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Acceleration of solar energetic particles: the case of solar flares

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Abstract

Solar energetic particles are believed to originate from two different sources, solar flares and coronal mass ejections. These two sources are the most energetic particle accelerators in the heliosphere, as they can accelerate electrons from 10 keV to a few MeV and protons from a few MeV to a few GeV. In this contribution, we restrict our presentation to the case of solar flares, by reviewing the key observations of solar energetic particles, as well as the theoretical acceleration models, such as wave–particle acceleration, DC electric fields, and shock acceleration. Finally, we present a new theoretical approach connecting the acceleration with the energy release during solar flares, which might lead to a global modeling of solar flare energetics.
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1. Introduction

Solar energetic particles (SEP) play a major role in our efforts to study fundamental processes in space plasmas. As these particles often propagate to the near Earth space they carry information, in their energy spectra and elemental composition, on the properties of their source plasma and the acceleration process. Complementary observations of the electromagnetic emissions from the sun, produced by the SEP in their interactions with the solar atmosphere, allow us to study indirectly the energetic processes on the sun.

In our study of SEP, numerous difficulties arise from the observational limitations, such as the spatial and the temporal resolution of our instruments, and from the theoretical interpretation of the analyzed data, as there is always the need to deconvolve the various processes involved during solar energetic particle events. It is evident that the acceleration of SEP is a challenging and difficult problem to solve.

In this review, the role of solar flares in the acceleration of SEP is presented. There are a number of review articles on the role of coronal mass ejections (CMEs), in comparison with solar flares, in the acceleration of SEP (e.g. Kahler, 1992; Reames, 1999) and this issue is beyond the scope of our review. In the next section, the key observations of the SEP related to the acceleration models are outlined. In Section 3, the basic acceleration mechanisms are presented together with a short discussion of the other different processes that a successful theoretical model should incorporate. Finally, in Section 4, we present a new theoretical approach that will connect the acceleration mechanisms with the energy release process during solar flares.

2. Solar flares and solar energetic particles—observations

The magnetic field of the sun is the main driver of its flaring activity. Solar flares are the manifestation of an energy release process. During solar flares, magnetic energy of 10^{28}–10^{34} erg is released in the solar chromosphere and corona over a few minutes, by means of magnetic reconnection processes. It is clear that an understanding of the role of the magnetic reconnection process in solar flares is crucial, but also complex and difficult to understand mainly due to the complex magnetic environment associated with this process (for details on magnetic reconnection processes see Priest and Forbes, 2000). It is believed that this energy

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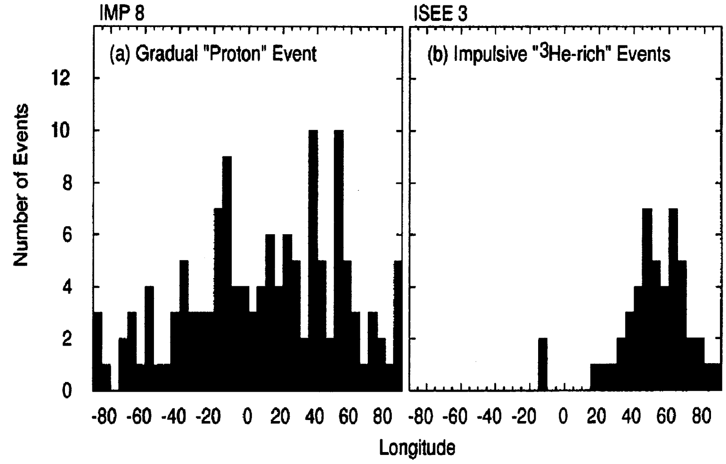

Fig. 1. The distributions of the source longitude of the associated flares for gradual and impulsive events (adapted from Reames, 1999).

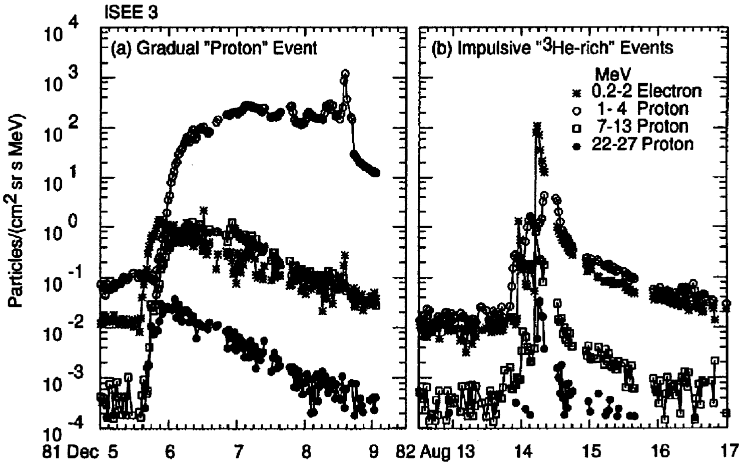

Fig. 2. The intensity time profiles of a gradual and an impulsive event. The gradual SEP event is connected with a CME and not with a flare (adapted from Reames, 1999).

release process gives rise to plasma heating, bulk mass motions and the acceleration of particles (electrons and ions).

The importance of SEP for solar physics is evident as they transport a large fraction of the flare energy to other sites, carrying information on the properties of their source plasma as well as of the acceleration process. The SEP can be measured indirectly from their radiation signatures, extending over the entire electromagnetic spectrum (for recent reviews see Hudson and Ryan, 1995; Bastian et al., 1998, and references therein), as well as directly in the interplanetary medium by means of space born instruments (for recent review see Reames, 1999 and references therein).

It is customary to divide the solar energetic particle events, on the basis of their duration of soft X-ray emission, into two major classes: (1) gradual and (2) impulsive. The duration of the accompanying soft X-ray emission, however, is not the only difference between the above two classes. The detailed comparison between gradual and impulsive solar energetic particle events can be found in a number of review articles (e.g. Reames, 1990, 1997, 1999; Kahler, 1992; Gosling, 1993); in the following, we present a short summary of their main characteristics.

(1) The gradual or eruptive events are associated with Types II and IV radio bursts and CMEs that can produce coronal and interplanetary shocks. The energetic particles observed during gradual events are dominated by protons. These large proton events are seen over a wide range of solar longitudes relative to the associated flare and have extended time profiles that can last for days (see Figs. 1(a) and 2(a)). Gradual events have small ^{4}He/H ratios and do not exhibit ^{3}He/^{4}He or Fe/C enhancements. The elements are observed in ionization states similar to those in the solar wind,

corresponding to an ambient coronal temperature of $\approx 2 \times 10^6$ K. It must be pointed out that some gradual SEP events have no connection with solar flares but are associated only with CMEs (see Kahler et al., 1984).

(2) The impulsive events are associated with Type III radio bursts and hard X-ray and radio bursts, which are produced by high-energy electrons. The impulsive events are dominated by electrons and are characterized by large ^{3}He/^{4}He ratios and enhancements of heavier ions, such as Fe/O. It is believed that the ^{3}He-rich, Fe-rich ions are a common property of all impulsive solar flares. The impulsive events are associated with flares observed in a narrow range of the western solar longitudes (see Fig. 1(b)) and exhibit a very short time profile (see Fig. 2(b)).

The distributions of the source longitude of the associated flares for gradual and impulsive events are presented in Fig. 1 (from Reames, 1999). The observational evidence that the distribution of gradual events is nearly uniform across the sun surface, in comparison with the narrow range distribution of the impulsive events, strongly suggests the presence of shock wave that can propagate across field lines and accelerate particles. In Fig. 2, the intensity time profiles of a gradual proton event and an impulsive electron event are shown for comparison on the same time scale (from Reames, 1999). The gradual SEP event is connected only with a CME and not with a solar flare.

Over the last decade, a large number of observations of SEP events including the particle composition and the heavy ion enhancements, the maximum energies, the shape of the energy spectra, as well as the acceleration time have become available. Most of the information on the number of interacting electrons and their acceleration time is provided by fitting hard X-ray bremsstrahlung emissions, while the relevant information for ions is obtained by modeling the nuclear deexcitation line and pion radiation emission. Let us now outline the key observations related to the particle acceleration during solar flares (Miller et al., 1997; Reames, 1999; Aschwanden, 1999):

- Abundances of Mg, Si, S, Ca, Ne, Fe enhanced by a factor of 3–10 above the coronal value, a factor of 2000 for He^3/He^4, and a factor of 10–20 for Fe. It must be pointed out that the particle composition can vary with time during an event and it depends on the energy observed in individual events.
- Electrons up to 100 MeV and protons up to 1 GeV.
- Energy spectra with the form of power-laws (single or broken) for electrons and protons, as well as with the form of Maxwellians (for electrons) or Bessel functions (for protons).
- Acceleration times of 0.1–1 s for 10^{37} electrons s^{-1} (> 25 keV) and 1–2 s for 10^{35} protons s^{-1} (> 1 MeV).

Note that we do not distinguish between gradual and impulsive events in the above list of observational characteristics. The above observations form a frame of constrains that any successful theoretical model for particle acceleration in solar flares should incorporate. We must emphasize that with the term successful theoretical model, we mean a model that not only reproduces or predicts the observations, but also has as few free parameters as possible.

3. Particle acceleration mechanisms and other processes

In this section, we will try to present the basic characteristics of the acceleration models proposed for solar energetic particle events. In addition, we refer to the various other processes (besides the acceleration) that are taking place during solar flares and are important for the solar energetic particles.

3.1. Acceleration mechanisms—models

As it was stated in Section 2, solar flares are the manifestations of an energy release process through magnetic reconnection. The magnetic reconnection process generates a pair of slow mode shock waves and a high-speed plasma beam in the form of a jet. The high-speed plasma jet, as it propagates, can possibly generate MHD turbulence and a fast mode shock wave that may terminate the jet. In addition, direct electric fields are present in the vicinity of the reconnection site (for details see Priest and Forbes, 2000). Following this picture of magnetic reconnection, the acceleration mechanisms proposed for the solar energetic particles during solar flares can be divided into three major classes: (a) acceleration by DC electric fields, (b) stochastic particle acceleration and (c) acceleration by shock waves. In this section, we are going to present the basic concepts of the above mechanisms.

3.1.1. Acceleration by DC electric fields

The most direct and simple way to accelerate particles is by a large-scale quasi-static electric field. If we consider a thermal distribution of particles and we apply an external electric field $\vec{E}$, then each particle, besides the force of the electric field, will also experience the Coulomb drag force from the other particles in the distribution. Based on this argument, Dreicer (1960) found that there is a critical electric field value where the Coulomb drag force for a given thermal speed equals the electric field force. This critical electric field is called Dreicer field, and for the case of typical solar flare parameters it is of the order $E_{\mathrm{D}} \approx 10^{-4}$ V cm^{-1}. We usually compare the electric field value to the Dreicer field and thus we have two different types of acceleration models: the ones involving sub-Dreicer fields ($E < E_{\mathrm{D}}$) and those where super-Dreicer fields ($E > E_{\mathrm{D}}$) are present.

A number of acceleration models with sub-Dreicer electric fields ($E \approx 10^{-5}$ V cm^{-1}) have been proposed for the case of solar flares (see e.g. Tsuneta, 1985; Holman and Benka, 1992). These models can explain the bulk energization of electrons up to 100 keV, but they are facing several problems such as: the requirement of a very long electric field parallel to magnetic field or the existence of highly filamented current channels, causing current closure and particle escaping problems. In addition, these models cannot produce ions and electrons in energies 1–100 MeV as well as the observed abundance enhancements. Application of super-Dreicer electric field models to solar flares have been also carried out in the past (e.g. Martens, 1988; Litvinenko, 1996). These models invoke a current sheet with a significant magnetic field, which, together with the assumed inflow plasma velocity, can produce a convective electric field of a super-Dreicer value ($E \approx 10\ \mathrm{V\ cm^{-1}}$). Recently, Litvinenko (2000), in applying this model to impulsive electron-rich solar flares, showed that electrons can be accelerated to a few tens of MeV in $< 10^{-3}$ s, while the energy gain of heavier protons is more modest. The models involving super-Dreicer electric fields are more promising than the ones with sub-Dreicer electric fields, but the production of the observed abundance enhancements is still missing.

3.1.2. *Stochastic acceleration*

With the term stochastic acceleration we define any acceleration process in which the particles can either gain or lose energy on short time scales, but they gain energy on long time average. Typical examples of such an acceleration mechanism are the wave–particle interactions. The basic elements of the wave–particle interactions are resonance and resonance overlap.

Resonance occurs when the following condition is fulfilled:

$$\omega - s\frac{\Omega}{\gamma} - k_{\parallel} v_{\parallel} = 0, \tag{1}$$

where ω is the frequency of the excited plasma wave with a wave vector $\vec{k}$, Ω is the gyrofrequency of the particle with a velocity v and Lorentz factor γ, and s is the harmonic number. At resonance the frequency of the wave is an integer multiple of the particle's gyrofrequency in the particle's guiding center frame. When the particle is at resonance with a single small-amplitude wave its parallel velocity performs a simple harmonic motion and there is no energy gain (Karimabaldi et al., 1992). On the other hand, when the particle interacts with a large-amplitude wave, it can effectively resonate with the wave without the fulfillment of the above resonance condition. Furthermore, if a spectrum of waves is present, resonance overlap occurs. During resonance overlap a particle which initially resonates with one wave might change its velocity in such a way that it can be found in resonance with a higher frequency wave. Under these conditions, the particles in the velocity space are suffering stochastic kicks of energy gains or losses but they achieved a net energy gain.

Depending on the frequency of the excited waves and the assumed particle population, we find that low-frequency plasma waves, with $\omega \leqslant \Omega_i$ (i.e. Alfvén waves), accelerate ions efficiently, while waves with frequencies below the electron gyrofrequency (i.e. Whistler waves) can accelerate electrons efficiently. Finally, high-frequency waves with $\omega \gg \Omega_e$ (i.e. Langmuir waves, electromagnetic O and X waves) can efficiently accelerate a small fraction of the electron distribution and thus produce electron beams.

The stochastic wave–particle interaction process is an attractive acceleration mechanism for the solar flares. The basic parameters for the wave–particle interaction are the wave turbulence level, the dispersion relation of the resonant waves and the particle velocity distribution. A large number of acceleration models, based on this acceleration process have been proposed in the past, especially in order to explain successfully the enhancements of elemental abundance in solar flares (e.g. Ryan and Lee, 1991; Temerin and Roth, 1992; Miller and Vinas, 1993; Zhang, 1995; Miller and Roberts, 1995; Miller, 1997).

The main problem of the stochastic wave–particle acceleration mechanism is the origin of the waves used. Furthermore, some models require an initial bulk or seed acceleration mechanism for the generation of a super-thermal tail in the particle distribution. Finally, it is important to note that we have no direct indications of the wave turbulence level and the nature of the wave spectrum in solar flares, which would allow us to evaluate the proposed stochastic acceleration models.

3.1.3. *Acceleration by shock waves*

Shock wave acceleration has been invoked in many areas of space physics and astrophysics. Shock waves can be formed in solar flares directly as products of the occurring magnetic reconnection processes (see, for example, Cargill, 1991) or indirectly due to intense local heating of the ambient plasma (see simulations by Cargill et al., 1988). Particles can, in general, be accelerated by shock waves by either the *drift* or the *diffusive* acceleration mechanism (for a review see Jones and Ellison, 1991).

In the case of drift acceleration, the particles gain energy as they drift along the electric field at the front of a quasi-perpendicular shock (Sarris and Van Allen, 1974; Armstrong et al., 1985; Decker, 1988). The efficiency of the shock drift acceleration mechanism is limited by the fact that the particles escape from the shock neighborhood, after their interaction with the shock, either into the upstream or the downstream region, without returning back to the shock front again. In order to confine the particles to the vicinity of an oblique shock, Decker and Vlahos (1986) proposed the presence of upstream and downstream turbulence. In this case, the particles are accelerated by a combination of the drift and the diffusive mechanism.

In the case of diffusive shock acceleration mechanism, the particles are accelerated as they scatter many times back and forth across the front of a quasi-parallel shock due to the presence of magnetic irregularities upstream and down-

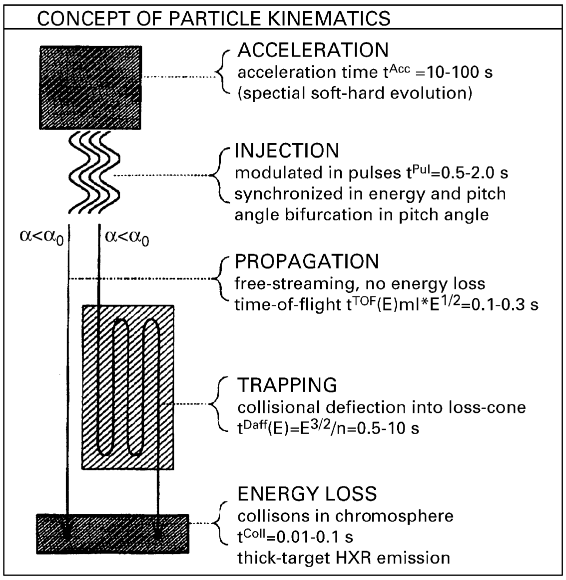

Fig. 3. A conceptual breakdown of the flare kinematics according to Aschwanden (1999).

stream (i.e. wave activities) of the shock (Drury, 1983; Scholer, 1985). During the diffusive acceleration, the particles remain close to the shock. Although the diffusive acceleration has been used extensively to account for the energetic interplanetary particles, it has not been widely applied for the case of solar flares. Several problems are related to the efficiency of the diffusive shock acceleration such as: the need of pre-accelerated particle population (know as the injection problem) and the generation of resonant waves (turbulence) upstream and downstream of the shock front. Several studies has shown that the ions can overcome the injection problem and that the accelerated ion distribution can excite the necessary resonant turbulence (see Lee, 1983). For the case of electrons these problems are still unsolved.

3.2. *Other processes involved during solar flares*

The acceleration is not the only process that takes place during solar flares. In Fig. 3, a conceptual breakdown of the flare kinematics is presented (Aschwanden, 1999). It is clear that besides the acceleration process any theoretical model should include various other processes such as transport of the particles, trapping and escape, radiation losses, etc. The location of the acceleration site or sites and the injection of the particles into these are additional parameters which must be taken into account. The goal of a successful theoretical model is to reproduce at least qualitatively the existing observations regarding the energy gain, the duration, the composition and the shape of the particle distributions of the solar energetic particle events. It must be pointed out that the various processes which take place during solar flares may also occur simultaneously in a complex or interconnecting way. In the majority of the theoretical models, proposed so far for the acceleration of SEP, the acceleration usually is decoupled from the other processes.

In the next section, we will present the role of the energy release process in the acceleration of particles during solar flares. We are going to present some newly proposed models which are trying to interconnect the released energy with the acceleration environment.

4. Acceleration models and the energy release process

All the above acceleration mechanisms are localized processes which are usually applied to explain individual events, without considering the statistical properties of the solar flare energetic events. In addition, recent observations of flare radio emission (Benz, 1985; Benz and Aschwanden, 1992; Vilmer, 1993; Aschwanden et al., 1995; Vilmer and Trottet, 1997) indicate that the energy released during solar flares is fragmented. Following the observational evidence of the fragmentation of energy release process during solar flares, a number of qualitative models have been developed (for reviews see van den Oord, 1994; Vlahos, 1996; Bastian and Vlahos, 1997). These models revealed the necessity to study and understand the global behavior of the evolution of the complex active regions. Two approaches are used to model the dynamic evolution of solar flares:

(1) MHD simulations (e.g. Galsgaard and Nordlund, 1996; Einaudi et al., 1996; Dmitruk and Gomez, 1998; Georgoulis et al., 1998). According to these models, random shearing motions of the magnetic field lines at the photospheric boundary lead to the formation of a number of current sheets inside the active region, where magnetic reconnection occurs. The MHD approach gives detailed insight into the small-scale processes in active regions, but has difficulty modeling the complexity of the entire active regions and solar flares.
(2) Cellular automata (CA) models (e.g. Lu and Hamilton, 1991; Lu et al., 1993; Vlahos et al., 1995; Georgoulis and Vlahos, 1996, 1998). These models have shown that the energy release inside active regions may well be a result of an internal self-organization process. The continuous loading of the active region with new magnetic flux can produce several magnetic discontinuities. Simple rules were applied for the redistribution of magnetic fields and for the release of magnetic energy at these discontinuities. The CA models can rapidly and efficiently treat the complexity of spatially extended, large systems but they face problems describing in detail the small-scale processes occurring.

Several qualitative attempts to study the problem of particle acceleration in the framework of a concrete proposal for a fragmented energy release process have been made

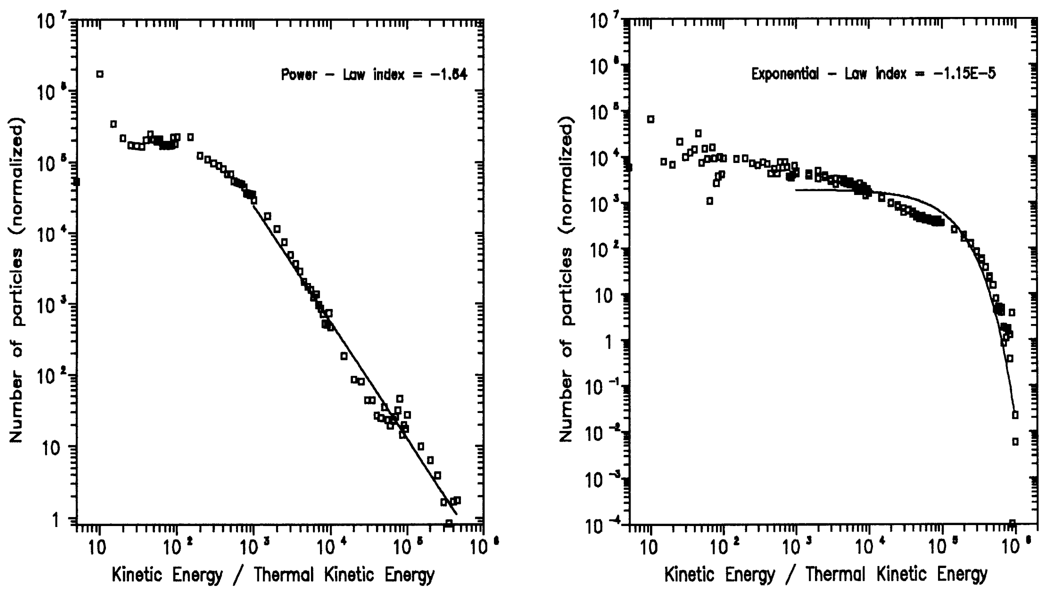

Fig. 4. The numerically calculated kinetic energy distributions of accelerated electrons (average of 10 sample runs) as a function of the maximum trapping time (in arbitrary units). Left $N_{\max} = 500$, Right $N_{\max} = 20000$ (adapted from Anastasiadis et al., 1997).

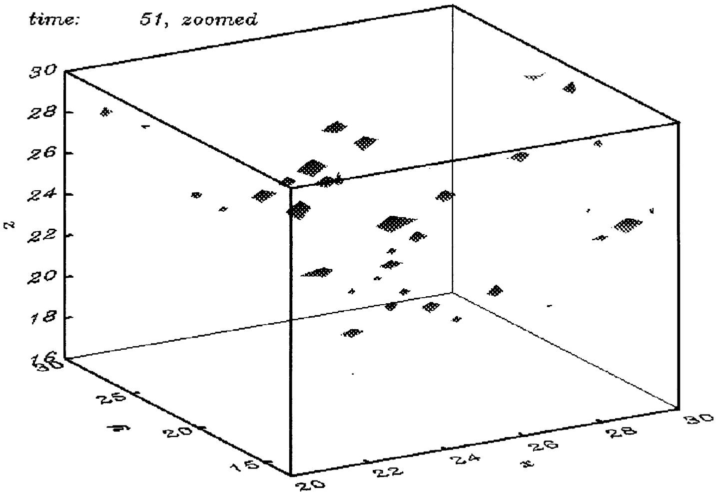

Fig. 5. A 3-D representation (zoom of a 30 × 30 × 30 simulation box) of the current sheets yield by an extended cellular automaton model during a flare (adapted from Isliker et al., 2001).

in the past (e.g. Holman, 1985; Khan, 1989; Haerendel, 1994). Anastasiadis and Vlahos (1991, 1994) proposed a model for the acceleration of particles (electrons and ions) by an ensemble of shock waves. In their model, the energy was assumed to be released by means of many localized, small-scale explosive phenomena which were the drivers of a number of shock fronts (small-scale, short-lived discontinuities). Particles were accelerated by the shock drift acceleration mechanism, based on the adiabatic theory, and lost energy by Coulomb collisions, as they were transported in the stochastic magnetic fields. In the context of homogeneous MHD turbulence and turbulent magnetic reconnection, Gray and Matthaeus (1991) performed similar test particle simulations for the particle acceleration in solar flares.

In order to avoid the vague association present in almost all the acceleration models, of the released energy with the acceleration process, Anastasiadis et al. (1997) proposed a model for the acceleration of electrons in solar flares based on the energy release produced by the Vlahos et al. (1995) CA model. They were able to derive the spatial–temporal evolution of an active region and the resulting energy release time series, which was associated with an electric field time series. They traced an injected electron distribution in this environment, assuming that the acceleration process is due to randomly placed localized DC electric fields. They used as a free parameter the maximum number of interactions with the electric fields allowed for each electron of the injected distribution ($N_{\max}$) before escaping the acceleration volume. This parameter is a rough measure of the maximum trapping time. The final energy distribution of the accelerated electrons showed a power law or an exponential behavior, depending upon the maximum trapping time of particles inside the acceleration volume (see Fig. 4).

It is clear that the energy release process is the main driver for the solar flare energetic phenomena. The mechanism and the amount of the energy release are very important parameters for any acceleration model, as they set up the environment for the acceleration and transport of particles in solar flares. Recently, we attempted to understand the physical interpretation of the various components of the proposed CA models (see Isliker et al., 1988; Vassiliadis et al., 1998) and to explore their consistency with the MHD approaches (Isliker et al., 2000). Based on these efforts, we introduced a new CA model (named *extended CA*), in which all the MHD-inconsistencies were removed (Isliker et al., 2001). In Fig. 5, a 3-D representation of the current sheets produced by the extended CA model during a fare is presented. Our goal is to introduce particles into the extended CA model, in order to study their acceleration at the produced current sheets as well as their transport and radiation. We believe that a new and highly promising field of research, which differs from the localized acceleration approach of SEP, is now emerging.

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