field lines connecting the spacecraft to the Sun. The arrow indicates the longitude of the flare associated with the event. Lengths are in units of AU. Lower panels: Left: SEP intensity-time profiles at spacecraft widely separated in heliolatitude: 4 November, 2001 event as seen by Ulysses and SOHO. Right: Projection of the positions of Ulysses and SOHO onto a meridional plane. The difference in longitude between the two spacecraft was 31° .

spacecraft far apart in longitude. The first multi-spacecraft studies were carried out during the Pioneer era (McCracken *et al.*, 1967; McKibben, 1972). Later, several studies combining Helios 1 and 2 and IMP-8 data (e.g. Cane *et al.*, 1988; Kallenrode, 1993) showed that, at energies >20 MeV, the spacecraft with apparent magnetic connection closest to the flare nearly always detects the highest peak intensity. In contrast, the peak intensities at the spacecraft farthest in longitude from the flare are typically orders of magnitude lower. These features are displayed in the left top panel of Figure 2, with the right top panel giving the spacecraft positions.

Data from the Ulysses passages over the solar poles during 2000–2002 allowed us for the first time to look at the dependence of SEP event characteristics on heliolatitude (see e.g. Simnett, 2001, for a review). Several high heliolatitude events were detected, at heliocentric radial distances between 1.6 and 3.2 AU. A comparison between particle arrival times at Ulysses and at near-Earth spacecraft showed very large delays in onsets at high heliolatitudes (~ 100 – 400 minutes) well ordered by the separation in latitude between flare and spacecraft (Dalla *et al.*, 2003a). Times of peak intensities were also found to be very delayed at high heliolatitude, and

also well ordered by latitudinal separation (Dalla *et al.*, 2003b). On the other hand, during the 14 July, 2000 event (Zhang *et al.*, 2003), high energy protons arrived at Ulysses before relativistic electrons, and the arrival direction was not along the local magnetic field. These findings revived the discussion of cross-field diffusion in the interplanetary transport of solar energetic particles (e.g. Cane and Erickson, 2003). In contrast to measurements near the ecliptic plane, the high heliolatitude SEP data are characterised by very small anisotropies, which are field aligned during the onset phase (Sanderson *et al.*, 2003; Lario *et al.*, 2003b). The bottom panels of Figure 2 show an example of simultaneous observation of an SEP event at high and low latitudes.

A feature common to many SEP events is that intensities in the decay phase become very similar at widely separated spacecraft, as can be seen in the examples in Figure 2. This was first noticed in data from the Pioneer missions (McKibben, 1972). Roelof *et al.* (1992) reported periods of time when particle intensities at different radial distances from the Sun (1.0 and 2.5 AU) were essentially the same during the decay phase. They described the observation as the formation of particle reservoirs in the inner heliosphere. Reames *et al.* (1997) plotted SEP spectra at the two Helios spacecraft and IMP-8 during the decay phase of large events. The spectra were very similar at the three spacecraft, in the proton energy range from ~ 1 –40 MeV, showing that similarities in the decay phase are present in a wide range of SEP proton energies. Because of these similarities, they introduced the term invariant spectra to describe the phenomenon.

Several explanations have been put forward to explain the multi-spacecraft decay phase observations. Magnetic trapping between the shock and the Sun, trapping by magnetic barriers produced by earlier solar events, as well as cross-field transport have been suggested (Roelof *et al.*, 1992; Reames *et al.*, 1997; Lario *et al.*, 2003b).

2.2. ELEMENT ABUNDANCES, IONISATION STATES, AND ENERGY SPECTRA OF SEPS

B. KLECKER, H. V. CANE, M. A. POPECKI

The variations of elemental and isotopic abundances by several orders of magnitude, or variations in the mean ionic charge, are the basis for dividing events into two classes (e.g. discussion in Reames, 1999, and Cane and Lario, 2006, this volume). (1) Gradual Events show large interplanetary ion intensities, small electron to proton ratios, on average coronal elemental abundances and ionic charge states consistent with source temperatures of $\sim 1.5 - 2 \times 10^6$ K, characteristic for the solar corona. These events are associated with interplanetary shocks. (2) Impulsive Events show high electron to proton intensity ratio, enhanced abundances of heavy elements, enhancements of ^3He relative to ^4He by up to a factor of 10^4 , and high ionic charge states for Si (~ 14) and Fe (~ 20), which were interpreted as being due to

temperatures of $\sim 10^7$ K. These events are usually associated with impulsive solar flares and the isotopic and elemental enhancements are interpreted as being due to resonant wave-particle interactions, for example selective heating of ^3He by electrostatic ion cyclotron waves (see Section 3.1.1). However, new results from the novel instrumentation with much improved sensitivity and resolution onboard several spacecraft (e.g. WIND, SAMPEX, SOHO and ACE) have shown that this picture was oversimplified. In this section we will concentrate on the new elemental, isotopic, and ionic charge measurements and their implications.

2.2.1. *Event Integrated Abundances*

Event integrated SEP abundances have been used extensively to infer solar or solar system abundances, that may not be accessible otherwise, or to relate SEP abundances to photospheric, coronal or solar wind abundances (e.g. Meyer, 1985). When comparing SEP abundances with coronal and photospheric abundances it was realized for many years that both, coronal and SEP abundances, show a dependence on the first ionisation potential (FIP) (Hovestadt, 1974; Meyer, 1985; Geiss, 1998), suggesting ion-neutral separation in the chromosphere as an important fractionation mechanism. For a review on FIP-fractionation mechanisms see e.g. Hénoux (1998). Furthermore, abundances in individual large SEP events generally show fractionation effects that monotonically depend on mass (M) or mass per charge (M/Q), usually approximated by a power law in M/Q (Breneman and Stone, 1985). This M/Q fractionation is not only observed for elemental abundances, but also for isotopic abundances (e.g. Leske *et al.*, 1999) and the correlation between isotopic and elemental abundances in individual events has been used to infer the abundances of the coronal source (Leske *et al.*, 2003).

Large enrichments of ^3He and heavy ions found in event-integrated abundances of impulsive events are their defining characteristic. However, Mason *et al.* (1999) reported small enrichments of ^3He in a survey of 12 large gradual events, with an average value of $^3\text{He}/^4\text{He} = (1.9 \pm 0.2) \times 10^{-3}$. Even larger enrichments of ^3He with $^3\text{He}/^4\text{He}$ between 0.0014 and 0.24 have been found near the passage of 25 out of 56 IP shocks at 1 AU (Desai *et al.*, 2001). Furthermore, large abundances of Fe at energies of ~ 1 MeV/amu (Mason *et al.*, 1999) and at energies > 12 MeV/amu (Cohen *et al.*, 1999) and > 25 MeV/amu (Cane *et al.*, 2003) have been observed in many large events. Thus, enrichments of ^3He and heavy ions are apparently not limited to small, impulsive, events as considered earlier. As a possible source of ^3He in large events Mason *et al.* (1999) proposed remnant suprathermal particles from previous impulsive events, serving as seed particles for the injection at the IP shock. This suggestion is qualitatively supported by the recent finding (Desai *et al.*, 2003) that the elemental abundances near 72 IP shocks observed during 1997–2002 were poorly correlated with (slow) solar wind abundances, but positively correlated with the elemental abundances upstream, suggesting the acceleration of suprathermals with a composition different from solar wind composition. In this scenario, high heavy ion abundances (e.g. Fe/O) could then be also interpreted as an admixture

of suprathermal ions from previous impulsive events with heavy ion enrichment (Mason *et al.*, 1999). However, from a study relating suprathermal iron densities at $E > 0.01$ MeV/amu during quiet periods to the corresponding densities in Fe-rich events, Mewaldt *et al.* (2003a) concluded that there is not enough iron at quiet times to account for the overall enrichment of Fe. In fact, at high energies, where for most of the events the acceleration is close to the Sun, an alternative process may be more important: direct injection of particles from the CME-related flare (e.g. Klein and Trotter, 2001 and references therein; Cane *et al.*, 2003), with or without further acceleration by the coronal and/or IP shock.

2.2.2. Compositional Variations During SEP Events

The intensity–time profiles and elemental abundances during large SEP events show a complex variation with time. The intensity-time profiles strongly depend on the location of the observer relative to the passing IP shock and ICME (e.g. Figure 2 of Cane and Lario, 2006, this volume). A common feature is the large variation of elemental abundances of particles with the same velocity, but different rigidity (e.g., Fe/O) during the event onset, i.e., before the time of maximum (e.g., Klecker, 1982; Mason *et al.*, 1983; Tylka *et al.*, 1999; Reames *et al.*, 2000). The decrease of, for example, Fe/O during the rise of the event can be explained by the particles' mean free path λ increasing with rigidity in the background Kolmogoroff–type spectrum of the interplanetary magnetic field fluctuations. If λ is increasing with rigidity, then Fe/O at equal velocity will decrease during the rise of the event as a result of the larger M/Q of Fe. This has been reproduced by propagation models, assuming acceleration close to the Sun (e.g. Scholer *et al.*, 1978; Mason *et al.*, 1983). The very complex abundance variations later in the events, before and after the passage of the IP shock, can be understood in terms of models including proton-amplified waves, and scattering of all ions by these waves (Ng *et al.*, 1999; Tylka *et al.*, 1999; Ng *et al.*, 2003). Shock acceleration is heuristically (and not self-consistently) implemented in these models by continuous injection of particles with abundances derived from solar wind abundances and spectral slopes used as a model parameter. Nevertheless, a detailed comparison of the observed time variations with model calculations can be used as a tool to infer, as a function of distance of the IP shock from the Sun, important parameters such as injection efficiency, injection abundances, shock strength, and wave power near the shock.

2.2.3. Energy Spectra

The energy spectra as observed in interplanetary space near Earth are a result of the acceleration and propagation processes between the acceleration site and the observer. Typical energy spectra observed in large events can often be fitted by power laws with exponential roll-over at high energies. These spectral forms can be explained by shock acceleration: in the ideal case of an infinite and planar shock geometry and steady-state conditions, the energy spectra would be power laws and could be described as $dJ/dE \propto E^{-\gamma}$, where γ is related to the shock compression

ratio (Axford *et al.*, 1978; Blandford and Ostriker, 1978). However, the IP shock driven by an ICME will not be planar, particularly close to the Sun. Whether steady-state conditions at a specific energy are reached will depend on the shock strength, the number of injected protons and the intensity of proton-amplified waves. Thus, steady state may be reached at low energies but not at high energies. Non steady-state conditions (Forman and Webb, 1985) and losses at the shock due to particles escaping upstream (e.g. Ellison and Ramaty, 1985) will result in a roll-over of the power-law spectra at high energies. This spectral form is frequently observed and can be fitted by $dJ/dE \propto E^{-\gamma} e^{-E/E_0}$, where E_0 depends on M/Q of the ions (Tylka *et al.*, 2000). The roll-over energy E_0 shows a large event-to-event variability ranging for protons from ~ 10 MeV (Tylka *et al.*, 2000) to ~ 800 MeV (Lovell *et al.*, 1998).

2.2.4. Ionic Charge Composition in Interplanetary Shock-Related Events

The ionic charge of solar energetic particles is an important parameter for the diagnostic of the plasma conditions at the source region in the solar corona. Furthermore, the acceleration and transport processes depend significantly on velocity and rigidity, i.e. on the mass and ionic charge of the ions. Several methods have been developed over the last ~ 30 years to determine the ionic charge of energetic ions (e.g. Popecki *et al.*, 2000a). At low energies of ~ 0.01 – 3 MeV/amu techniques involving electrostatic deflection provided the first direct ionic charge measurements (Gloeckler *et al.*, 1976; Hovestadt *et al.*, 1981) of SEPs. At higher energies, the SAMPEX instrumentation (Baker *et al.*, 1993) provided for the first time ionic charge measurements for many elements in the range C to Fe over the extended energy range of 0.3 – 70 MeV/amu, utilizing the Earth's magnetic field as a magnetic spectrometer.

Indirect methods use the rigidity dependence of diffusive interplanetary propagation to infer average ionic charge states of heavy ions from the time-to-maximum (O'Gallagher *et al.*, 1976; Dietrich and Tylka, 2003) or from the time profile in the decay phase (Sollitt *et al.*, 2003) of SEP events. Furthermore, the M/Q dependence of the roll-over energy E_0 (see above, Tylka *et al.*, 2000), and elemental fractionation depending on M/Q (Cohen *et al.*, 1999) have been successfully used to infer mean ionic charge states of heavy ions. Although these indirect methods are limited to the determination of average charge states and rely on the assumption of the mean ionic charge being independent of energy, they provide a valuable tool if direct measurements are not available.

The early measurements from about 25 years ago revealed for IP shock-related events an incomplete ionisation of heavy ions in the range C–Fe at energies of ~ 1 MeV/amu, with $Q(\text{Fe}) \sim 10 - 14$, indicative of source temperatures of about $1.5 - 2 \times 10^6$ K (Gloeckler *et al.*, 1976; Hovestadt *et al.*, 1981; Luhn *et al.*, 1984). It was also found that the mean ionic charge in ^3He - and heavy-ion-rich events was significantly higher (Klecker *et al.*, 1984; Luhn *et al.*, 1987), with $Q(\text{Fe}) \sim 20$ and $Q(\text{Si}) \sim 14$. This was interpreted as being indicative of a high temperature

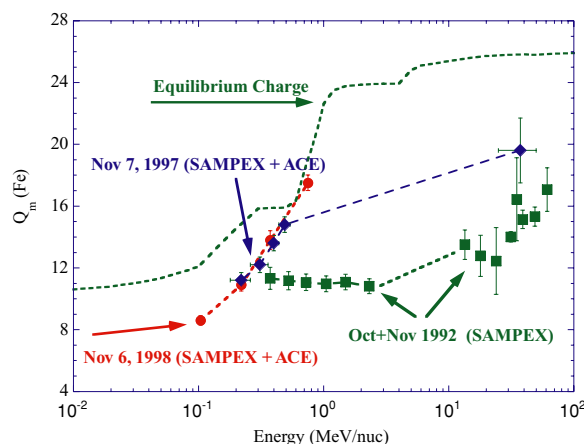


Figure 3. Mean ionic charge of Fe as a function of energy for 3 large SEP events (data from summary of Popecki *et al.* (2003) and energy dependence obtained for equilibrium conditions in a charge stripping model (Kocharov *et al.*, 2000).

of $\sim 10^7$ K in the source region. However, with SAMPEX, a significant increase of the mean ionic charge of heavy ions with energy was found in several large gradual events, with $Q(\text{Fe})$ increasing from $Q \sim 10$ at ~ 0.3 MeV/amu to ~ 18 – 20 at ~ 40 MeV/amu (Mason *et al.*, 1995; Leske *et al.*, 1995; Oetliker *et al.*, 1997; Leske *et al.*, 2001; Labrador *et al.*, 2003). Recent measurements with SOHO and ACE showed an increase of $Q(\text{Fe})$ even below 1 MeV/amu: The mean ionic charge of Fe in IP shock-related events at suprathermal energies (~ 0.01 – 0.1 MeV/amu) is consistent with solar wind charge states (Bogdanov *et al.*, 2000; Klecker *et al.*, 2000). At somewhat higher energies (0.2–0.6 MeV/amu) in many events the mean ionic charge increases with energy (Möbius *et al.*, 1999; Popecki *et al.*, 2003), with a large event-to-event variability (e.g. Möbius *et al.*, 2002 and Figure 3). It should be noted that in Fe-rich impulsive events a large increase of $Q(\text{Fe})$ with energy by ~ 4 – 6 charge units is systematically observed at $E < 0.6$ MeV/amu (Möbius *et al.*, 2003).

A small increase of the mean ionic charge with energy by 1–2 charge units in the energy range 0.2–1 MeV/amu, or a somewhat larger increase as observed above ~ 10 MeV/amu could be due to the acceleration process (Klecker *et al.*, 2000, 2003). However, a large increase of Q at energies < 1.0 MeV/amu, as sometimes observed in gradual events, but systematically observed in impulsive events, requires a different mechanism and can be explained by ionisation in a dense environment. If the particles propagate in a sufficiently dense environment in the lower corona during or after the acceleration, a large increase of the mean ionic charge with energy is a natural consequence. This has been investigated quantitatively in recent years (Ostryakov and Stovpyuk, 1999; Barghouty and Mewaldt, 1999; Kocharov *et al.*,

2000; Stovskyuk and Ostryakov, 2001). The model calculations show that the mean ionic charge increases monotonically as a function of Nt , where N is the plasma density and t is the residence time. It approaches asymptotically an upper limit (the equilibrium mean charge) Q_{eq} , where $(Nt)_{eq}$ for 0.5 MeV/amu Fe ions is typically $\sim 10^{10} \text{ cm}^{-3}\text{s}$ (Kocharov *et al.*, 2000). Figure 3 shows as an example the mean ionic charge of Fe as a function of energy, computed for the limiting case of equilibrium mean charge states caused by stripping in the corona. Ionization by electrons and protons, as well as radiative and dielectronic recombination, are taken into account in the calculation (Kocharov *et al.*, 2000). In these models, the large variability of the increase of Q with energy can be reproduced by variable acceleration rates and non-equilibrium conditions for charge stripping (e.g. Kovaltsov *et al.*, 2001). In the case of near-equilibrium conditions (as observed in the 6 November, 1997 event) and acceleration time scales of $\sim 1\text{--}100$ seconds, this corresponds to coronal densities of $10^8\text{--}10^{10} \text{ cm}^{-3}$, i.e. altitudes of $< 2R_{\odot}$ in the corona.

In summary, the interpretation that the presence of high ionic charge states of heavy ions in small impulsive events is an indication of high temperatures at the acceleration site must be seriously questioned. However, considering that the source plasma in these events may be far from thermodynamic equilibrium, it is not surprising that temperature may not be the organising parameter. The only explanation for the strong energy dependence of the ionic charge of Fe (as consistently observed in impulsive events) is acceleration in a dense environment in the low corona, i.e. high charge states (e.g. Fe^{20+}) can be used as a tracer for a source low in the corona. Whether these high charge states, when observed in large gradual events, are accelerated in the contemporary flare, or whether they are accelerated at the coronal or IP shock from a suprathermal distribution from previous flares, is presently under investigation.

2.3. ELECTRONS IN THE INTERPLANETARY MEDIUM

G. M. SIMNETT

The electron intensity in the inner heliosphere as a result of solar activity is both very variable and hard to predict from observations of other transient activity. This is probably due to the variety of sources of electrons which range from those probably accelerated in the high corona (Potter *et al.*, 1980; Lin, 1985); those released in conjunction with CMEs (Haggerty and Roelof, 2002; Simnett *et al.*, 2002); to those accelerated in solar flares (Lin *et al.*, 1982; Evenson *et al.*, 1984; Moses *et al.*, 1989). Electrons are tied closely to magnetic field lines, so that it may be quite difficult at times for electrons to escape quickly from a flare site into space. Any observations at 1 AU, therefore, may be both difficult to interpret and arise from several of the above sources. Krucker *et al.* (1999) showed that some low energy events were released from the Sun at the time of a type III radio burst, which presumably indicates direct injection onto open magnetic field lines; other events may take up to half an hour

to reach a spacecraft at 1 AU, presumably due to unfavourable propagation. Events with an inferred delayed onset relative to the type III radio bursts tend to be proton rich, which may well indicate that the protons escape more readily from closed magnetic field lines. For a discussion of electron onset times see also Section 6.4 of Pick *et al.* (2006, this volume).

Notwithstanding the electron origin, the transport from the site of acceleration (and release) is governed by the interplanetary magnetic field. It may happen that the inner heliosphere fills up with solar electrons which dissipate, either through escape or energy loss, only slowly. Therefore, at low energies below a few tens of keV, the observed intensity may be from a combination of *all* the sources outlined above. Therefore spectra such as presented by Lin (1985) (Figure 12 of that paper) for the 23 September, 1978 event are probably a superposition of these different sources. It is customary to characterise the differential electron energy spectrum as a power law, $dJ/dE \propto E^{-\gamma}$, although some events may have a variable γ . Potter *et al.* (1980) showed that some small, impulsive events have energy spectra that continue as unbroken power laws in kinetic energy down to 2 keV, with a power law index γ ranging from ~ 3.5 to 4.8; these tend to propagate from the Sun without scattering and therefore appear as a collimated beam. These events were also not flare-associated, which Potter *et al.* interpreted as indicating a high coronal origin. The observation of many impulsive solar electron bursts at energies below 1.4 keV with power law spectra extending down to ~ 0.14 keV (Gosling *et al.*, 2003) would also be compatible with a high coronal origin. However, because of their frequent association with type III radio bursts, Gosling *et al.* (2003) suggested as an alternative a low coronal origin, although they could not explain in this scenario that the power law spectra do not show any sign of energy loss effects at low energies.

Lin *et al.* (1982) carefully selected western hemisphere flare events to minimise the propagation effects, and showed that the events typically had differential energy spectra with $\gamma = 2.4\text{--}4.3$ above a few 100 keV, flattening to 0.6–2.0 at low energies. In addition, some events show a second spectral steepening above a few MeV.

At highly relativistic energies above a few MeV the situation becomes clearer. Evenson *et al.* (1984) investigated the association of intense events with solar gamma-ray production and showed that electron-rich events are likely to be associated with gamma-ray events, and have hard energy spectra. Such events are not associated with interplanetary shocks, which therefore are not a source of electron acceleration above a few MeV (Simnett, 2003). The electron/proton ratio (at the same energy) may vary by 5 orders of magnitude (Evenson *et al.*, 1984).

At large events, electrons with energies up to around 100 MeV are produced. Some typical spectra are shown in Figure 4. We have plotted the spectra as functions of kinetic energy. There are significant spectral differences between the various events, which may possibly be related to the different interplanetary and acceleration/release properties.

One of the first comprehensive studies of electron spectra was done by Moses *et al.* (1989) who showed that the spectra, when expressed in terms of rigidity, could

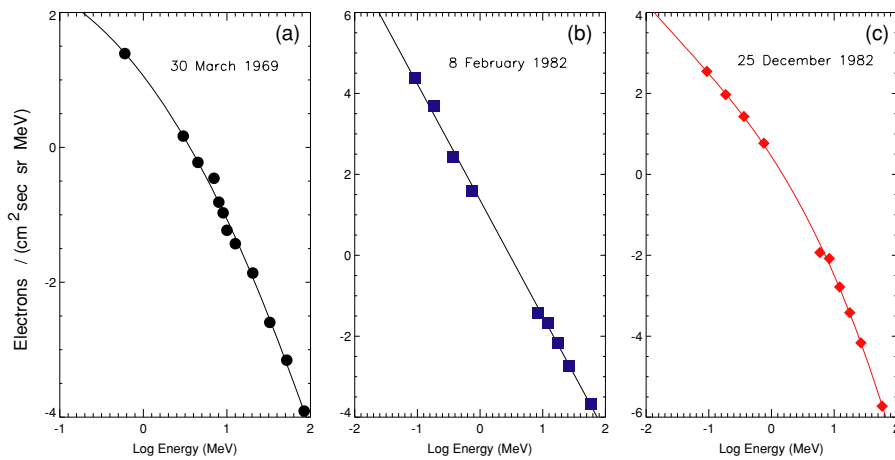


Figure 4. Interplanetary electron spectra for events extending to ~ 100 MeV. (a) A very long-lived event following a major flare on 30 March, 1969, where the inner heliosphere acted as a particle reservoir. (After Simnett, 1974). (b) An impulsive flare event from a $W88^\circ$ flare on 8 February, 1982. (c) A long duration event from an $E45^\circ$ flare associated with an interplanetary shock on 25 December, 1982. (After Moses *et al.*, 1989).

be ordered into two groups, those with single power laws in rigidity and those where the spectrum hardened with increasing rigidity. They found that those events with near power law spectra were well correlated with long duration soft X-ray events, whereas those with hardening spectra were correlated with short-duration events. We know that the long duration events are normally accompanied by coronal mass ejections, which in turn are accompanied by the injection into the interplanetary medium of near-relativistic electrons. Whether the latter are actually accelerated by the CME or merely gradually released is a matter for debate. Nevertheless, when analysing the spectrum generated by using the maximum flux at a given energy, this would tend to increase the lower energy part of the spectrum for the long duration events. We should point out that event (b) plotted as a function of rigidity would fall into the class of “hardening spectra” as defined by Moses *et al.* (1989).

Observations above 100 MeV are almost non-existent, so it is unclear if the solar electron spectrum continues to beyond 100 MeV. Longer duration events are illustrated by the spectrum from the 25 December, 1982 event, which exhibits the spectral steepening above a few MeV observed by Lin *et al.* (1982). This event is typical of those flare events which have a CME-driven shock. For the event shown in Figure 4 the inner heliosphere filled with electrons following a major flare on 30 March, 1969. The e-folding decay of the intensity at relativistic energies was 125 hours for over a week (Simnett, 1974), indicating that if conditions are favourable, even highly relativistic electrons have small losses. This flare event, which was from just behind the solar west limb, had a power law index γ of 3.04 above 5 MeV and would have certainly been accompanied by a major CME. Thus

it would come into the category of events such as shown in Figure 4 c, except with impeded escape from the inner heliosphere.

The energy emitted in electrons is generally low in comparison to that in the protons at the same energy. At relativistic energies (above a few MeV) a typical electron/proton ratio is 10^{-3} (Evenson *et al.*, 1984), although as noted above there is a huge variation. Events associated with gamma-ray flares have a ratio closer to 10^{-2} . As the differential energy spectra have power law indices steeper than -2 , the bulk of the energy resides at low energies. Here the propagation issues, plus the fact that low energy (<1 MeV) protons (a) have long travel times from the Sun and (b) are accelerated by strong interplanetary shocks means that an electron/proton ratio at low energies is hard to interpret in terms of production mechanisms. This merely emphasises that there are a variety of sources for both protons and electrons, having different efficiencies which are functions of time, energy and space.

3. Acceleration and Transport

3.1. ACCELERATION

H. KUCHARÉK, M. A. LEE, B. KLECKER, H. V. CANE, G. SIMNETT

There is a long history of studies of SEP events and their association with acceleration processes at the Sun and in interplanetary space. However, the relative importance of the various acceleration mechanisms is still controversial (see also discussion in Section 2). The questions are: How important are CMEs in producing the energetic particle population in different energy ranges measured in the heliosphere? Where does the acceleration occur and what are the sources of the energetic particles? How important are shocks associated with CMEs for accelerating ions? These are key science issues which are currently under intense investigation. In the following sections we will review the injection and acceleration models and discuss how well they are supported by observations.

3.1.1. *Acceleration Sites and Mechanisms*

For impulsive events several acceleration mechanisms have been proposed, including stochastic acceleration in the turbulence generated by the flare (Ryan and Lee, 1991; Holman, 1995), direct electric field acceleration at the site of magnetic reconnection (Holman, 1995; Litvinenko, 1996); resonant acceleration by electrostatic ion cyclotron (EIC) waves (Fisk, 1978) and by electromagnetic ion cyclotron (EMIC) and shear Alfvén waves (Miller and Vinas, 1993), and shock acceleration by the shock formed as the reconnection plasma jet impinges on the denser plasma below the flare arcades (Tsuneta and Naito, 1998; Aurass and Mann, 2004). A challenging test for any theory of impulsive events is to explain the observed large enrichments of ^3He (by several orders of magnitude), of heavy ions like Fe (by

about a factor of ~ 10), and of ultra-heavies in the mass range ~ 80 – 200 (by a factor of ~ 40 – 200 , (Mason *et al.*, 2004)). Promising candidates are theories including resonant wave-particle interaction: for example, selective heating and acceleration of ^3He by EMIC waves and of heavy ions by cascading turbulence of shear Alfvén waves (Miller and Vinas, 1993). For a recent review of particle acceleration in solar flares see Aschwanden (2002).

Particle acceleration also occurs at CME-driven shocks. In the idealised model of a planar, infinite shock under steady-state conditions, the particles' momentum spectra downstream of the shock are power laws, with a spectral exponent depending on the shock compression ratio (Axford *et al.*, 1978; Blandford and Ostriker, 1978). Particles are scattered on the proton-amplified waves, pick up energy by multiple encounters of the shock, and escape upstream at a distance depending on the scattering mean free path, λ . For the discussion of a quasi-parallel shock geometry see Lee (1983) and Gordon *et al.* (1999). However, due to the limited spatial extent of coronal and interplanetary shocks and the limited time available for acceleration, the spectra will roll over at some energy E_0 (see also discussion in Section 2.2.3). This leads us to the important questions of injection mechanisms and source populations injected into the acceleration process.

3.1.2. *Injection Mechanisms and Seed Particles*

Although the shock acceleration mechanism is well studied and widely accepted, the origin and injection of the seed particles into the acceleration process is much less clear. There are several seed particle populations: the solar wind, interstellar pickup ions, prominence material, ions that are pre-accelerated in interplanetary space (suprathermal tails, see below), and suprathermal particles from previous SEP events filling the inner heliosphere (in particular during solar maximum (Mason *et al.*, 1999)). A detailed description of the injection process is certainly a challenging task because wave dissipation, large amplitude waves, and the shock structure play an important role. In addition the shape of the particles' distribution function is a significant factor. While solar wind ions can be described by Maxwellian or kappa distributions in the solar wind frame of reference, interstellar pickup ions form a shell-like distribution. Thus, compared to solar wind ions, pickup ions are already suprathermal and therefore easier to inject into any acceleration process.

Numerical simulations such as hybrid simulations (Quest, 1988; Giacalone *et al.*, 1992; Liewer *et al.*, 1993; Kucharek and Scholer, 1995) or Monte Carlo codes (Ellison *et al.*, 1990) have been very useful over the last two decades in investigating shock acceleration for a range of Mach numbers and magnetic obliquities and in estimating injection rates. These codes allow us to study highly nonlinear processes which play an important role in the injection and acceleration of particles at shocks. Most of the analytical models are not able to include these nonlinear processes.

For injection at quasi-parallel shocks, Malkov (1998) introduced an analytical model in which particles are trapped in the large-amplitude magnetosonic wave of the shock and then may leak upstream. Hybrid simulations suggest a different

mechanism. Solar wind ions perform a non-adiabatic motion when they reach the shock so that their velocity parallel to the magnetic field is small. Due to electric and magnetic forces in the shock ramp, particles may be trapped at the shock and gain energy in the electric field while in gyro-resonance with the upstream waves convected into the shock (e.g. Scholer *et al.*, 2000). Multiple encounters with the shock after scattering upstream and downstream then lead to large energy gains.

At quasi-perpendicular shocks a larger minimum energy is required for multiple shock encounters. At the first encounter with a quasi-perpendicular shock some particles are specularly reflected and gain energy while traveling along the motional electric field in the shock foot and ramp. During this process they gain up to twice the incoming velocity. However, the energy gain may not be enough for a particle to interact with the shock several times before it is convected downstream. Rapid scattering in the shock ramp may be one process to make this happen. Multi-dimensional hybrid simulations (Giacalone *et al.*, 1992; Scholer and Kucharek, 1999) suggest that specular reflection in combination with cross-field diffusion may be sufficient to inject and accelerate ions at quasi-perpendicular shocks. However, if the seed population is comprised of suprathermal particles they already start at higher energies and are more easily injected.

3.1.3. *Pickup Ions: A Tool for Studying Particle Injection and Acceleration*

Pickup ion distributions and suprathermal tails of the solar wind are frequently observed in Corotating Interaction Regions (CIRs) at distances of ~ 5.5 AU (Gloeckler *et al.*, 1994) and can be explained by statistical acceleration by fluctuations of the magnetic field magnitude within the CIR (Schwadron *et al.*, 1996). Significant increases of He^+ pickup ions at the injection speed of $2V_{SW}$ have also been found at ~ 1 AU in solar wind compression regions (Saul *et al.*, 2003). In fact, the abundance of energetic He^+ ions in the inner heliosphere can be rather large ($\text{He}^+/\text{He}^{2+} \sim 1$, Hovestadt *et al.*, 1984). In IP shock related events He^+ can constitute, after H^+ and He^{2+} , the third most abundant ion species in the energetic particle population in the inner heliosphere (e.g. Kucharek *et al.*, 2003, and references therein). The measurements of the He^+ pickup ion source and He^{2+} solar wind source populations and the distribution of accelerated particles can be used to study the influence of the distribution function on particle injection and acceleration.

3.1.4. *Comparison of Observations with Predictions from Theory*

The observations of energetic particles at IP shocks are in agreement with many of the predictions of the theory of shock acceleration (Forbes *et al.*, 2006; Mikić and Lee, 2006, this volume). For example, the exponential intensity increase upstream of quasi-parallel shocks, the power law spectra as observed at low energies and the increased power seen in the magnetic field fluctuations are predicted by the theory. However, quantitative comparisons show a highly variable degree of precision of the predictions (e.g. Kennel *et al.*, 1986; Bamert *et al.*, 2004). Furthermore, different processes of acceleration, injection, or both, might prevail in different energy ranges.

In this sub-section we will therefore limit the discussion to energies of less than a few tens of MeV and review more qualitative comparisons of shock acceleration theory with some of the observations.

Intensity-time profiles: The time profiles of SEP events depend on the magnetic connection of the acceleration site with the observer. Therefore, the large variability of the intensity-time profiles and the longitude distributions of SEP events can qualitatively be explained by the extended longitudinal range of CME-driven IP shocks and by the relative location of the observer to the presumed source location of the CME (Cane *et al.*, 1988, see also Figure 4 of Cane and Lario, 2006, this volume). Early in the event, much before the shock arrival, many large SEP events show a maximum-intensity plateau not exceeding several 100 protons per ($\text{cm}^2 \text{ s sr MeV/amu}$) at ~ 1 MeV. This plateau level can be explained by the scattering of escaping particles by the proton-amplified waves, limiting the intensity of escaping particles (the ‘streaming limit’) to a specific value (Reames and Ng, 1998, and references therein).

Composition: Shock acceleration theory usually assumes injection of ions at some threshold energy, E_{min} , with abundances given by the source population. Thus, in the idealised case of an infinite, planar shock and steady-state conditions, the composition of accelerated particles near the shock would reflect the composition of the seed particles, possibly modified by any mass or mass/charge dependent injection effects. However, the particle distributions usually measured at ~ 1 AU are also influenced by the non-local effects of acceleration over the extended distance between the Sun and Earth (in a plasma environment that changes with space and time), and the effect of rigidity-dependent propagation. Therefore, the mass per charge dependent abundance variations found in large events are not surprising (see also Section 2.2.2). However, a prediction of observed abundance variations from the observed variations of shock parameters has so far not been successful.

Compositional variations during SEP events: The complex compositional variations of ions with different rigidity at the same velocity (e.g. Fe/C, He/p) during the onset phase of SEP events and before the shock passage can basically be understood in terms of a rigidity dependent scattering mean free path and by scattering of heavy ions by the proton-amplified waves near the shock (see discussion in Section 2.2.2).

Energy spectra: In general, IP shock related events do show power-law energy spectra, at least at low energies, and a roll-over at high energies (see also discussion in Section 2.2.3). However, in a statistical study using 72 events, Desai *et al.* (2004) compared the spectral slope predicted from the local shock compression ratio with the power law spectral index for C, O, and Fe and did not find a significant correlation.

3.1.5. Theoretical Challenges

The theoretical challenges for the ions are (1) a quantitative description of the acceleration in impulsive flares, including the energy dependent ionic charge states

and ^3He - and heavy ion enrichment; (2) to unfold injection, acceleration and propagation processes for a better understanding of the fractionation effects observed in elemental and isotopic abundances; (3) to determine where and how energetic particles in large events are accelerated to high energies (>20 MeV/amu). This would shed light on the current debate on the origin of flare particles in large events: do these particles originate at the CME-related flare or from unrelated flares (suprathermal remnants), further accelerated by the CME-driven shock? Results from theory and numerical simulations, as well as from observational investigations, need to be combined to obtain a clearer view of the interplay of all these processes.

3.2. ENERGETIC PARTICLE PROPAGATION

D. LARIO, E. C. ROELOF

Energetic particle time histories detected by instruments aboard spacecraft and on the ground are determined by the mechanisms that control the transport of energetic particles throughout the heliosphere and, in particular, by the effects that magnetic field structures have on this transport. Two transport mechanisms that are always operative are field-aligned transport and particle energy loss. A third mechanism is the transport across the moving magnetic field lines; i.e., in addition to the deterministic convection of the guiding center of the particles along with the field lines that are “frozen” into the solar wind.

Field-aligned transport results from weak pitch-angle scattering combined with the focusing effect of the outwardly decreasing interplanetary magnetic field (e.g. Roelof, 1969; Dröge, 2000). The amount of interplanetary scattering depends on both the level of turbulence existing in the interplanetary magnetic field (IMF) and the possible amplification of plasma waves produced by the energetic particles streaming along the IMF (Ng *et al.*, 2003). The energy loss is due to the gradient of the magnetic field in the diverging solar wind and the curvature drifts of the particles moving against the $\mathbf{V} \times \mathbf{B}$ electric field in the solar wind (Webb and Gleeson, 1979; Roelof, 2000). In the limit of very weak scattering, the energy loss process can be expressed in terms of a fractional momentum loss rate that depends only upon particle velocity and not on mass or charge (Roelof, 2000). The role of perpendicular diffusion across moving field lines is still under debate. One underlying physical process is the “random walk” or “braiding” of field lines arising from random diffusion of their photospheric foot points (Jokipii and Parker, 1968). An important mechanism in forming the global structure of the heliosphere stems from differential rotation of the solar magnetic field, the latitudinal flows of the photospheric magnetic field, combined with the tilt between the Sun’s rotation axis and the magnetic dipole axis (Fisk, 1996). In strongly turbulent fields, it has been argued that guiding centers of the particles are displaced across the field in

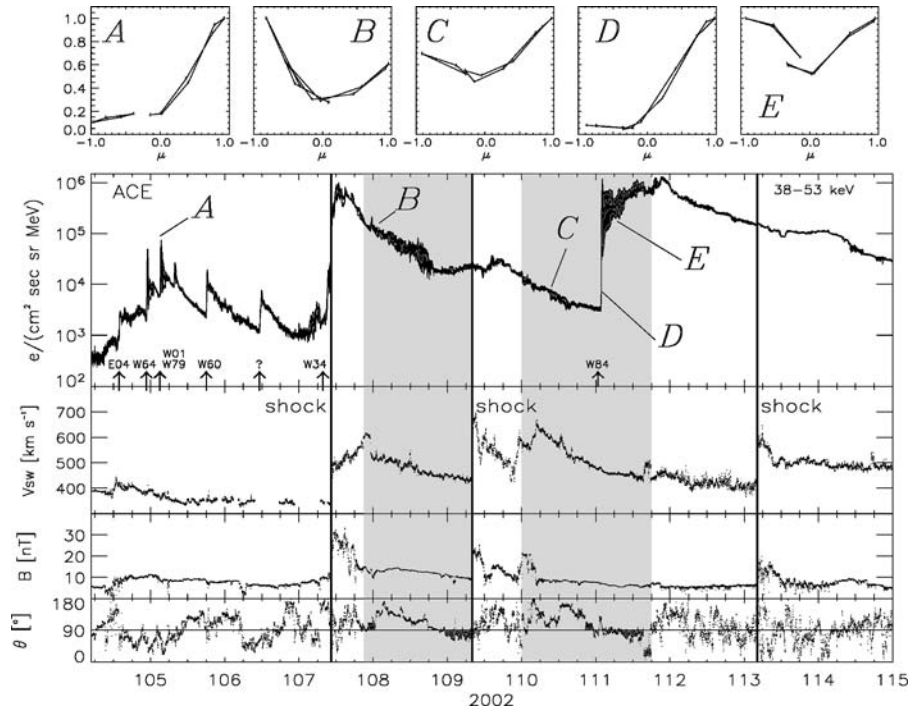


Figure 5. From top to bottom: 5 minute averages of normalized near-relativistic electron intensity distributions as a function of the pitch-angle cosine (μ) at five different time intervals (A–E). Time intensity profiles of the near-relativistic electrons as measured by ACE. Solar wind speed, magnetic field magnitude and elevation angle from 14 April, 2002 (day of year 104) to 25 April, 2002 (day of year 115). Solid vertical lines indicate the passage of shocks and gray vertical bars the passage of ICMEs. Vertical arrows show the occurrence of solar flares associated with the origin of the electron events.

single scattering processes by as much as their gyroradius (Jokipii, 1971). Persistent field-aligned anisotropies observed during solar energetic particle (SEP) events, however, suggest that cross-field diffusion is indeed small (Reinhard and Wibberenz, 1974; Sanderson *et al.*, 2003).

Increases (ΔB) in the IMF associated with ICMEs play a major role in controlling the intensity histories of SEP events (Barouch and Raguideau, 1970). Figure 5 shows 38–53 keV electron intensities observed by the ACE spacecraft during an intense period of solar activity in April 2002. At least eight electron events were observed throughout this 11-day period. Solar wind and magnetic field data show the passage of three interplanetary shocks (solid vertical lines) and two ICMEs (gray bars) as identified by Cane and Richardson (2003). On 15 April, 2002 (day of year 105) several small electron events were observed with rapid intensity increases and gradual slow decays characteristic of impulsive events. These impulsive SEP events usually exhibit pitch-angle distributions (PADs) that are strongly collimated

outward along the magnetic field during the rise to maximum (panel A, top of Figure 5).

On day 107 an M2/2N flare occurred at 07:46 UT from the NOAA Active Region 9906 at S14W34 just before the arrival of an interplanetary shock at ACE at 10:21 UT on the same day. The arrival of the electrons injected at the time of the solar flare was modulated by the presence of the traveling CME-driven shock propagating between the Sun and the observer, reducing the pitch-angle anisotropy during the rising phase of the event. During the decay of the event bidirectional PADs were observed (panel B in top of Figure 5). These bidirectional flows have been alternatively interpreted as a result of either particle propagation in closed magnetic field configurations (e.g., Marsden *et al.*, 1987) or a reflection of particles by the magnetic field increase ΔB associated with the CME-driven shock and located beyond the spacecraft (e.g., Anderson *et al.*, 1992; Malandraki *et al.*, 2002, and references therein).

Bidirectional PADs were observed during the passage of the second ICME on day 110 (panel C in top of Figure 5). These lasted until the occurrence of an X1/1F flare from NOAA Active Region 9906 at S14W84 on day 111, producing the onset of a new SEP event with unidirectional outward PADs (panel D in top of Figure 5). These PADs gradually evolved into a distribution with a “seagull” profile (panel E). In less than 4 hours the intensities with pitch-angle cosine $\mu < 0$ gradually increased to reach values similar to those observed with $\mu > 0$. The flat intensity profile observed during the peak of this event, coupled with the fact that PADs do not show the U-shape typical of bidirectional flows but rather the characteristic “seagull” shape, suggests that nearly field-aligned particles ($\mu = \pm 1$) were indeed able to escape from this structure. These observations also suggest that particles were not completely confined in a closed magnetic field structure but they were also reflected by the magnetic field increase ΔB that crossed ACE on day 109 and that at the time of the X1 flare (W84) was located at ~ 1.55 AU.

To summarize, the time interval shown in Figure 5 shows several examples of the effects that magnetic field (ΔB) increases produce on the properties of the SEP events. While an increase (ΔB) is en route to the observer, it can attenuate the intensity of the higher energy SEPs that are injected after the CME is launched, while possibly shock-accelerating the lower energy SEPs. When an increase (ΔB) is beyond the observer at the time of an SEP injection, it can enhance the SEP intensity by forming a reflecting barrier that impedes the escape of the SEPs into the outer heliosphere. When no significant increase (ΔB) is between the Sun and the spacecraft, we observe beam-like impulsive SEP events whose back-scatter depends, among other factors, upon whether or not there is an increase (ΔB) beyond 1 AU. Therefore, when using *in situ* SEP observations to interpret processes of particle acceleration and particle release into the interplanetary medium, it is important to analyze first the evolving global configuration of the IMF during the development of the SEP events and its effects on the particle transport.

4. Particle Release Time and the Electromagnetic Signature of SEP Events

A. POSNER AND K.-L. KLEIN

4.1. DETERMINATION OF SOLAR RELEASE TIME

Because of interplanetary transport it is difficult to distinguish signatures of different particle sources and different accelerators in SEP time profiles at 1 AU. However, the timing of the event onset can be used to infer the solar release time of the *first* particles of an SEP event that reach a spacecraft, and to compare this time with electromagnetic signatures of energetic particles in the solar atmosphere. Particles of speed v that are released at the Sun at time t_{SRT} will arrive at a spacecraft at t_{arr} after travelling a path length S :

$$t_{arr} = t_{SRT} + \frac{S}{v}. \quad (1)$$

For parallel propagation along the nominal interplanetary magnetic field, S is the length of the archimedean spiral (at 1 AU: 1.04–1.3 AU). However, large excursions from this average geometry exist due to nonradial expansion of the solar wind, e.g. near the Sun, to transient disturbances such as CMEs, and to MHD wave activity that scatters the pitch angles of the particles. A linear relationship is indeed commonly observed between the first arrival of particles of a given speed range at a spacecraft and the inverse speed, with path lengths between 1 and 2 AU (e.g. Reames *et al.*, 1985; Krucker *et al.*, 1999; Krucker and Lin, 2000; Mewaldt *et al.*, 2003b; Tylka *et al.*, 2003). Examples are shown in Figure 6. The left figure shows an event where electrons and protons seem to be released simultaneously, but the protons have a longer path length (2 AU) than the electrons (1.3 AU). In the right figure both species have the same path length, but the protons seem to be released nearly 1 hour after the electrons. For a discussion of electron onset times see also Section 6.4 of Pick *et al.* (2006, this volume) in this volume.

Energy dispersion of the onset times of SEP events can hence be used to infer the initial solar release time of the particles, provided (i) all particles travel the same path, i.e. are released from a volume small compared with S , and (ii) all particles start essentially at the same time. A systematic error is induced in the release time estimation if the acceleration time is finite. Delayed release of high-energy (low-energy) particles would flatten (steepen) the onset time vs. $1/\beta$ function. Assuming a straight-line fit would imply an average release time for all particles and a path length which is different from the one actually travelled by the particles. Krucker and Lin (2000) explain the steeper slope of the proton graph in the 13 November, 1997 event (Figure 6) as a signature of the delayed release, at greater coronal heights, of low-energy protons in the course of acceleration at the bow shock of a CME.

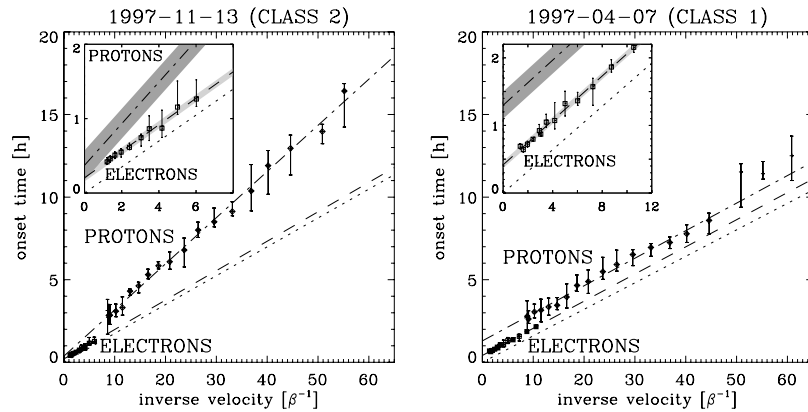


Figure 6. Plots of the onset time of protons between 0.1 and 6 MeV (diamonds) and electrons between 2 and 500 keV (squares; *Wind/3DP*) during two SEP events. The solar release time is the intercept of the straight lines fitted to the data with the vertical axis. The slope of the straight lines gives the path length travelled by the particles. (From Krucker and Lin, 2000).

Transport effects may alter onset times. Magnetic field irregularities lead to pitch angle scattering and drifts. Conservation of the magnetic moment in the expanding interplanetary magnetic field near the Sun leads to pitch angle focusing. The observed pitch angle distribution must therefore be field-aligned at the onset of an event. However, the scattering mean free path is uncertain, specifically close to the Sun (<0.3 AU), where no *in situ* observations exist. Large connection distances inferred from the onset time analysis can result from pitch angle scattering. This can be accounted for by assuming a non-zero average pitch angle for the first arriving particles.

Instrument-specific limitations are: (a) the width ΔE of the energy channels used, (b) the temporal resolution of the instrument and (c) the counting statistics in each channel. Larger instrumental geometric factors provide better statistics for a given event. On the other hand, the maximum size of events that can be analysed with large geometric factor instruments is limited. Electrons and ions behave differently in matter (straggling, bremsstrahlung) with the effect that ion channels are better defined in ΔE . Electrons with their largely higher speeds for any given kinetic energy have the advantage of smaller statistical uncertainty of inferred release times. Without corrections, these effects lead to delayed release times of ions over electrons.

In summary, with current instrumentation and single spacecraft observations, the release time determination cannot be better than a few minutes for measurements at 1 AU. This can be illustrated by the onset times and release times reported by different authors for a given event. Bieber *et al.* (2004) derived the injection function of relativistic protons during a ground level enhancement (GLE). The inferred release time is 3 to 4 min earlier than deduced from onset time analyses

(Kahler *et al.*, 2003; Tylka *et al.*, 2003). The solar release times reported for less energetic electrons and protons in the simple impulsive event of 1 May, 2000 show a scatter of 5–10 min (Tylka *et al.*, 2003; Mewaldt *et al.*, 2003b; Klein *et al.*, 2005; Klein and Posner, 2005). Similar uncertainties of release times were inferred from the analysis of simulated proton data (Lintunen and Vainio, 2004). Therefore only delays exceeding a minimum of, say, ~ 10 min between the release of particles of different species or between particles and photons are likely to be relevant indicators of the acceleration and transport of SEPs.

4.2. COMPARISON WITH DYNAMIC PROCESSES IN THE SOLAR CORONA

Knowing the release time of energetic particles allows us to study and identify several possible acceleration mechanisms when the times are compared with those derived from the solar electromagnetic signatures. Radio emissions from electrons accelerated in the corona were found to start up to several tens of minutes before the releases of protons and mildly relativistic electrons (Cliver *et al.*, 1982; Kallenrode, 1993; Krucker *et al.*, 1999; Haggerty and Roelof, 2002). Such delays are frequently ascribed to CME-shock acceleration of the escaping particles at heights of several solar radii (Lockwood *et al.*, 1990; Kahler, 2002; Simnett *et al.*, 2002). However, distinct radio signatures of late acceleration in the corona, well behind the CME and its presumed bow shock, were reported at the time of delayed releases of relativistic protons (Kocharov *et al.*, 1994; Akimov *et al.*, 1996; Klein *et al.*, 1999) and mildly relativistic electrons (Laitinen *et al.*, 2000; Maia and Pick, 2004; Klein *et al.*, 2005). This means that particles are accelerated in the corona for a time that may exceed the typical impulsive flare duration. If they are injected into different magnetic flux tubes extending into interplanetary space, a given spacecraft will detect only a portion of the escaping particles, and a one-to-one correspondence between particle acceleration in the corona and detection by the spacecraft becomes unlikely.

Altogether the onset time analyses reveal a complex timing of particles of different species or different energies. Time-extended particle acceleration in the aftermath of a CME or at its shock, particle transport in complex closed and open structures of the corona, and field line wandering or cross-field transport may all play a role in the timing.

5. ICMEs and Energetic Particles

J. RODRIGUEZ-PACHECO, D. LARIO, H. V. CANE, B. HEBER
AND T. R. SANDERSON

Energetic particle signatures associated with the passage of ICMEs over spacecraft located at 1 AU from the Sun and in the ecliptic plane have been described by several

authors, e.g. Palmer *et al.* (1978), Bame *et al.* (1981), Kutchko *et al.* (1982), Sarris and Krimigis (1982), Sanderson *et al.* (1983), Tranquille *et al.* (1987), Richardson (1997), Torsti *et al.* (2004). These signatures include bidirectional ~ 1 MeV ion intensities, bidirectional cosmic ray intensities, energetic particle intensity depressions (i.e., Forbush decreases, see Section 2.1), and unusual flow directions of particles injected at the Sun at the time an ICME passed over an observer.

Energetic particle observations within and around the passage of an ICME can be used not only to detect the passage of the ICME but also to infer the magnetic topology of these structures (Richardson, 1997). For example, bidirectional particle flows, unusual solar particle event flows, and energetic particle intensity depressions are consistent with the presence of regions of looped magnetic field lines rooted at the Sun at both ends (Richardson, 1997). These signatures, however, may not be detected in all ICMEs, either because they are not present or as a result of either instrumental limitations or data gaps, or simply because no SEPs were injected at the Sun. Sometimes these signatures are only observed during a sub-interval within an ICME but not throughout its entire passage over an observer.

The origin of the energetic particles occasionally observed during the passage of ICMEs is uncertain. For events observed in the ecliptic plane near 1 AU, Richardson (1997) suggested three possible origins for the intra-ICME particles: (1) they are a fraction of particles accelerated by the CME-driven shock that are able to penetrate into the ICME, (2) particles accelerated at the time of the CME lift-off at the Sun (which would imply the existence of a particle acceleration mechanism different from the CME-driven shock), and/or (3) particles injected into the ICME by unrelated solar events, i.e. by flares not related to the CME lift-off. Energetic particle access into and out of ICMEs depends on both the magnetic topology of ICMEs and the way energetic particles propagate within and around ICMEs. Whereas open magnetic field topologies allow the relatively free access of shock-accelerated particles into ICMEs, the access into closed magnetic topologies is more difficult and requires particle diffusion perpendicular to field lines (Cane *et al.*, 1995).

In the case of intensity increases due to the injection of particles from unrelated impulsive solar flare events with their unique compositional and ionic charge signatures (i.e. case (3) above), these intensity increases can be used to probe the connection of the magnetic field lines to the Sun (Mazur *et al.*, 1998). Several energetic electron (Larson *et al.*, 1997) and ion observations (e.g. Popecki *et al.*, 2000b, and references therein) indicate that the footpoint of magnetic clouds may remain attached to the Sun long enough for a cloud to reach 1 AU.

To study both the origin of the intra-ICME energetic particles and the topology of ICMEs, it is also essential to analyse both the temporal and spatial variations of particles within and around ICMEs.

A subset of ICMEs have simple flux rope-like magnetic fields with enhanced magnetic fields that rotate over a large angle, known as magnetic clouds (MCs). Rodríguez-Pacheco *et al.* (2003) studied the energetic particles observed within the

MC illustrated in Figure 1 (Section 2.1). The magnetic field topology of this MC was inferred from fitting the magnetic field observations with the model developed by Hidalgo *et al.* (2002). Under the scenario of a flux rope anchored at the Sun and for a given particle energy, the bidirectional character of the particle distributions should be higher at the center of the cloud than at its borders, because there the ions encounter a much shorter way to the Sun (i.e., a shorter time in reaching the mirroring points closer to the footpoints of the magnetic loop). Nevertheless, the bidirectional flows observed within this specific MC did not fit with this scenario; moreover, they were independent of the ion energy. Therefore, Rodríguez-Pacheco *et al.* (2003) concluded that the energetic particle mirroring at the footpoints of the loop was not the cause of the bidirectional flows found in that event. Instead, they claimed that the intra-ICME particles came from the sheath region formed ahead of the MC and behind the CME-driven shock and that the intrinsic properties of the injection mechanism were responsible for the bidirectional properties of the event (see details in Rodríguez-Pacheco *et al.*, 2003).

Energetic particle measurements within ICMEs allow us to distinguish multiple components within these large-scale structures. Figure 7 shows energetic particle, plasma and magnetic field observations as measured by the ACE spacecraft during the passage of an ICME identified by Cane and Richardson (2003). The first three panels show from top to bottom the 1.9–4.8 MeV ion intensities, the first-order parallel (A_1) and second-order (A_2) anisotropy coefficients computed in the solar wind frame following the method described in Lario *et al.* (2004). Bidirectional 1.9–4.8 MeV ion flows were not observed throughout the passage of the ICME but only during the first half of day 303. Changes in the energetic particle distribution were observed in association with changes in both solar wind proton density and temperature as well as with a change in the magnetic field rotation, suggesting that the magnetic field configuration of this ICME was formed by a double flux rope. Similar examples of multiple flux-rope configurations have been also proposed by Vandas *et al.* (1999), Haggerty *et al.* (2000) and Hu *et al.* (2004). Simultaneous changes in both plasma, magnetic field and energetic particle distributions suggest spatial changes within the structure of the ICMEs and that those structures may be more complex than simple flux ropes anchored at the Sun.

6. Summary

B. KLECKER, K.-L. KLEIN, AND H. V. CANE

We have shown that there is now a wealth of observations of energetic electrons and ions in the atomic mass range from hydrogen to iron, covering a wide energy range from \sim keV to \sim 100 MeV for electrons and 10s of keV/amu to 100s of MeV/amu for ions, respectively. New observations with instruments of much improved resolution and sensitivity onboard several spacecraft provide detailed information on the time-intensity profiles, energy spectra, elemental, isotopic, and ionic charge composition

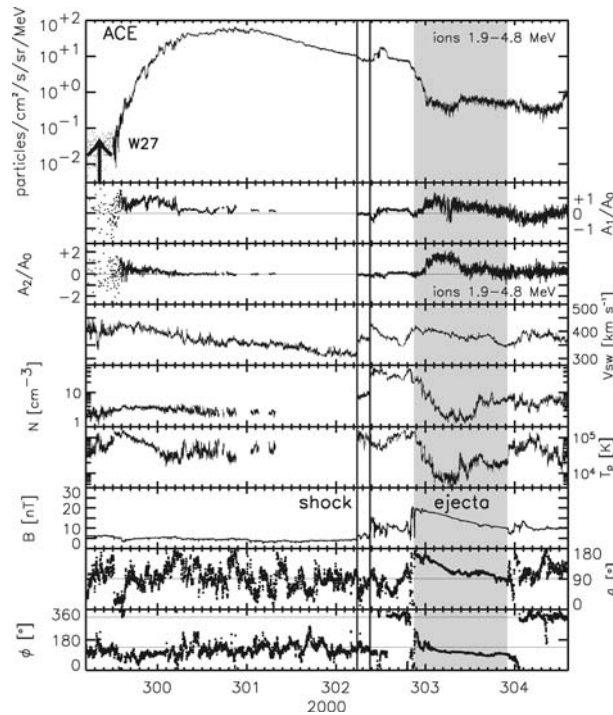


Figure 7. Observations of an event with experiments on the ACE spacecraft. From top to bottom: 1.9–4.8 MeV ion intensities measured by the EPAM instrument on board ACE. 1.9–4.8 MeV ion first-order parallel anisotropy coefficient in the solar wind frame. 1.9–4.8 MeV ion second-order anisotropy coefficient in the solar wind frame. Proton solar wind speed, density and temperature as measured by the SWEPAM instrument. Magnetic field magnitude and directions (in the GSE coordinate system) as measured by the MAG instrument. Solid vertical lines mark the arrival of the CME-driven shocks and gray bar indicates the passage of the ICME.

of energetic particles, accelerated either in solar flares and/or at CME-driven coronal and interplanetary shocks. These particle signatures carry fundamental information on the particle source, and on the injection, acceleration and propagation processes. However, with the particle observations being remote from the actual acceleration site, we always observe the combined effect of all these processes that are in general difficult to untangle.

Although there is considerable progress in our understanding of SEPs, there are a number of open questions that need to be addressed in the future, for example:

1. The systematic M/Q dependence of the elemental and isotopic composition in the energy range of a few MeV/amu is well documented. However, we are not able yet to relate this to the physical parameters of the plasma environment or the acceleration conditions.

2. The elemental abundances in the MeV/amu energy range at interplanetary shocks are strongly related to the suprathermal population upstream, suggesting acceleration at the shock. However, the spectral slopes derived from the local shock parameters are not consistent with the measured spectra.
3. Ionic charge states can strongly depend on energy. This implies that ionic charge states are not determined by the single parameter temperature, but rather by the combined effects of the plasma environment, impact ionisation during or after acceleration, the acceleration process, and interplanetary propagation. Thus, high charge states of Fe, e.g. Fe²⁰⁺, can be used as tracers for acceleration low in the corona. However, whether ions in high ionic charge states as observed in gradual events are accelerated from a suprathermal distribution from previous flare events or whether they are injected in the contemporary flare, needs further investigation.
4. We have time-resolved measurements of both SEPs (electrons and ions) and particles interacting in the solar atmosphere (hard X-rays, gamma-rays, radio), but due to transport to 1 AU the SEP time profiles are smeared out and only their start can be compared with electromagnetic signatures. This prevents us from identifying the traces of different acceleration mechanisms.

Further improvement in our understanding will require more modelling efforts, in particular:

1. Three dimensional simulation of CMEs and ICMEs, including the effect of particle acceleration in the dynamically evolving magnetic field configuration with parallel and perpendicular shock geometries;
2. to unfold injection, acceleration and propagation processes for a better understanding of the fractionation effects observed in elemental and isotopic abundances;
3. a quantitative description of the acceleration in impulsive flares, including impact ionization and propagation in interplanetary space for a better understanding of the abundance enhancements of ³He and heavy ions, the correlation between heavy ion abundances and charge states, and the energy-dependent charge states.

Significant progress can also be expected from future missions, for example

1. the STEREO mission (Solar Terrestrial Relation Observatory), to be launched in 2006, with its two spacecraft separated in solar longitude will provide a stereoscopic view of CMEs and improve our understanding of their three-dimensional structure;
2. the Solar Orbiter mission (e.g. Marsden and Fleck, 2002) with its perihelion at ~0.2 AU, in sync with the solar rotation for several days, will provide a close-up look at CMEs and allow much better correlation of the electromagnetic signatures and the characteristics of ions and electrons, because interplanetary propagation effects are minimal at this distance.

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