Current views on impulsive and gradual solar energetic particle events

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Abstract
Solar energetic particles (SEPs) are one manifestation of violent energy releases on the Sun. The study of their acceleration and propagation reveals information about basic plasma-physical processes, such as reconnection, shock acceleration and wave–particle interaction, in astrophysical objects, such as stars, magnetospheres or the diluted plasma of the interstellar or interplanetary medium. This paper introduces the current classification scheme for solar energetic particle events, its relation to the underlying acceleration processes, and addresses open questions regarding the better understanding of SEPs as well as the underlying physical processes. Modifications to the current paradigm considering more recent observations will be suggested.

1. Introduction
Solar energetic particles (SEPs) are one population of near-Earth particles. They have intermediate energies from some 10 keV/nuc to the GeV range and occur in events that last from some hours to a few days and increase above background by many orders of magnitude. The occurrence of SEP events is directly related to flares and coronal mass ejections (CMEs): SEPs therefore are much more frequent at times of solar maximum than during solar minima.

Originally, the flare was believed to be the source of the energetic particles; particles were released impulsively in the flare process on the Sun and the long-lasting intensity-time profiles at the Earth were attributed to interplanetary scattering (Meyer et al 1956). Shocks should add only a rather small number of particles, the energetic storm particles (ESPs), right at the time of shock passage (e.g. Bryant et al 1962).

In the 1980s and 1990s, a new paradigm evolved. It is based on the assumption of three distinct classes of flares (Pallavicini et al 1977) and consequently two distinct classes of SEP events, impulsive and gradual (Cane et al 1986). This paradigm has drawn our attention to the importance of CME-driven shocks for SEP acceleration: the shock accelerates and injects particles continuously as it propagates outwards. In this picture, impulsive SEPs are
accelerated in flares while gradual SEPs are accelerated at CME-driven shocks; mixed events consisting of both particles accelerated in the flare and at the shock do not exist (Reames 2002) and particles propagate scatter-free through interplanetary space—except for very large events where they are scattered at self-generated turbulence (Reames 1990b).

In this review, I will discuss some recent observations that suggest modifications to the current paradigm. This review agrees with the current paradigm in the idea of two distinct particle populations, namely flare accelerated particles (FAPs) and particles accelerated at CME shocks (PACSs). It differs in the following proposition: nature is able to convert stored magnetic energy to kinetic energy of FAPs and PACSs via different mechanisms; since the ultimate source of the SEPs’ energy is magnetic energy, the different acceleration mechanisms are not necessarily mutually exclusive. Thus SEP events should consist of both, FAPs and PACSs, with the only FAPs or only PACSs events being the limiting cases. This view suggests a rather continuous transition between different kinds of SEP events rather than a clear-cut division.

In this paper, the development of the current paradigm is sketched in section 2. Section 3 describes the acceleration mechanisms for FAPs and PACSs. Section 4 reviews observations that suggest modifications to the current paradigm; section 5 gives a revised view on event classes. The paper closes with a summary in section 6.

2. The current paradigm

The classification scheme for solar flares was introduced by Pallavicini et al (1977) on the basis of Skylab soft x-ray images and time profiles. Flares are divided into three distinct groups: (a) point-like flares, (b) flares in small and compact loop structures and (c) flares in large systems of rather diffuse loops. Flares of groups (a) and (b) are associated with short-duration x-ray emission, less than an hour, while in flares of group (c) the soft x-ray emission can last for some hours. The compact and point-like flares are called impulsive; the flares in the large diffuse loops are termed gradual. Over the years, the classification scheme has been extended to other frequency ranges (cf table 1). This phenomenological classification is not necessarily unambiguous (Dennis 1985, 1988): a flare might appear gradual in soft x-rays but impulsive in hard x-rays or vice versa. de Jager (1986) suggested a more physical classification in confined and eruptive flares with the CME being the distinguishing feature.

For SEP events a similar classification scheme evolved. The first general classification criterion for particle events was the $e/p$ ratio (Cane et al 1986) and subsequently the $p/\text{He}$ ratio (Kallenrode et al 1992), both being larger in gradual events. In addition, gradual events could be observed at large azimuthal distances from the flare site while in impulsive events a good magnetic connection between observer and flare site is required (cf figure 1). These observations were interpreted in terms of a CME-driven shock that accelerates particles in gradual events, allowing for their wider spread in longitude as well as the high proton abundance. The classification scheme was introduced for nuclei in the MeV/nucl range.

The analysis of charge states gave hints on different acceleration mechanisms in both classes of SEP events. Averaged over a large number of $^3\text{He}$-rich events, which are impulsive, Luhn et al (1987) obtained an average $Q_{\text{Fe}}$ of $20.5 \pm 1.5$ at energies 0.3–2 MeV/nucl compared to the average value of $14 \pm 0.2$ in gradual events. Similar low-charge states in gradual events later also have been observed at higher energies: $Q_{\text{Fe}} = 11.0 \pm 0.2$ between 0.5 and 5 MeV/nucl (Mason et al 1995), $Q_{\text{Fe}} = 15.2 \pm 0.7$ between 15 and 70 MeV/nucl (Leske et al 1995), and $Q_{\text{Fe}} = 14.1 \pm 1.4$ between 200 and 600 MeV/nucl (Tylka et al 1999). The charge states indicate temperatures at the acceleration site of about 10 Mio K in impulsive and
Solar energetic particle events

Figure 1. Current paradigm: SEP can be accelerated in flares (left) and at shocks (right), with the double-ended arrow indicating the longitude range over which particles are injected.


<table>
<thead>
<tr>
<th>Feature</th>
<th>Impulsive</th>
<th>Gradual</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration in soft x-rays</td>
<td>&lt;1 h</td>
<td>&gt;1 h</td>
<td>PSV77</td>
</tr>
<tr>
<td>Decay constant soft x-rays</td>
<td>&lt;10 min</td>
<td>&gt;10 min</td>
<td>PSV77, C+89</td>
</tr>
<tr>
<td>Height in corona</td>
<td>≤10⁴ km</td>
<td>~5 × 10⁴ km</td>
<td>PSV77</td>
</tr>
<tr>
<td>Volume</td>
<td>10²⁶–10²⁷ cm³</td>
<td>10²⁸–10²⁹ cm³</td>
<td>PSV77</td>
</tr>
<tr>
<td>Energy density</td>
<td>High</td>
<td>Low</td>
<td>PSV77</td>
</tr>
<tr>
<td>Size in Hz</td>
<td>Small</td>
<td>Large</td>
<td>B86</td>
</tr>
<tr>
<td>Duration in hard x-rays</td>
<td>&lt;10 min</td>
<td>&gt;10 min</td>
<td>O+83</td>
</tr>
<tr>
<td>Duration in microwaves</td>
<td>&lt;5 min</td>
<td>&gt;5 min</td>
<td>D+87</td>
</tr>
<tr>
<td>Metric type II</td>
<td>75%</td>
<td>Always</td>
<td>C+86</td>
</tr>
<tr>
<td>Metric type III</td>
<td>Always</td>
<td>50%</td>
<td>C+86</td>
</tr>
<tr>
<td>Metric type IV</td>
<td>Rare</td>
<td>Always</td>
<td>C+86, K+83</td>
</tr>
<tr>
<td>Coronal mass ejection</td>
<td>Rare</td>
<td>Always</td>
<td>C+86</td>
</tr>
</tbody>
</table>

1 to 2 Mio in gradual flares. Thus particles are accelerated out of hot flare material in impulsive events and out of the ambient plasma (corona, solar wind) in gradual events.

The assumption of different acceleration mechanisms is also supported by peculiarities in composition. Aside from the original division into electron-rich and proton-rich, other particle ratios also showed variations. The first reported abundance anomaly was a strong enhancement in the rare isotope ³He in some small events (Hsieh and Simpson 1970). ³He/⁴He could be of the order of 1, compared to 2 × 10⁴ in the solar wind or corona. Such events always are impulsive (Reames and Stone 1985, Reames et al 1988). Large gradual events show no enrichment above the detection threshold of about 0.1. Subsequently, for the ³He-rich events enrichments relative to coronal abundances were also found in Fe/O (up to a factor of 10), Ne/O (about 4), in Ne/C, Mg/C and Si/C (about 2.8) and in Fe/C (about 6.7). Other ratios, such as ³He/C, N/C or O/C do not differ significantly from coronal ones (Reames et al 1994). The heavy element abundances, specifically Fe/C, are not correlated with the ³He/⁴He ratio. In gradual events, at energies around 1 MeV/nucl, abundances approached coronal values with minimal event to event variation (Mazur et al 1992) while at energies above 10 MeV/nucl an increasing divergence is observed: an enrichment in ³He does not automatically include strong enrichment in other rare species and vice versa. The abundances in gradual events thus are compatible with acceleration out of the ambient plasma while in impulsive events a special acceleration mechanism is required. Since it must lead to a selective enrichment of certain elements and isotopes and requires a strong heating of the plasma, the process is termed ‘selective heating’.
Table 2. Classes of solar energetic particle events.

<table>
<thead>
<tr>
<th>Particles</th>
<th>$^3$He-rich</th>
<th>Impulsive</th>
<th>Gradual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He/$^4$He</td>
<td>$\sim 1$</td>
<td>$\sim 0.2$</td>
<td>$\sim 0.0005$</td>
</tr>
<tr>
<td>H/He</td>
<td>$\sim 10$</td>
<td>$\sim 10$</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>Fe/O</td>
<td>$\sim 1.23$</td>
<td>-</td>
<td>$\sim 0.15$</td>
</tr>
<tr>
<td>$Q_\text{Fe}$</td>
<td>$\sim 20$</td>
<td>-</td>
<td>$\sim 14$</td>
</tr>
<tr>
<td>Duration</td>
<td>Hours</td>
<td>Hours–days</td>
<td>Days</td>
</tr>
<tr>
<td>Long. distrib.</td>
<td>$&lt; 30^\circ$</td>
<td>$\sim 100^\circ$</td>
<td>$\leq 180^\circ$</td>
</tr>
<tr>
<td>CMEs</td>
<td>No</td>
<td>Sometimes (small, slow)</td>
<td>Yes</td>
</tr>
<tr>
<td>Solar wind</td>
<td>-</td>
<td>-</td>
<td>Ipl. shock</td>
</tr>
<tr>
<td>Event rate</td>
<td>$\sim 1000/a$</td>
<td>Some ten/a</td>
<td>$\sim 10/a$</td>
</tr>
</tbody>
</table>

But before we turn to the acceleration mechanisms, a word of caution. The first SEP event classifications (Cane et al 1986, Kallenrode et al 1992) started from rather large events, termed impulsive and gradual in table 2. In this picture, the shock was regarded as an additional acceleration mechanism (Reames et al 1990, Cane et al 1991) rather than the only one as proposed first by Kahler et al (1986) and assumed in the current paradigm. With the closer inspection of the above-mentioned $^3$He-rich events (Reames et al 1988, Evenson et al 1990, Reames 1990a), the picture started to shift and the much smaller $^3$He-rich events were used as synonymous for impulsive events (Reames 1993, 1999) while the large impulsive events from the first classification schemes vanished (Kallenrode 1993). Thus, table 2 gives three classes of particle events with their corresponding properties; only the left and right ones are considered in the current paradigm. Such a scheme led Kallenrode et al (1992) argue for a rather continuous variation of event parameters rather than a clear-cut division into two classes. The large impulsive events are one touchstone for the modifications that will be suggested in section 5.

3. Acceleration mechanisms

Independent of whether the classification scheme is clear-cut or continuous, the limiting cases define the acceleration processes: in impulsive events, acceleration occurs in the flare by selective heating and particles escape in a narrow cone along open field lines, while in gradual events particles are accelerated out of the ambient plasma over a broad range of longitudes at the CME-driven shock.

3.1. Acceleration at CME-driven shocks: PACSs

A shock can accelerate particles via three processes which all show distinct features (Scholer and Morfill 1977, Jones and Ellison 1991).

1. In shock drift acceleration (SDA, also called scatter-free shock acceleration), the particles gain energy due to grad-B drift along the $\vec{v} \times \vec{B}$-field in the shock front (e.g. Armstrong et al 1985). Thus SDA works best for the quasi-perpendicular shocks where the electric induction field is the largest.

2. In diffusive shock acceleration, the particles are scattered back and forth in the plasmas converging at the shock front (e.g. Forman and Webb 1985). Diffusive shock acceleration is thus a Fermi 1 process. It dominates at quasi-parallel shocks and requires a sufficient amount of scattering.
(3) Stochastic acceleration works in the turbulence behind the shock front, it is a Fermi 2 process (Scholer and Morfill 1977).

Depending on the dominant process, the particle profiles show distinct features: SDA is characterized by a shock spike around the time of shock passage while diffusive shock acceleration leads to smoother variations and a long-lasting high intensity in the event. Stochastic shock acceleration can be seen as a sudden increase in intensity in the turbulent zone behind the shock.

Since the relative importance of these acceleration mechanisms depends on the angle $\theta_{Bn}$ between shock normal and magnetic field, the dominant acceleration mechanism varies along the shock front from shock drift acceleration at the western flank (quasi-perpendicular shock) to diffusive shock acceleration at the eastern flank (quasi-parallel shock). The corresponding characteristics of the acceleration process can be observed directly at the time of shock passage in energies up to some 100 keV (Tsurutani and Lin 1985, Sanderson et al 1985) while in MeV energies, the dependence on the location of the observer influences the entire particle profile (Cane et al 1988): since at MeV energies shock acceleration is most efficient close to the nose of the shock, an observer at the shock’s eastern flank initially is connected to the efficient nose of the shock and therefore sees a fast rising profile. As the shock propagates outwards, its intersection with the observer’s magnetic field line moves towards the less efficient flank of the shock and the intensity decays. With a similar reasoning we also can understand the rather flat profiles for observer close to the nose of the shock and the continuously rising profiles for observer at the shock’s western flank. Although a statistical analysis of SEP events (Cane et al 1988) supports this view, it should be noted that in multi-spacecraft observations the variations with location of the observer, although they show the general trend, often are rather small (Kallenrode et al 1993, Cliver et al 1995, Kallenrode 1997b, 2001).

A fundamental problem in all processes is the escape of particles from the acceleration region: once a particle has gained sufficient energy to be significantly faster than the shock, it will escape from the shock front. Then it is lost from the acceleration process and cannot be accelerated any further. Energy gain therefore is limited. For particle acceleration up to MeV/nucleon or even higher energies relatively strong scattering upstream of the shock is required to feed particles back into the acceleration process (e.g. Malkov and Diamond 2001, Bessho and Ohsawa 2002). An increase in acceleration efficiency in diffusive shock acceleration due to the turbulence generated by streaming protons, the so-called self-generated turbulence, first has been proposed by Lee (1982) for the bow shock and later for travelling interplanetary shocks (Lee 1983). For the 12 November 1978 event, Kennel et al (1986) report a good agreement between observations and predictions from the model (cf Lee 1986 and Volkm 1987). Observations of self-generated turbulence upstream of a shock in resonance with MeV protons have not been reported so far; for waves interacting with 10 MeV protons the typical evolution of magnetic field turbulence towards the shock shows no indication for self-generated waves at the observer’s site (cf Kallenrode 2001). This does not necessarily exclude the presence of self-generated turbulence because scattering conditions derived from magnetic field turbulence and from fits of a transport equation on particle intensity and anisotropy time profiles lead to different results (e.g. Wibberenz et al 1970, Wanner and Wibberenz 1993, Bieber et al 1994), probably due to a miss-interpretation of the magnetic field turbulence (Matthaeus et al 1990, Jaekel et al 1994). It should be noted that there is a general correlation between the two approaches (Wanner 1993), which suggests that variations in scattering conditions could be identified although the total strength might be inaccurate. On the other hand, as we will see below, for $>10$ MeV protons, the shock seems to be most efficient close to the Sun and thus the wave field might have decayed until the shock has propagated to the observer.
The shock acceleration of SEPs was first proposed by Wild et al. (1963) who interpreted the metric type II burst as evidence for a coronal shock wave. Svestka and Svestka-Fritzova (1974) even suggested that a metric type II burst is a sufficient condition for a SEP event in interplanetary space. Later, observations with more sensitive instruments suggested that the metric type II burst is neither a sufficient nor a necessary condition (Kahler 1982a, b, Kallenrode et al. 1991). Today, the interpretation of the metric type II burst and its relation to other aspects of solar activity has become more refined (Classen and Aurass 2002, Vrsnak and Lulic 2001a, b, Warmuth et al. 2001) and it is used less as an indicator for particle acceleration at a shock. Instead, our attention is drawn to the CME and its relevance for SEP acceleration (Kahler et al. 1994, 1990, Cane et al. 1990, Kahler 1993).

The resulting picture of gradual flares and shock acceleration of SEPs is summarized on the right-hand side of figure 2: magnetic field instabilities cause an initially slow rise of the filament with reconnection in the core region as a by-product (Sterling et al. 2001, and references therein). The temporal development of a CME then consists of three phases (Zhang et al. 2001): (i) an initiation phase before the onset of the flare, (ii) an impulsive acceleration phase, coinciding well with the flares’ rising phase and (iii) a propagation phase, characterized by a constant or slowly decreasing speed of the CME. Before the onset and after the peak of the flare, there are no significant changes in CME speed. If the CME is not accompanied by flare activity, the acceleration in general is slower and lasts longer (gradual acceleration phase). Details of the CME evolution depend on the magnetic configuration, e.g. bipolar versus multipolar (Machado et al. 1988, Moore et al. 2001, Klein and Mouradin 2002) or normal versus inverse (Low and Zhang 2002). While for some time the flare was believed to be a mere by-product of the CME (e.g. Gosling 1993), today it is assumed to be an integral part of the early development of a fast CME although it might be missing in slow ones (Zhang et al. 2002).

In the configuration on the right-hand side of figure 2, the particle acceleration occurs in two places. Escaping particles are accelerated at the shock in front of the CME, at least if the latter is fast enough to drive a shock wave. Particles accelerated in the reconnection region below the core of the CME, on the other hand, precipitate into the denser solar atmosphere and produce electromagnetic radiation. These particles are believed to be trapped below the CME (Reames 2002). Long-duration flares result from either continuous reconnection below the

Figure 2. Particle acceleration in impulsive (left) and gradual (right) flares.
core of the CME or free-falling plasma, visible as down-flows in soft x-ray images (Shibasaki 2002).

The occurrence of a SEP event after a CME and its properties depend on CME properties. Kocharov et al (2001b) considered gradually \( (a < 10 \text{ m s}^{-2}) \) and impulsively accelerating \( (a > 20 \text{ m s}^{-2}) \) CMEs. The SEP-producing CMEs typically are impulsively accelerated CMEs accompanied by flares and coronal shocks. These CMEs moved at a constant speed whereas prominence-related mass ejections accelerated (MacQueen and Fischer 1983). An accelerating CME may produce a shock later than a CME with constant speed (Kahler 1999; Kahler et al 1999). This supports a kind of ‘closed-chain scenario’ (Torsti et al 2001): an early rise of CME triggers the x-ray flare that starts a coronal wave, which initiates proton acceleration away from the flare site. Thus the near-Sun dynamics of a CME is a significant factor contributing to the intensities of \( \sim 10 \text{ MeV} \) proton events.

The variation of shock’s acceleration efficiency during its propagation depends on particle energy. In the hundreds of keV/nucl range, efficient particle acceleration occurs even at 1 AU and beyond. In the tens of MeV/nucl range, the acceleration at the shock preferentially occurs close to the Sun as inferred from: (a) an analytical solution of diffusive shock acceleration (Lee and Ryan 1986, Lee 1997), (b) the correlation between CME heights and particle injection (Lockwood et al 1990, Kahler et al 1990, 1994, Debrunner et al 1997, Klein et al 2002), (c) a transport model combined with a particle source and self-generated turbulence (Ng et al 1999) and (d) a transport model with the shock as a moving source of particles (Kallenrode and Wibberenz 1990, Kallenrode 1997a). This might be the reason for the missing upstream enhancements in waves in resonance with \( > 10 \text{ MeV} \) protons.

3.2. Acceleration in the flare: FAPs

The peculiarities in composition in impulsive events require an acceleration mechanism that is highly variable with rigidity and/or \( Q/A \). For \(^3\text{He}-\text{rich} \) flares, the process of selective heating has been suggested (Kochar and Kocharov 1984, Reames 1990a): particles are accelerated due to reconnection in a compact closed magnetic field loop (cf left-hand side of figure 2). The particles then are confined and, on interaction with the denser solar atmosphere, create hard electromagnetic radiation. Electron beams bouncing back and forth along the loop excite a wide spectrum of electromagnetic waves. These waves propagate across the field and, on absorption by the local plasma, accelerate particles. The acceleration occurs for the particles with gyro-frequencies comparable to the wave frequency, thus different waves accelerate different particles. Major species, such as H and \(^4\text{He} \), absorb most of the wave energy inside the loop while waves in resonance with minor species, such as \(^3\text{He} \), are absorbed at larger distances. These latter particles are therefore preferentially accelerated on open field lines and escape into interplanetary space, leading to the observed peculiarities in composition. Since there is a strong association between \(^3\text{He}-\text{rich} \) events, streaming 10–100 keV electrons (Reames et al 1985) and type III radio bursts (Reames and Stone 1986), this process can be compared with the ion conics in the Earth’s aurora produced by oblique electromagnetic ion cyclotron (EMIC) waves which in turn are produced by downward streaming electrons (Roth and Temerin 1997).

This scenario has been developed for the rather small localized energy releases in typical \(^3\text{He}-\text{rich} \) events. In the larger impulsive flares, other (or additional) mechanisms of energy release are required. Although it is evident that the ultimate source for the energy of the solar energetic particles is the magnetic field, it still remains a mystery that which process is most important for SEP acceleration (Miller et al 1997, Priest and Forbes 2002). These acceleration processes include:
(1) Particle acceleration in the magnetic reconnection region above the flares loops (Craig and Litvinenko 2002), a mechanism that can also be applied to time extended proton acceleration in large gradual flares (Heerikhuisen et al 2002). Observational evidence is provided by hard x-ray sources above the soft x-ray loops (Masuda et al 1994, Alexander and Metcalf 1997, Harra-Murnion et al 1998).

(2) Magnetic field reconnection accelerates newborn ions produced by ionization of neutral atoms in the lower corona (Wu 1996). This acceleration process can produce protons with energies in the range of 10–100 MeV with a timescale of $10^{-4}$ s to $10^{-3}$ s in a reconnection layer via the so-called ion pickup process (Wang et al 2001). The primary idea is that a fast-moving plasma can pick up motionless newborn ions via pitch-angle scattering by enhanced Alfvén waves (e.g. Yoon and Wu 1991). Thus, ions with initially low energies can be accelerated to high energies, provided that the background plasma is moving with a velocity much higher than its Alfvén speed.

(3) By scaling the process of auroral particle acceleration in parallel potential drops to the solar atmosphere, Haerendel (2001) obtained acceleration timescales and rates which are capable of explaining the occurrence of $\gamma$-ray emissions with energies of many tens of MeV and time scales of $\ll 1$ s.

If an impulsive flare is violent enough to cause large-scale restructuring of the solar magnetic field, turbulence at long wavelengths is generated. Large-amplitude long-wavelength Alfvén waves cascade down via shorter waves into the dissipation range where they are absorbed by the thermal plasma. The ions encountered first are those with lowest gyro frequency, namely Fe. The process then continues towards higher $Q/A$, cascading through resonances with Si, Mg, Ne, later also O and C, eventually He and finally H, leading to the observed enhancements of heavy elements (Miller and Reames 1996). Miller and Roberts (1996) infer timescales for this process in agreement with those observed in hard electromagnetic radiation.

4. Questions to the paradigm

The current paradigm assumes a clear-cut division between impulsive and gradual SEP events and a one-to-one relation between acceleration mechanisms and classes of flares. The relation between interacting and escaping particles, the existence of mixed events and long-duration $\gamma$-ray events, as well as the fast acceleration of particles to GeV energies challenge this paradigm.

4.1. Interacting and escaping particles

The distinction between impulsive and gradual SEP events is based on escaping particles observed in interplanetary space. Although we cannot measure them directly at the flare site, the hard electromagnetic radiation provides information about interacting particles: electrons produce hard x-rays and a $\gamma$-ray continuum while nuclei cause $\gamma$-ray line emission. The flare’s hard electromagnetic radiation therefore contains information on spectra and composition of particles accelerated on the Sun.

A comparison of peak intensities of 10 MeV protons observed in interplanetary space in well-connected events with the 4–8 MeV $\gamma$-ray line fluence reveals a broad event-to-event scatter with higher ratios of interacting to escaping particles in impulsive than in gradual flares (Cliver et al 1989). Interplanetary electrons and $\gamma$-ray continua (Kallenrode et al 1987, Klecker et al 1990) as well as electrons and hard x-rays (Kallenrode 2001) show a similar broad scatter and an even more pronounced separation between impulsive and gradual events.
Again, the ratio of interacting to escaping particles is higher in impulsive flares, although it is always, for electrons as well as for protons, less than 1 (Cliver et al 1989, Klecker et al 1990, Daiborg et al 1990, Ramaty et al 1993). This small ratio does not necessarily indicate particle acceleration in closed loops, in particular since the timescales of curvature drift are too long to explain the observed particle escape (Ramaty and Mandzhavidze 1994). Instead, it can be interpreted in terms of a primarily downward accelerated isotropic particle distribution (Share et al 2002) or from acceleration on open field lines with the bulk of the particles trapped in self-generated turbulence (Vainio and Kocharov 2001). However, the escape of only a small part of the flare-accelerated particles is sufficient to cause a significant particle event in interplanetary space.

Looking at the interacting particles in impulsive and gradual events, one finds: (a) the e/p ratio is the same (Ramaty et al 1993) while in interplanetary space the e/p is higher in impulsive than in gradual flares (Cane et al 1986, Kallenrode et al 1992); (b) the spectra are the same (Ramaty et al 1993) while in interplanetary space spectra are different (Moses et al 1989); (c) the composition is essentially the same (Ramaty et al 1990, 1993, 1997, Murphy et al 1991, 1997, Mandzhavidze et al 1999, Share and Murphy 1999, Cohen et al 1999). This points to a common acceleration mechanism for the interacting particles: ‘in both impulsive and gradual flares the particles that interact and produce γ-rays are always accelerated by the same mechanism that operates in impulsive flares, namely, stochastic acceleration through gyro-resonant wave–particle interactions (Mandzhavidze et al 1999).

One special case of γ-ray events is long-duration events. In long-duration γ-ray flares (LDGRFs) (Ryan et al 2000), the γ-ray line emission at energies above 50 MeV can last for many hours (Kanbach et al 1993), implying either a prolonged acceleration or efficient storage. Storage is unlikely since such high energetic particles certainly would be lost into the denser solar atmosphere in time. LDGRFs also cannot be understood in terms of backward propagating nuclei accelerated at the outward propagating CME because the thick-target hard x-ray emission resulting from this process is not observed (Murphy et al 1999, Ramaty et al 1997). Alternatively, the particles could have been accelerated in large static loops filled with MHD turbulence (Ryan and Lee 1991), in the electrostatic potential behind the CME in the reconnection sheet (Litvinenko and Somov 1995), or in an episodical acceleration process (van den Oord 1993) with successive episodes of particle acceleration and subsequent trapping for moderately long times (Mandzhavidze et al 1996). For the June 1991 LDGRF, Rank et al (2001) suggest a continuous though evolving acceleration process.

### 4.2. Mixed events

From the above discussion, the following picture emerges: interacting particles are accelerated by the same mechanism in both impulsive and gradual flares. In gradual flares, additional particles are accelerated at a CME-driven shock. But which particles contribute to the SEP event in interplanetary space? Only the shock-accelerated particles as suggested by Reames (2002) or particles from both processes?

ACE observations reveal peculiarities in composition and charge states which can be interpreted as mixed or hybrid SEP events. In some large events, Q_{Te} shows a distinct peak at low charge states, indicative for particle acceleration out of the ambient medium, with a tail extending up to Q_{Te} ≈ 20, indicative for particle acceleration out of the heated flare plasma. In addition, the charge states of all heavy ions increase with energy (Oetlicker et al 1997, Mazur et al 1999, Möbius et al 1999). Cohen et al (1999) inferred from the charge states of 12 elements with energies of 12–60 MeV/nuc source temperatures of (3–6) × 10^6 K, significantly higher than at lower energies—which rules out acceleration out of the ambient material.
In addition, the abundance variations are not as clear-cut as suggested in the current paradigm. At energies above $\sim100$ MeV/nucl, the Fe/O ratios seem to increase in several of the largest events observed during the last two solar cycles (Tylka et al 1997). The composition evolves from initial values resembling the ones in impulsive flares to the values of the ambient medium at the time of shock passage.

This evolution can be interpreted in two different ways. Reames (1999) suggests that everything is done by the shock because flares are too small. A shock working with electron stripping (Reames et al 1999) and self-generated waves (Ng et al 1999) can produce the observed charge states and composition variation. This interpretation rises the question: why do the charge states at high energies resemble impulsive events—would not it be natural to assume the same acceleration mechanism at work (Cliver 2000)? And how can the stripping process reproduce charge states typical for heated plasma, in particular since the model used in Reames et al (1999) is highly dependent on proton-impact cross sections which are not measured accurately (Kovaltsov et al 2001) and on assumptions about the acceleration and transport processes (Kocharov et al 2001).

A much simpler interpretation is the superposition of FAPs and PACSs. Owing to the interplanetary scattering, even a $\delta$-like FAP injection combined with a continuous PACSs injection can produce a temporal development on the Fe/O ratio similar to the one reported by Tylka et al (1999) (cf figure 3).

Another factor influencing the composition and charge states is re-acceleration of originally flare-accelerated material by a CME-driven shock. Evidence for such a process is found, e.g. in a $^3$He-rich event extending up to about 50 MeV (Torsti et al 2002). Desai et al (2001) report $^3$He acceleration at interplanetary shocks for times of high remnant $^3$He fluences from earlier flares in interplanetary space. The importance of shock acceleration from the solar wind supra-thermals and a small ($\sim$5%) admixture of remnant flare particles is also stressed by Tylka et al (2001).
Timing information can help to relate particle acceleration and release from the Sun to different aspects of solar activity, such as flare acceleration as inferred from interacting particles, radio bursts, or CMEs—or more abstract to different phases, modes and steps (Bai 1986b). Unfortunately, even timescales of the first arriving particles strongly are influenced by interplanetary transport (Kallenrode and Wibberenz 1990): estimated arrival times therefore give an upper limit only. Nonetheless, valuable insights can be gained from this analysis. For instance, the comparison of particle onsets or maxima and CME heights showed that the bulk of particle acceleration at CME-driven shocks occurs close to the Sun (Kahler et al 1990). With the better temporal resolution of the LASCO coronograph, Torsti et al (2001) identified three distinct periods of CME injection in the 9 May 1999 event: (i) the first, extremely hard spectrum injection triggered by the passage of the flare initiated coronal (shock) wave, (ii) a moderately hard spectrum phase starting about half an hour later, proceeding and ceasing concurrently with metric continuum radio burst, (iii) a prolonged soft spectrum injection dominating the late phase of the event for about 1.5 h from the first proton production. The authors interpret these features as a combination of coronal and interplanetary acceleration processes contributing with varying importance at different stages of the solar eruption associated with both flare and CME and suggest from a comparison with other events that such a combination is a common property of mixed SEP events. Similarly, Kundu et al (2000) argue from the non-thermal flare emission of electrons that several distinct electron populations are produced in flares. These observations support the existence of mixed SEP events, as in the scenario in figure 4. Thus, the CME-driven shock contributes significantly to the gradual SEP events, but is not necessarily its only source.

Continuation to higher energies

Probably, the strongest constraints on particle acceleration are provided by the particles with highest energy, namely particles with neutron monitor energies. Ryan et al (2000) found that (a) several tens of MeV protons must have been accelerated early in the impulsive phase within seconds to explain the observed $\gamma$-ray line emission and (b) the injection of some ten MeV protons and protons with neutron monitor energies occurs significantly later. This delay can be interpreted in terms of different acceleration mechanisms for interacting and escaping...
particles or in terms of a delayed injection of escaping particles, e.g. due to a high level of turbulence close to the Sun, as suggested, e.g. in the model by Vainio and Kocharov (2001). Nonetheless, particle acceleration to GeV energies must be fast and must occur only close to the Sun, because particle intensities at these energies decay fast.

If we adopt the suggestion by Ryan et al (2000) to apply Occam’s razor, that is any model that describes the behaviour of lower energy particles in space should extend gracefully to higher energies to explain ground level events (GLEs), two possibilities exist: particles at neutron monitor energies can be accelerated at the shock or in the flare. The shock picture is consistent in so far as fits at MeV energies show that shock acceleration efficiency ceases as the shock propagates outwards and that the injection spectrum steepens, that is with increasing energies particle injection is more and more confined to regions close to the Sun (Kallenrode 1997b).

4.4.1. Multiple CMEs. LASCO observations reveal high rates of occurrence of CMEs varying between one every other day and up to four per day (St Cyr et al 2000). Since the speeds of CMEs are vastly different ranging from a less than 100 km s\(^{-1}\) up to more than 2000 km s\(^{-1}\) (Burkepile et al 1993, St Cyr et al 2000), CMEs can overtake each other. Such interaction between subsequent CMEs of different speeds can be observed in LASCO images as well as in radio signatures. Gopalswamy et al (2001) interpret these signatures as evidence for CME interaction with the observed radio enhancement being a consequence of shock strengthening close to the Sun, that is within about 10\(R_\odot\). This CME cannibalism has a couple of consequences: (a) the CME is deflected, (b) composition anomalies inside the CME can occur as observed, e.g. by Gloeckler et al (1999), (c) complex ejecta can result as observed, e.g. by Burlaga et al (2001) and, as mentioned before, (d) the strengthening of the interplanetary shock. This interaction appears to be an important aspect of SEP production: for most SEP events, the primary CME overtakes one or more slower CMEs within a heliocentric distance of \(~20R_\odot\) (Gopalswamy et al 2002). The authors suggest that the stronger shock resulting from the CME interaction is responsible for the SEP production and that SEPs are accelerated from the preceding CME’s material rather than from the quiet solar wind.

While in the cannibalizing CMEs, the interaction and the efficient particle acceleration take place close to the Sun, the particle acceleration between two converging CMEs also might happen in interplanetary space. Such an effect was first proposed by Levy et al (1976) to explain the unusual high particle fluxes in the August 1972 SEP and later suggested for many other unusually large events (Kallenrode and Cliver 2001a). The modelling of these events suggests the CMEs rather than the shocks being responsible for the efficient particle trapping and the resulting high fluences (Kallenrode and Cliver 2001b). From fine structures in large events, Struminsky (2002) argues for storage between reflecting walls which can be identified as disturbances in the magnetic field. Whether one of these effects also takes place in the cannibalizing CMEs or whether the apparently stronger shock after the interaction is responsible for the extremely efficient acceleration, remains to be analysed.

5. An alternate view on classes of flares

The main conclusions from the previous sections can be summarized as follows:

(1) there are two distinct kinds of acceleration mechanisms which produce different kinds of particle populations, FAPs and PACSs;
(2) the flare, as inferred from the observation of interacting particles, is the same in impulsive and gradual events;
(3) there are mixed events, during which the composition evolves from typical for impulsive to typical for gradual events;
(4) the highest particle energies are produced early in the event, that is when the shock is close to the Sun;
(5) the charge states increase with increasing energy;
(6) SEP events are also influenced by re-acceleration from remnant supra-thermal particles and by the presence of earlier CMEs and other interplanetary disturbances. The latter point should serve as a warning signal: the properties of a SEP event are not only determined by the properties of the acceleration mechanism(s) but also by earlier CMEs and remnant SEPs from previous flares or shocks. In addition, temporal features are smeared out due to interplanetary scattering.

Nonetheless, it seems reasonable to link SEPs to the acceleration processes. We will not stick to a clear-cut division into two classes with a one-to-one correspondence between particle event class and acceleration mechanism but argue, based on the arguments given above, for a more continuous transition. The reasoning is as depicted in figure 4. The ultimate source of SEPs energy is magnetic energy stored in the complex fields of the lower corona. An instability causes a release of magnetic energy combined with a restructuring of the field. Visible manifestations are flares and/or coronal mass ejections. Depending on the amount of energy released, the height at which the instability occurred, and on the details of the field configuration, most or all of the energy might go into one of the phenomena, flare or CME. Part of the energy imparted on the flare is converted into electromagnetic radiation, the other part into the acceleration of FAPs, which partly interact with the denser solar atmosphere to produce hard electromagnetic radiation and partly escape into interplanetary space and can be observed as SEPs.

If the instability also triggers a CME, this can be either slow (which is the case for the bulk of the CMEs (cf St Cyr et al. 2000, and references therein)) or fast. A slow CME does not contribute to the particle acceleration but since it is accompanied by a restructuring of the coronal magnetic field it might open field lines and, if the CME was accompanied by a flare, allow more FAPs access to open field lines.

For an observer in space, the scenarios discussed so far would lead to SEP events that consist of FAPs only. Depending on the amount of energy released and possibly on the occurrence of a slow CME, these events would correspond to the $^3$He-rich events or the classical impulsive events in table 2. This scenario is supported, for instance, by the observation that some of the larger impulsive events are accompanied by narrow, sometimes even fast, CMEs (Kahler et al. 2001). These narrow CMEs do not necessarily correspond to the classical picture of CMEs as in figure 2, but might result from jets or plasmoids that are ejected upwards from magnetic reconnection sites over active regions (Shibata et al. 1985), which in turn might produce shock-excited radio bursts (Aurass et al. 2002)—but do not necessarily accelerate PACs.

In the case of a fast CME, the particle can be accelerated at the CME-driven shock. If the fast CME is the only consequence of the primary energy release, the resulting SEP event is a classical gradual one with all particles being accelerated at the shock. If the CME is accompanied by a flare, most likely also FAPs escape, leading to a mixed event in interplanetary space. FAP escape is likely because of two reasons: (a) as the very small ratio of escaping to interacting particles indicates, the escape of only a small number of FAPs is necessary to produce a significant SEP event in space; and (b) since the coronal magnetic field is highly filamented and highly variable (Goloub et al. 1999), even three-dimensional reconnection is not likely to produce only closed field lines under the CME and thus keeps the FAPs confined. These events then are mixed events.
Compared to the classical form of the current paradigm with its clear-cut division into two classes of particle events the above scenario leads to a more continuous development of SEPs from the small ³He-rich events to the pure gradual events with event properties depending on the relative contributions of the two different acceleration mechanisms and the total magnetic energy released. We might even speculate about the existence of pure interplanetary SEPs which are accelerated at a CME-driven shock but only in interplanetary space and not close to the Sun because the CME accelerated not fast enough to drive a shock in the corona. The continuous classification also offers the advantage to allow for the ‘ambiguous’ cases, such as impulsive flares with CMEs or the ambiguity in the presence of coronal/interplanetary type II radio bursts in the different classes of events (Cliver et al 2002, Cliver and Cane 2002).

It should be noted that one important question is not addressed in the scenario sketched in figure 4: which process is responsible for the higher energies, in particular neutron monitor energies? The above picture, as well as the current paradigm, does not explain where the highest energies come from—in particular since there appear to be impulsive ground-level events. Mason et al (1999) suggest that it might be more reasonable to attribute the highest energies to the flare than to the shock—thus the relative contribution of flare and CME-driven shock in figure 4 in mixed events might shift from predominately shock at MeV energies to predominantly flare at several tens or even hundreds of MeV.

6. Summary

The current paradigm of particle acceleration as summarized, e.g. in Reames (1999) has contributed greatly to our understanding of solar energetic particles, in particular since it has drawn our attention from the flare towards the shock. However, there are still open questions regarding, for instance, the timescales of acceleration and the acceleration site, the relationship between interacting and escaping particles and changes in composition from typically impulsive to rather gradual in the course of the event. These observations can be accommodated in the current paradigm of the shock acceleration of all particles in gradual events but also in a picture where both, flare and shock, accelerate particles. The resolution of this debate is so difficult because in both scenarios, the most interesting things, namely acceleration up to neutron monitor energies and acceleration of the bulk of particles, happen close to the Sun. Thus, aside from the additional theoretical and modelling efforts new observations are required, preferably multi-spacecraft observations close to the Sun covering a broad energy range with good angular and compositional resolution. These observations should be complemented by the local measurements of plasma and field.

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