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Current understanding of SEP acceleration and propagation

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Abstract. The solar energetic particle (SEP) populations of electrons and ions are highly variable in space and time, in intensity, energy, and composition. Over the last ~20 years advanced instrumentation onboard many spacecraft (e.g. ACE, Coronas, GOES, Hinode, RHESSI, SAMPEX, SDO, SOHO, STEREO, TRACE, Ulysses, Yokoh, to name a few) extended our ability to explore the characteristics of solar energetic particles by in-situ measurements in interplanetary space and by observing their source characteristics near the Sun by remote-sensing observation of electromagnetic emission over a wide frequency range. These measurements provide crucial information for understanding the sources of the particle populations and the acceleration and propagation processes involved. We are now able to measure intensity-time profiles and anisotropies, energy spectra, elemental and isotopic abundances, and the ionic charge of particles over an extended energy range of 0.01 to several 100 MeV/nuc and for a large dynamic range of particle intensities. Furthermore, multi-spacecraft in-situ observations at different solar longitudes and latitudes provide new insight into the acceleration and propagation processes of SEPs near the Sun and in interplanetary space. In this paper we present an overview of SEP observations, their implications for SEP acceleration and propagation processes, and discuss open questions.

1. Introduction

The solar energetic particle (SEP) populations of electrons and ions as observed in interplanetary space are highly variable in space and time, in intensity, energy, and composition. Over the last ~20 years advanced instrumentation onboard many spacecraft (e.g. ACE, Coronas, GOES, Hinode, RHESSI, SAMPEX, SDO, SOHO, STEREO, TRACE, Ulysses, Yokoh, to name a few) extended our ability to explore the characteristics of solar energetic particles by in-situ measurements in interplanetary space and by observing their source characteristics near the Sun by remote-sensing observation of electromagnetic emission over a wide frequency range. In their intensity-time variations, anisotropies, energy spectra, elemental, isotopic, and ionic charge composition these particle populations carry fundamental information on the source population of the particles, and their acceleration and propagation processes. These new measurements improved our understanding of SEPs and showed that the scenario developed in the 70s to 90s needs modifications. In this scenario the SEPs were subdivided into 2 classes, i*mpulsive* and *gradual*, where *impulsive* events are related to solar flares and *gradual* events are related to the acceleration by coronal and interplanetary shocks, driven by coronal mass ejections (CMEs) and their interplanetary manifestations (ICMEs), respectively. Furthermore, multi-spacecraft in-situ observations at different solar longitudes and latitudes provide new insight into the acceleration and propagation of SEPs near the Sun and in interplanetary space. The observations at large separation distances as made available by the two

STEREO spacecraft provide, in combination with measurements near Earth, a sensitive tool for testing propagation models of SEPs. This paper provides an overview of SEP characteristics, emphasizing new SEP observations and their implications for SEP acceleration and propagation processes, and discusses open questions.

2. Impulsive and gradual solar energetic particle events

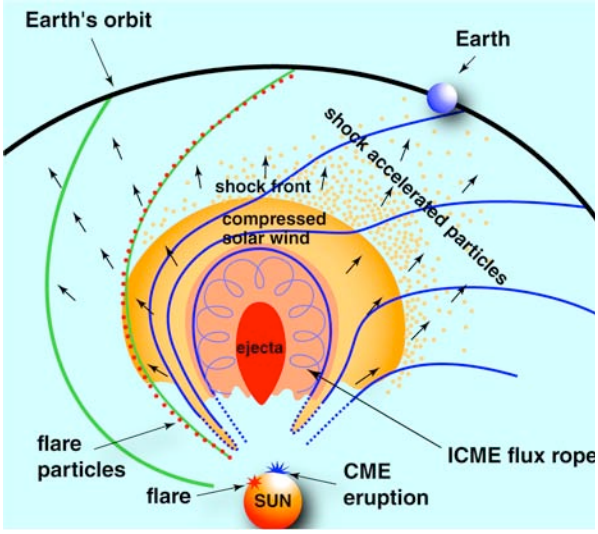

Figure 1. Illustration of different sources of solar energetic particles: (1) particle acceleration at a CME-driven coronal and / or interplanetary shock ("shock accelerated particles"); (2) particle acceleration related to flares ("flare particles") in the corona (adopted from the Multimedia STEREO/ IMPACT web site at http://sprg.ssl. berkeley.edu/ impact/ multimedia.html).

High-energy particles originating at the Sun were first reported about 65 years ago [1]. At that time there was little doubt that these particles were closely related to solar flares. Later it became clear that acceleration at coronal and interplanetary shocks is also an efficient mechanism for particle acceleration (e.g. [2]). In the early 70s a new type of event was discovered that showed enhanced ^{3}He abundances with ^{3}He/^{4}He>1 [3], while the corresponding ratio in the corona or solar wind is ~$5\mathrm{x}10^{-4}$ [4], [5]. Such events were later found to exhibit also enhancements of heavy ions by an order of magnitude relative to coronal abundances [6]. Based on these observations and on other characteristic differences (for example the electron to proton ratio, the intensity-time profiles, the distribution in solar longitude as observed from the near-Earth environment, and the mean ionic charge of heavy ions [7]) solar energetic particles (SEP) were classified as *impulsive* and *gradual,* following a classification of flares based on the duration of soft X-ray emission [8]. In this scenario *impulsive* SEP events were related to flares and the *gradual* SEP events were related to coronal mass ejection (CME) driven coronal and interplanetary shocks as schematically shown in figure 1 (e.g. [7], [9]).

However, new results with advanced instrumentation from several missions (e.g. WIND, SAMPEX, SOHO, ACE) have shown that this picture was oversimplified. New composition and ionic charge measurements show that enrichments in ^{3}He are also common in interplanetary shock accelerated populations [10], that enrichments in heavy ions are often observed in large events at high energies (e.g. [11]), and that high charge states of Fe are also observed in events usual classified as *gradual* [12], [13]. Therefore, the classification into two distinct types of events is presently in question and the relative contributions of flares and coronal / interplanetary shocks to the energetic particle intensities observed in interplanetary space are under debate. In this chapter we will summarize some of the previous and new observations and their implications.

2.1. Impulsive events

The large enrichments of ^{3}He and heavy ions found in event-integrated abundances of ^{3}He- and heavy ion-rich events have been used as one of their defining characteristics as impulsive events. Although

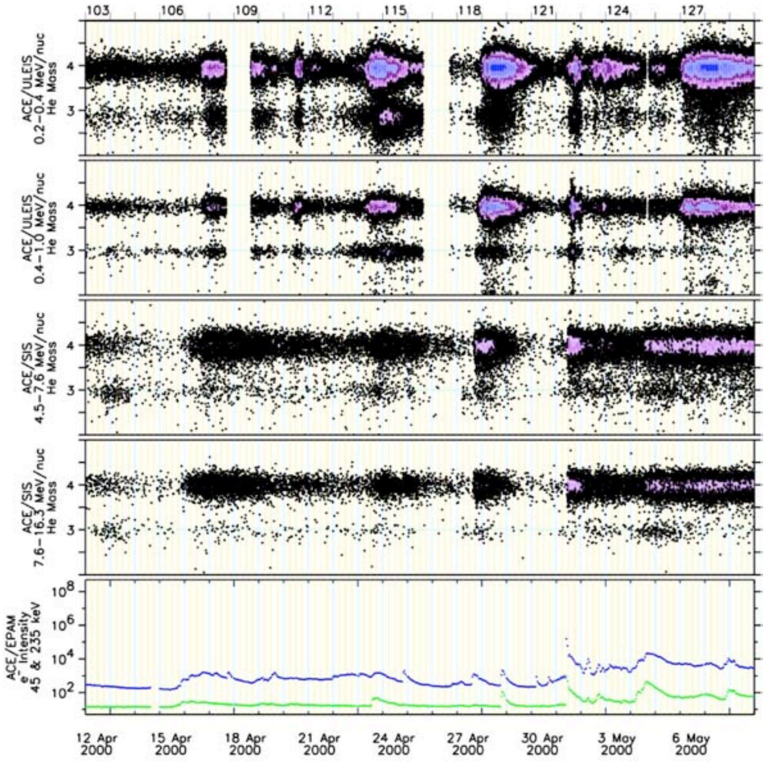

Figure 2. Mass spectrograms of helium in four energy ranges (panels 1-4), and electron fluxes at 45 keV and 235 keV (panel 5, EPAM/ACE) as observed during 12 April to 9 May 2000 (solar maximum conditions). The energy ranges of the He mass spectrograms are (from top to bottom): 0.2-0.4, 0.4-1.0 MeV/n (ULEIS/ ACE), 4.5-7.6, and 7.6-16 MeV/n (SIS/ACE). The figure is adopted from the ACE webpage http://www.srl.caltech.edu/ACE/ASC/DATA/level3/sis/heplots.html.

some of the characteristics (e.g. enrichment of ^{3}He relative to solar wind and coronal abundances, see section 2.2) are observed to some extend also in large (*gradual*) events, several signatures of the ^{3}He- and heavy ion-rich events are unique, suggesting a different acceleration process. Characteristics typical for impulsive events will be discussed in the following subsections.

2.1.1. Correlation of Electron Events and ^{3}He-rich events. One of the characteristics of impulsive events, first observed with ISEE-3 [14], is a strong correlation of ^{3}He enhancements with electron events, as can be seen (figure 2) from the new high-sensitivity measurements of helium ions onboard ACE. Figure 2 shows mass spectrograms of helium in four energy ranges between 0.2 and 16 MeV/nuc and electron fluxes at 45 and 235 keV. During the time period 12 April to 9 May 2000 several impulsive injections of electrons and ^{3}He, most pronounced at low energies, have been observed. These many injections of ^{3}He result in an almost continuous presence of ^{3}He in the inner heliosphere during solar maximum [15].

2.1.2. Characteristics of electron events. The intensity-time profiles, energy spectra and anisotropies of electrons provide valuable information on their acceleration and propagation processes. The typical electron energy spectra (figure 3) show a break below ~100 keV, with the spectra steepening at higher energies [16]. Furthermore, very often the spectra show a power law to energies of 1 keV and below. This places the acceleration region at sufficiently high altitudes where energy loss processes in the ambient corona are not important – otherwise the spectra would bend over to low energies [17].

The electron pitch angle distributions (PAD) in these impulsive evens show early in the event a large field aligned and energy dependent anisotropy. A typical example is given in figure 4 showing for electrons at 1.3 and 108 keV a PAD half width of 26° and 66° respectively [18]. This implies that there is not much scattering of electrons in interplanetary space during he onset phase of these events.

2.1.3. Time dispersion of SEP ions. The high sensitivity of new instrumentation provides unprecedented statistics also for small events. Figure 5 shows as an example the energy versus time profile for several events in August 1998 as observed with the ULEIS experiment onboard ACE [19]. This type of display, plotting the arrival time of individual ions versus their energy, shows velocity

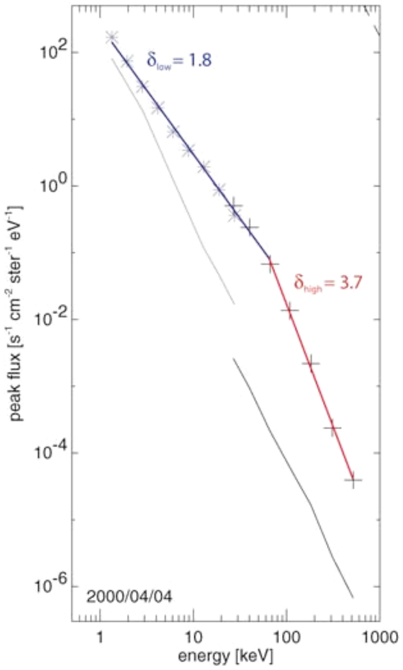

Figure 3. Electron peak flux energy spectrum of the 4 April 2000 SEP event, observed with the 3D plasma experiment onboard WIND. The thin black lines give an estimate of the background [16].

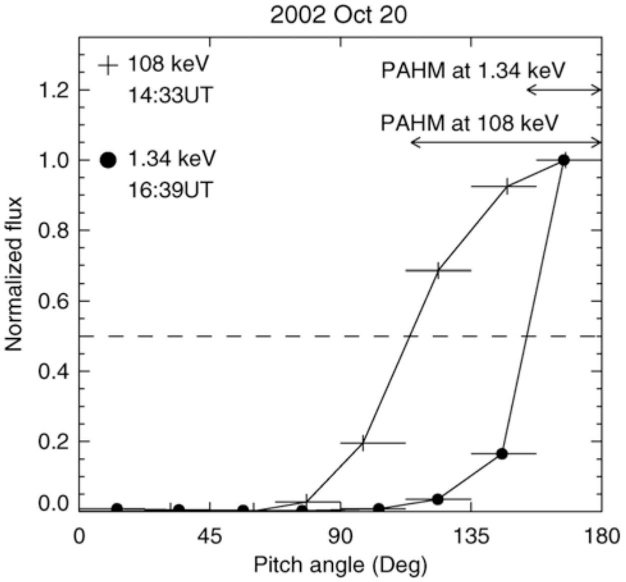

Figure 4. Electron pitch angle distributions (PAD) measured at 1.34 keV (dots) and 108 keV (crosses) during the time of peak intensity of the impulsive event on 20 October 2002. The arrows indicate the half width of the PADs [18].

dispersion that can be compared with scatter-free propagation along the interplanetary magnetic field, and allows the identification of individual injections at the Sun. This display also demonstrates that to correctly evaluate ion spectra and elemental and ionic charge composition in these events, start and stop times for the averaging of data need to be energy dependent, as indicated by the "boxes" enclosing individual injections. Figure 5 also demonstrates that some events exhibit a sudden intensity cut off. This is due to a loss of magnetic connection to the injection location at the Sun. These well defined injection profiles can also be used to infer large-scale diffusion parameters of ions in the heliospheric magnetic field [20], [21].

2.1.4. Ion energy spectra and elemental abundances. In a survey of energy spectra of ions in ^{3}He-rich events in the mass range He to Fe and in the energy range 80 keV/nuc to 15 MeV/nuc two classes of events have been identified [22]. Class 1 events exhibit power laws that often steepen above ~1MeV/nuc; in some cases the major species ^{3}He, ^{4}He, O, Fe have similar spectral slopes, while in other cases the ^{3}He slope below ~1 MeV/nuc is distinctly harder than the others. Class 2 events show curved ^{3}He and Fe spectra at low energies, while ^{4}He has power law spectra. As a consequence of the different spectral shapes of ^{3}He and ^{4}He the ^{3}He/^{4}He-ratio in Class 2 events is strongly energy dependent; also the largest ^{3}He/^{4}He-ratios are observed in this class of events [22].

It is also known since the early measurements of heavy ion composition in ^{3}He-rich events that these events can exhibit an enrichment in heavy ions by an order of magnitude (for Fe), relative to coronal abundances, although not all ^{3}He-rich events show enhancements of heavy ion abundances ([7], [23], [24]) and vice versa. With advanced instrumentation onboard the Wind and ACE spacecraft the measurements of heavy ions in these events has been extended to trans-iron elements and it has been shown that the enhancement factors are monotonically increasing from ~1 at mass 12 to ~200 in the mass range of ~240 [25], [26]. An estimate of the mean ionic charge of the ultra-heavy ions shows that the enhancement factor is also ordered by mass per charge ([26], [27]).

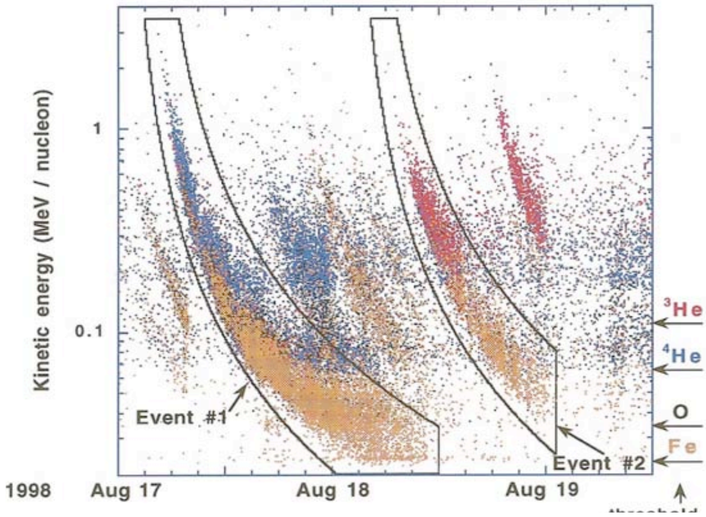

Figure 5. Ion energy–time spectrogram for 17–19 August 1998 from ACE / ULEIS showing several injections of ^{3}He, ^{4}He, O and Fe at the Sun. *Thin lines:* Event "boxes" indicating individual ion injection events [19].

In addition to information on the composition of heavy ions by particles escaping from the acceleration site in the corona into interplanetary space, γ-ray line observations provide information on the composition of heavy ions interacting with the ambient corona. It was found that the composition of interacting heavy ions is similar to the abundances in ^{3}He-rich SEP events as observed in interplanetary space [28].

2.1.5. Ionic charge states. Direct measurements and indirect determinations of heavy ion charge states at 1 MeV/nuc in the 70's showed in events that we would in retrospect identify as *gradual* for iron ions a mean ionic charge $<Q_{Fe}>$ in the range of $<Q_{Fe}>$ ~10-14 [29], [30]. However, for an average over several ^{3}He-rich events (for individual events the counting statistic was not sufficient) at the same energy a significantly higher mean charge of $<Q_{Fe}>$ ~19-20 was obtained [31], [32]. From this it was concluded that the ions in ^{3}He-rich events originate in a region of significantly higher temperature of ~10^7 K. However, new measurements of ionic charge states with instruments of improved sensitivity over a wide energy range (ACE, SOHO) have shown that this picture was oversimplified. The new measurements are now available for many individual impulsive events at lower energies (figure 6) and show a systematic increase of the mean ionic charge of Fe from ~11-15 at 100 keV/nuc to ~16-20 at 550 keV/nuc ([33]-[35], see also [36] for a recent review).

This large increase of the mean ionic charge of iron with energy above ~100 keV/nuc can be qualitatively explained in terms of impact ionization by protons and electrons in a dense environment in the low corona (e.g. [34], [37], [38]). However, for a quantitative description more realistic models, including the effect of stochastic acceleration, coulomb energy loss, and charge changing processes during acceleration, in combination with energy loss by adiabatic deceleration during interplanetary transport are needed to reproduce the observed strong energy dependence of the heavy ion ionic charge states [39]. Figure 7 shows as an example the mean ionic charge of Fe computed with such a model that simultaneously fits the intensity-time and anisotropy-time profiles, the heavy ion energy spectra and the mean ionic charge as a function of energy [40]. The mean ionic charge at low energies is essentially determined by the electron temperature. At energies above ~100 keV/nuc charge stripping effects are dominating and result in a strong increase of the mean ionic charge of Fe with energy [37].

One of the important parameters obtained from fitting the observed charge spectra with the model is the product $N_p\tau_A$, with proton density N_p and acceleration time scale τ_A. With $N_p\tau_A$ ~10^{10}-10^{11} s cm^{-3} [40] and assuming acceleration time scales of ~1-10 s, this corresponds to densities of ~10^9-10^{11} cm^{-3} at the acceleration site. This is similar to the density range of (0.6-10) x10^{10} cm^{-3} inferred from radio and electron measurements for the density of the acceleration region of electrons ([41], and references

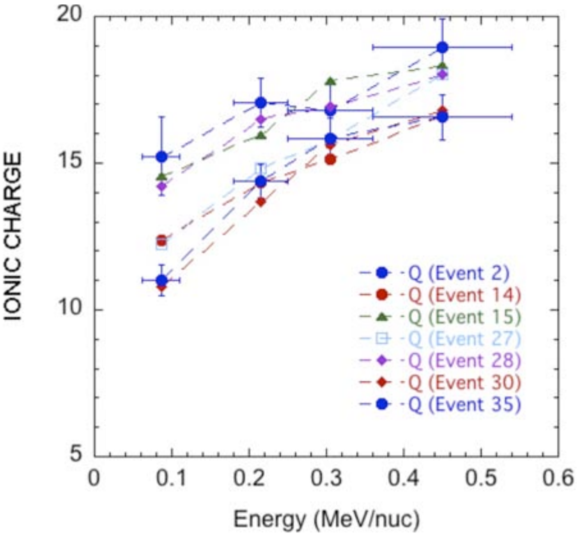

Figure 6. Mean ionic charge of Fe for several impulsive events showing the typical increase of the mean ionic with energy (adopted from [35]).

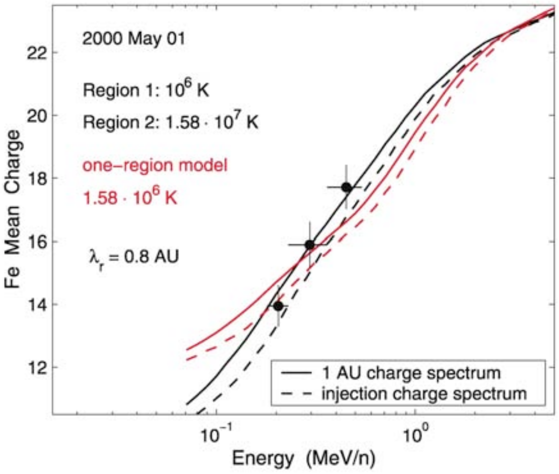

Figure 7. Calculated mean ionic charge of Fe as a function of energy at the Sun (injection spectrum, dashed line), and at 1 AU (solid line). For details of the model see [40].

therein), i.e. it indicates acceleration in the low corona, at altitudes ≤ 0.2 solar radii above the photosphere.

2.1.6. Acceleration processes and enrichment of ^{3}He and heavy ions. In order to cope with the large enrichments of ^{3}He and heavy ions by up to factors of 10^4 (for ^{3}He) and ~10 (for Fe) various processes have been proposed. Such scenarios include selective heating by resonant wave-particle interactions as a first step (e.g. [42], [43]), followed by a second step that could involve stochastic acceleration [44]-[46]. Curved spectra at low energies as observed for ^{3}He and Fe in Class 2 events can arise from stochastic acceleration processes by Alfvén turbulence [22]. At low energies these processes have been shown to provide good fits to the data. However, the spectra reported by [22] are much harder at high energies (e.g. above ~1 and 10 MeV/nuc for Fe and ^{3}He, respectively) than obtained with a stochastic acceleration model. Models based on cascading MHD turbulence ([22], [47], and references therein), and stochastic acceleration by parallel propagating Alvén waves [48] provide promising fits to the spectra of heavy ions [22], and of ^{3}He and ^{4}He [48], respectively. However, in all these models charge stripping effects that are essential for explaining the energy-dependent charge states of heavy ions and adiabatic energy loss during interplanetary propagation that could change the spectra at energies below a few hundred keV/nuc significantly, are not yet included.

2.2. Gradual events

Solar energetic particle events with long duration showing intensity increases of many orders of magnitudes and lasting up to several days are usually classified as *gradual*. These events are often accompanied by CME driven coronal and interplanetary shocks. However, whether ICME or interplanetary shock characteristics can be observed in the plasma and SEP signatures depends on the relative position of the spacecraft, the ICME and the interplanetary shock. For reviews on ICME signatures and characteristics of gradual SEP events, see for example, [49] and [50], respectively.

2.2.1. Intensity-Time Profiles. The intensity-time profiles of energetic particles in SEP events depend on the magnetic connection of the acceleration site with the observer. Therefore, the large variability

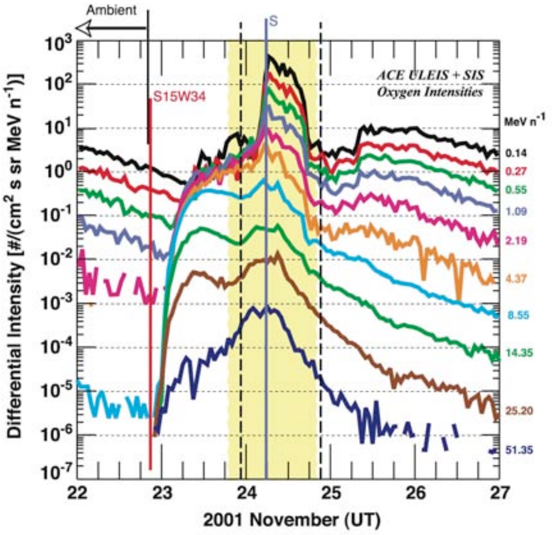

Figure 8. Hourly averages of the oxygen intensity between ~0.15 and 50 MeV/nuc measured onboard ACE during 22 – 27 November 2001 [53].

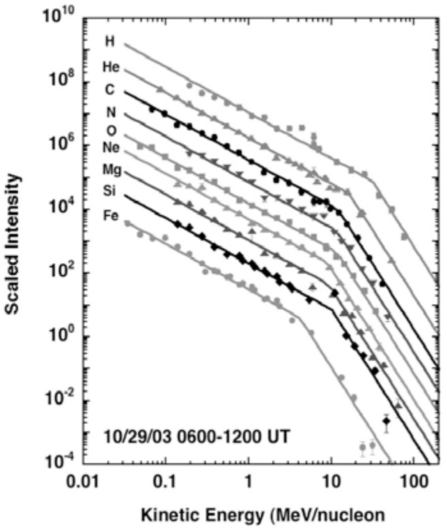

Figure 9. Energy spectra of H to Fe during a 6h period following an interplanetary shock on 29 October 2003, with a fit by two power-laws, showing the variation of the spectral break with energy for different elements [58].

of the intensity-time profiles and the longitude distributions of SEP events can qualitatively be explained by the extended longitudinal range of CME-driven interplanetary shocks and by the relative location of the observer to the presumed source location of the CME [51], [52].

Correlated with the arrival of the interplanetary shock, the particle intensities can increase by up to several orders of magnitude, dependent on energy. A typical example of oxygen ion intensities in the energy range 0.14 to 51 MeV/nuc as observed on ACE is shown in figure 8 [53].

Early in the event, much before the shock arrival, many large SEP events show a maximum-intensity plateau not exceeding (for protons) several 100 protons per (cm^2 s sr MeV/amu) at 1 MeV. This plateau level can be explained by the scattering of escaping particles by proton-amplified waves, limiting the intensity of escaping particles (the 'streaming limit') to a specific value (e.g. [54], and references therein).

2.2.2. Energy Spectra. The energy spectra as observed in interplanetary space are the result of acceleration and propagation processes between the acceleration site and the observer. In the ideal case of an infinite and planar shock geometry and steady state conditions, the particle differential intensity dJ/dE can be described by a power law: $dJ/dE \sim E^{--\gamma}$, where γ is related to the shock compression ratio (e.g. [55], [56]). However, because coronal and interplanetary shocks are not planar, and because only a limited time is available for acceleration, steady state will not be reached, in particular at high energies. Thus, non steady-state conditions [57] and losses due to particle escaping upstream will result in a roll-over of the fluxes at high energy. Therefore, fluence spectra in large (*gradual*) events can often be fitted with power laws with exponential roll-over ($dJ/dE \sim E^{-\gamma} \exp(-E/E_0)$ ([58], [59]) or with double power laws ([60], [61]), with the e-folding energy (E_0) or the spectral break (at energy E_B) systematically varying with mass per charge ([59]-[61]). This mass per charge dependence of E_0 and E_B may be approximated by a power-law dependence (e.g. $E_B \sim (Q/M)^{\alpha}$), where α depends on the angle between shock normal and magnetic field. The observed values of the exponent α are in the range ~0.7-1.75 ([59]-[62]), similar to the range predicted by SEP acceleration and transport models at quasi-parallel and quasi-perpendicular shocks [63]. If the energy spectra of heavy ions are available

2.2.3.

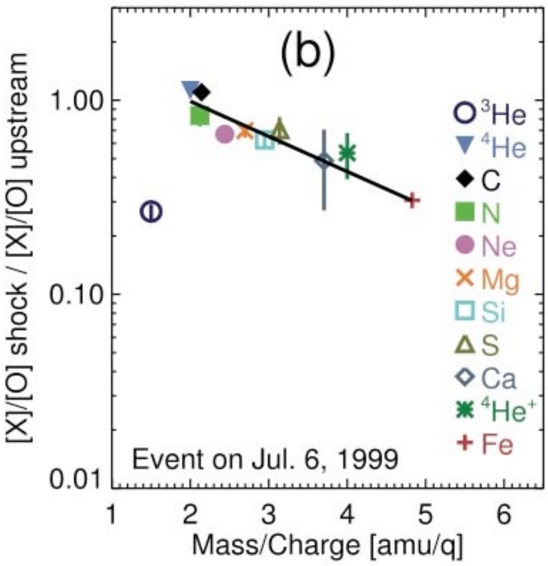

Figure 10. Shock to upstream abundance ratios relative to oxygen as a function of average M/Q ratio in the gradual SEP event of 6 July 1999 [73].

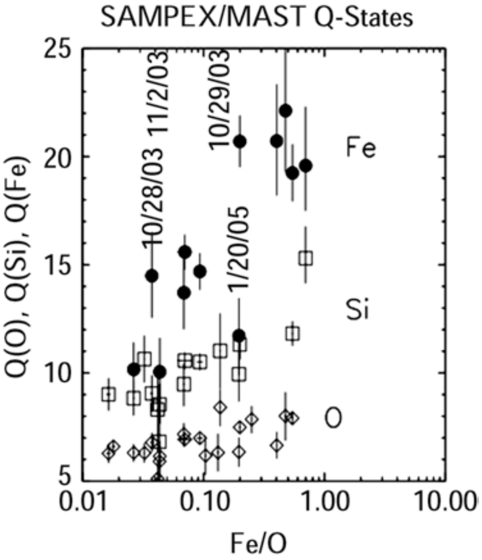

Figure 11 Correlation of the Fe/O-ratio with mean charge states of Si and Fe at > 10 MeV/nuc for several large (*gradual*) SEP events [78].

for a sufficiently large energy range, then the Q/M dependence of E_0 or E_B can be used to infer the mean ionic charge <Q> of heavy ions ([59], [64]).

2.2.4. Fractionation Effects. When comparing SEP abundances with photospheric abundances it has been realized since many years that both coronal and SEP abundances show a dependence on the first ionization potential (FIP) or first ionization time [65]-[67], suggesting ion-neutral separation in the chromosphere as an important fractionation mechanism (see [68], for a recent review). Furthermore, abundances in individual large SEP events show fractionation effects that monotonically depend on mass (M) or mass per charge (M/Q), usually approximated as a power law in M/Q [69]. This M/Q fractionation is observed for both elemental and isotopic abundances (e.g. [70]) and the correlation between isotopic and elemental abundances in individual events has been used to infer the abundance of the coronal source [71].

Mass per charge dependent fractionation has also been used to relate the elemental abundances observed at ~0.4 MeV/nuc at interplanetary shocks to their source. The observations show that the average abundances as observed at many interplanetary shocks are different from solar wind abundances. Furthermore the relative abundances of SEP particles around the shock passage do not show a monotonic dependence on mass per charge, as it would be expected from fractionation processes [72]. This provides evidence that the bulk solar wind is not the source of the accelerated heavy ion population. On the other hand, when compared with the upstream pre-event suprathermal population, a monotonic dependence of the abundance ratios on M/Q is observed, both for individual SEP events (figure 9) [73], and for the average of many shock events [72], supporting the evidence of acceleration of a remnant suprathermal component by the interplanetary shock.

2.2.5. Ionic Charge States. At interplanetary shocks the mean ionic charge of Fe, $<Q_{Fe}>$, at low energies (<250 keV/nuc) is usually ~ 9 – 11, independent of energy [74], similar to solar wind charge states [75]. The event integrated mean ionic charge of Fe at energies <1 MeV/nuc is also mostly constant, only in a view events increases with energy by up to 4 charge units have been observed [76], [77]. At higher energies a large variability is observed. At energies above ~10 MeV/nuc, the mean ionic charge is often observed to be significantly larger than at low energies, with $<Q_{Fe}> \sim$ 15-20 ([12], [13], [78]-[80]). Furthermore, at E ≥ 10 MeV/nuc high mean charges of Si and Fe are strongly correlated with high Fe/O abundances (figure 11, [78]), similar to the observation in impulsive events. These results indicate that the earlier interpretation of heavy ion charge states being solely related to the plasma temperature was too simplistic, and multiple sources contributing to gradual events may have to be considered (see below).

2.2.6. The Observation of 'Flare' material in gradual events. Increased abundances of ^{3}He and heavy ions relative to solar wind abundances and high charge states of heavy ions at high energies have now been also observed in gradual events or at interplanetary shocks. At sub-MeV energies, small and moderate enhancements of ^{3}He relative to ^{4}He, with ^{3}He/^{4}He in the range of 10^{-3} to 0.2 have been observed in 12 large gradual events [81] and at interplanetary shocks [10]. At higher energies (> 5 MeV/nuc) ^{3}He/^{4}He a factor of 10 larger than in the solar wind has been observed [82], and a statistical survey using daily averages of ^{3}He and ^{4}He fluxes in the energy range 15-30 MeV/nuc as measured by the ERNE experiment onboard SOHO showed for the years 1999 to 2002 an average value of ^{3}He/^{4}He ~0.015, also significantly higher than in the solar wind or corona [83].

Furthermore, large abundance enhancements of Fe at energies of ~1 MeV/nuc [84] and at energies of 12-60 MeV/nuc [85] and 25-80 MeV/nuc [11] have been observed in many large events. Also, high mean charge states of Fe with $<Q_{Fe}>$ ~20 at energies >10 MeV/nuc, another tracer for ions accelerated in impulsive events close to the Sun, are not uncommon (see above). Apparently, the previous classification of SEP events into two distinct classes, i.e. *impulsive* and *gradual*, needs to be reconsidered and possible scenarios are discussed in the following paragraphs.

As a possible source of ^{3}He in large, interplanetary shock related events remnant suprathermal particles from previous impulsive events have been suggested [81], serving as seed particles for the injection at the interplanetary shock. In this scenario, high (and variable) heavy ion abundances (e.g. Fe/C, Fe/O) could be interpreted as a mixture of two sources: suprathermal heavy ions from previous impulsive events and from gradual events. This suggestion is also supported by the finding that the interplanetary particle composition during quiet times shows enhancements in the ^{3}He/^{4}He and heavy ion composition: enhancements by a factor of ~10 over the coronal value were found for Fe/O in the energy range ~1-10 MeV/nuc during quiet times [86], and during times of moderate interplanetary fluxes ^{3}He/^{4}He (4-15 MeV/ nuc) and Fe/C (8-20 MeV/nuc) were found to be enhanced by two orders of magnitude and by a factor of ~8, respectively [87]. The observational evidence that the interplanetary shock related heavy ion population at energies of ~1MeV/nuc is not accelerated out of the bulk solar wind, as discussed above, would also support this view.

Scenario 1: In this scenario the large variability of spectral, compositional, and ionic charge state features at high energies (i.e. above 10s of MeV/nuc) in large gradual SEP events arises from the interplay of two factors: shock geometry and the mixture of two seed populations with coronal / solar wind composition and 'flare' composition, i.e. a composition as observed in ^{3}He- and heavy ion-rich events, respectively. In this scenario the shock geometry plays an important role. It is, in particular, assumed that quasi-perpendicular shocks require a higher initial speed of the ions for effective injection and therefore preferentially accelerate suprathermal seed particles from flares, whereas quasi-parallel shocks can draw their seed particles from the corona / solar wind suprathermals. In this scenario the shock geometry - via the injection threshold - and the mixing ratio determine which of the two components dominates and thus determines spectral shapes, heavy ion abundances and ionic charge states at high energies [88] - [90].

Scenario 2: In an alternative scenario, direct injection of the particles, accelerated in the CME related flare, has been proposed (e.g. [9], [11], [91]). In this scenario, gradual events generally consist of two populations: (1) a population at low energies predominantly accelerated at the coronal / interplanetary shock, and (2) a high energy component (above ~10s of MeV/nuc), probably flare generated, with composition and charge states similar to impulsive events, possibly re-accelerated in the CME related shock. The relative intensity of the two components as observed at Earth will vary from event-to-event, dependent on the shock parameters, the flare size and location, and the magnetic connection between the acceleration site and the observer. However, in this scenario the second component usually dominates at high energies, giving rise to the heavy ion enrichment and high charge states at high energies ([11], [92]).

3. Interplanetary Propagation

Multi-spacecraft observations of electrons and ions accelerated near the Sun, in combination with model calculations of their interplanetary transport, provide ideal tools for improving our understanding of transport processes near the Sun and in interplanetary space. With the two STEREO spacecraft at large separation distances [93] and the observations at L1 by ACE and SOHO, there are now in-situ ([94] [95]), and remote-sensing measurements of many SEP events in 3 widely separated locations available. An example is shown in figure 12 [96]. On 17 January 2010 at 3:49 UT a flare was detected with the EUVI instrument onboard STEREO-B, at a location of E59S25 as seen from STEREO-B. A schematic of the longitudinal configuration of the flare, the two STEREO spacecraft and Earth, and the electron and proton intensities observed on the STEREO spacecraft is provided in figure 12. The longitudinal separation between the flare position and the spacecraft magnetic footpoint was about 113° for STEREO-B and 117° for STEREO-A. Despite this large separation distance, both STEREO-A and STEREO-B observed large intensity increases of electron and protons.

The intensity – time profiles observed at STEREO-A and STEREO-B have been compared with two model calculations (1) a 1D model describing the particle propagation in a flux tube along the magnetic field [97] and (2) by a 3D propagation model including perpendicular diffusion [98]. While both models are capable of reproducing the observations, model 1 requires an injection function at the Sun of several hours. Unfortunately the pitch angle coverage is insufficient during this event, therefore the anisotropy cannot be used as an independent test for the injection duration. Model 2 reveals a relatively high value of 0.3 for the ratio between perpendicular to parallel diffusion, i.e. in this model the observations can be explained by significant lateral transport in the solar wind.

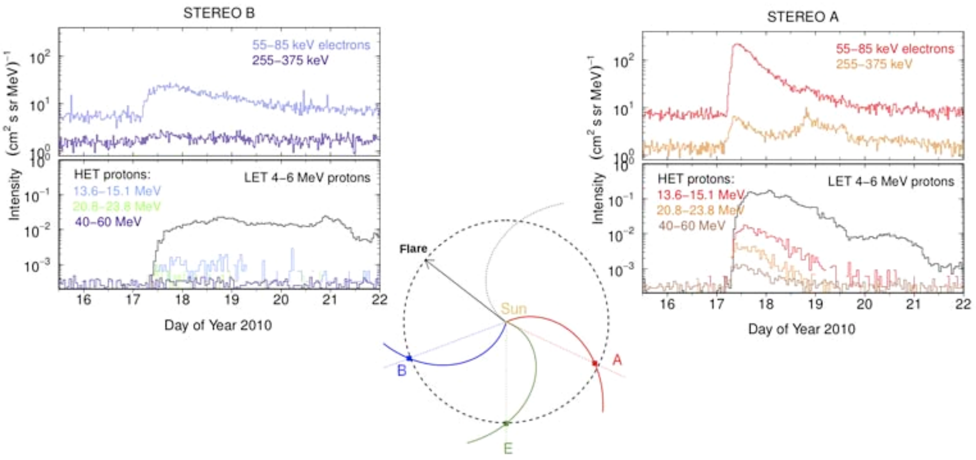

Figure 12. Schematic of the longitudinal configuration of Earth, the STEREO spacecraft and the flare on 17 January 2010. Also shown are electron (top panels) and proton (bottom panels) measurements by SEPT, LET and HET on board STEREO-A (right) and STEREO-B (left) [96].

4. Summary

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. There are, for example, promising model calculations on various aspects of impulsive events, as ^{3}He-enrichment, heavy ion enrichment, and energy dependent charge states of heavy ions. However, the models for ^{3}He and heavy ion enrichment do not include energy loss during interplanetary transport that is probably important at these low energies, whereas the charge stripping models can explain the energy dependent charge states below 1 MeV/nuc, but so far do not attempt to include the heavy ion enrichment.

Further improvement in our understanding will also require more modeling efforts of gradual events. In particular, 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 could provide important clues for the understanding of the observations in large events, related to CME / ICME driven interplanetary shocks. Also, by a systematic study of composition and energy spectra of energetic particles of different sources (e.g. solar wind / suprathermals, pickup ions), unfolding injection and acceleration processes might be possible and thus provide a better understanding of the fractionation effects observed in elemental and isotopic abundances.

Significant progress in our understanding of SEP propagation and acceleration can also be expected from a more systematic comparison of multispacecraft measurements, combining, for example, measurements from the two STEREO spacecraft separated in longitude by now up to 180°, with near-Earth measurements from SOHO and ACE.

Future missions like the Solar Orbiter (e.g. [99]-[101]) with perihelion distances of ~0.28 AU, or the Solar Probe Plus with several perihelion passes as close as ~9.5 solar radii [102], will provide a close-up look at CMEs and solar active regions and allow a much better correlation of the electromagnetic signatures at the Sun and the characteristics of ions and electrons, because interplanetary propagation effects are minimal at this distance.

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