PARTICLE ACCELERATION IN A THREE-DIMENSIONAL MODEL OF RECONNECTING CORONAL MAGNETIC FIELDS

PETER J. CARGILL[1,*], LOUKAS VLAHOS[2], RIM TURKMANI[1], KLAUS GALSGAARD[3] and HEINZ ISLIKER[2]

[1]*Space and Atmospheric Physics, The Blackett Laboratory, Imperial College, London SW7 2BW, UK*
[2]*Department of Physics, University of Thessaloniki, 54124 Thessaloniki, Greece*
[3]*Niels Bohr Institute, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark*
*(*Author for correspondence: E-mail: p.cargill@imperial.ac.uk)*

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Abstract. Particle acceleration in large-scale turbulent coronal magnetic fields is considered. Using test particle calculations, it is shown that both cellular automata and three dimensional MHD models lead to the production of relativistic particles on sub-second timescales with power law distribution functions. In distinction with the monolithic current sheet models for solar flares, particles gain energy by multiple interactions with many current sheets. Difficulties that need to be addressed, such as feedback between particle acceleration and MHD, are discussed.

Keywords: particle acceleration, solar flares

1. Introduction

The acceleration of charged particles to relativistic energies is a ubiquitous process in plasma physics and astrophysics. It is now known that particle acceleration can occur in energetic events in the galaxy, such as supernovae, at the solar wind termination shock, in the magnetosphere and importantly from the viewpoint of this paper, in solar flares. Particle acceleration mechanisms can be divided into three broadly different classes. Shock acceleration occurs in two forms: drift acceleration where particles interact with electric fields at the shock front, and diffusive acceleration where particles are continually scattered by hydromagnetic waves that are present both upstream and downstream of the shock front (a 1st order process). Turbulent acceleration occurs when particles interact with a spectrum of hydromagnetic waves, gaining energy because there are slightly more head-on than overtaking interactions with the waves (a 2nd order process). Finally, both weak and strong direct electric fields can accelerate particles. For a weak electric field, the magnitude must exceed the Dreicer field, but for any realistic case, the strong field case will apply, since the Dreicer field is usually rather small. Further discussion of the theory can be found in Miller *et al.* (1997).

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Solar flares have long been known to involve the release of large amounts of magnetic energy: in excess of 10^{32} ergs in some cases, and to be efficient particle accelerators. Following analysis of the initial data from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) mission (e.g. Lin *et al.*, 2003; Saint-Hilaire and Benz, 2005; Sui *et al.*, 2005), the following results are now widely accepted: (a) up to 10^{37} electrons per sec are accelerated in a very short time (sub-second) to energies between 20 keV and in excess of a few MeV; (b) up to 10^{35} ions per sec are accelerated to energies above 1 MeV; (c) a fraction of these electrons and ions attain relativistic energies; (d) the typical spectra consist of a thermal part at low energies, and a one- or two-part power law at higher energy; (e) acceleration occurs both before the main impulsive phase and well into the decay phase; (f) electrons are accelerated faster than ions. These results have affirmed the longstanding semi-conjecture that energetic particles may account for the largest share of the flare's energy budget. Indeed in some cases up to 50% of the energy released by solar flares seems to go to electrons alone (e.g. Miller *et al.*, 1997). When one adds energetic ions, especially the hard to determine component with energies under a few MeV, the energy conversion requirements are significant.

These results pose formidable challenges for theoretical models. The main one is the need to convert a large amount of magnetic energy into energetic particle kinetic energy. Another is that, despite the high spatial and temporal resolution of current observations, the majority of flares, especially medium and small ones, are still probably not yet adequately spatially resolved. It is plausible that the energy release processes may occur on subscales well beyond our observational means, and indeed theoretical models have shown that small scale energy release can answer many questions, in particular the observed fast timescales (e.g. Miller *et al.*, 1997; Dmitruk *et al.*, 2003; Arzner and Vlahos, 2004; Turkmani *et al.*, 2005). Finally, one needs to address how the small-scale acceleration physics can be incorporated into the large-scale coronal magnetic field configuration associated with a flare.

This paper addresses the last of these points. In Section 2 we discuss the difficulty of developing models that combine the physics of particle acceleration with large-scale magnetic field properties. Sections 3 and 4 present two examples of how one might address these problems using, respectively, cellular automata and MHD models. Section 5 outlines some potentially profitable future lines of investigation.

2. Multiple Scales and Magnetic Complexity in Solar Flares

Observations suggest that the hot plasmas and energetic particles produced in solar flares occupy large coronal structures: length scales between 10^9 and 10^{10} cm are reasonable. These structures are believed to outline the large-scale topology of the coronal magnetic field, although of course direct measurements of the coronal field strength and direction itself are very difficult. Despite this, all our understanding of particle acceleration suggests that it occurs on very small length scales, certainly sub-km, and perhaps much less. Considering the three processes discussed in the introduction, for direct electric field acceleration at a coronal current sheet, the scale is $L \sim \eta/V$. For a velocity of 50 km/s, temperature of 2×10^6 K, density of 10^{10} cm^{-3} and a classical conductivity ($\eta = 10^9/T^{3/2}$ m^{2}s^{-1}), $L \ll 1$ m. In turbulent acceleration a 1 MeV proton will resonate with an Alfvén wave of wavelength ($2\pi V/\Omega_i$) of 100 m, and for the same energy particle, shock acceleration involves regions several times this size, of order 1 km. In addition, particle acceleration is intrinsically a kinetic process: the details of the distribution function and how particles at different parts of the distribution interact with, for example waves, are of importance.

Another issue concerns the spatial distribution of acceleration sites. While the present-day preference for flare particle acceleration at a monolithic current sheet (e.g. Shibata, 1999) may be of relevance for the later stages of the largest (eruptive) flares, it is by no means clear that it is relevant for the impulsive phase, and for smaller (compact) flares. Instead, complex coronal geometries with multiple acceleration sites need to be considered. In the following two sections we discuss why this can be expected from theoretical considerations, but note here that such a scenario implies that a given particle can be accelerated at more than one location, perhaps enhancing the energisation process.

How can theoretical models address these problems? Most models for particle acceleration in flares consider a single accelerating site (current sheet, shock etc.) with simplified background parameters (constant density, magnetic field), permitting analytic or semi-analytic calculations. This often enables very detailed calculations of the kinetic physics in the acceleration processes, but of course ignores the global environment.

In order to model the kinetic physics in a large-scale environment, some workers have carried out full particle simulations of a coronal magnetic field (e.g. Winglee *et al.*, 1991). Provided enough particles can be included, kinetic modelling in regions of varying magnetic field and plasma can be carried out. The difficulty with this approach lies in the compression of scales. Particle codes are required to resolve scales of order the Debye length (for coronal plasma of order 1 mm), whereas computer memory limitation implies that the overall system scale can be only 10^3 Debye lengths. The problems are obvious, yet these simulations are unique in showing how the global coronal electric circuits that are important for maintaining quasi-neutrality can be set up. But it needs to be said that even with the most optimistic projections, such modelling with the correct scales will be beyond the capabilities of computers for decades.

Thus it is clear that modelling acceleration in a global corona involves sacrificing something. Full particle codes retain much kinetic physics, but the length scales are irrelevant to the solar corona. MHD models have the right global scales, but have artificially low magnetic Reynolds numbers and no kinetic physics. The question is whether there is an intermediate approach.

3. Acceleration in Cellular Automata Models

The idea of multiple dissipation sites in flares is longstanding, but the first serious effort at modelling this was by Lu and Hamilton (1991) who took ideas associated with self-organised criticality (SOC) and applied them to the solar corona. They considered a coronal magnetic field that was gradually stressed by the injection of magnetic energy at random points inside the 3D structure of the active region. A series of simple rules governed the behaviour of the field, and dissipation was deemed to occur when the local current reached a threshold. Lu and Hamilton showed that (a) if the right conditions were met, the triggering of dissipation at a single point could lead to a "spreading" of dissipation across a large coronal volume and (b) the distribution of event size as a function of energy followed a power law similar to that observed in flares. Extensive debate followed, much of which centred on how to satisfy Maxwell's equations (e.g. Vlahos *et al.*, 1995; Vassiliadis *et al.*, 1998; Isliker *et al.*, 2000). However, a fundamental question remains: can existing MHD models verify that the main scenarios behind the SOC theory are valid?

These SOC (and associated cellular automata: CA) models identify dissipation occurring at many spatially separated regions. This is illustrated in Figure 1 taken from Vlahos *et al.* (2004). Figure 1a shows a coronal field geometry, reconstructed from photospheric magnetograms, in a volume with characteristic dimensions of 10^9 cm. Figure 1b shows isosurfaces of current in a small part of a coronal volume as yielded by the MHD-consistent CA model of Isliker *et al.* (2001), while Figure 1c shows the local sub-structure not evident in Figure 1b. Finally, a snapshot of the locations where the currents are in excess of the threshold for dissipation in the CA model (referred to as Unstable Current Sheets: UCS) is shown in Figure 1d. Energy release at this time thus occurs at a number of locations.

To assess particle acceleration in such a coronal geometry, Vlahos *et al.* (2004) developed a model in which the particles move between the UCS, gaining (or losing) energy at each one, and undergoing ballistic motion in a background magnetic field between the UCS. The main ideas behind these models are the following. Using the SOC hypotheses we can identify the structure of the spatial distribution of the UCS inside a complex active region. The spatial distribution of the UCS exhibits a specific fractal structure (McIntosh *et al.*, 2002). The knowledge of the spatial distribution of the UCS can help us to reconstruct the probability distribution of the distances between the UCS and as such the probability of a particle colliding with the UCS (Isliker and Vlahos, 2003). An aspect that remains open is the statistical properties of the energy gain or loss for a particle colliding with an UCS, but this is easy to study using three dimensional MHD codes (see Section 4). Therefore we can start from a global reconstruction of the distribution of UCS and recover the kinetic properties of the particles assuming that the SOC theory is valid.

This is illustrated in Figure 2 where a particle first interacts with site i, escapes along the magnetic field, encounters site $i + 1$, escapes again, and so on. The energy gain thus occurs in many increments, rather than at a single location, as

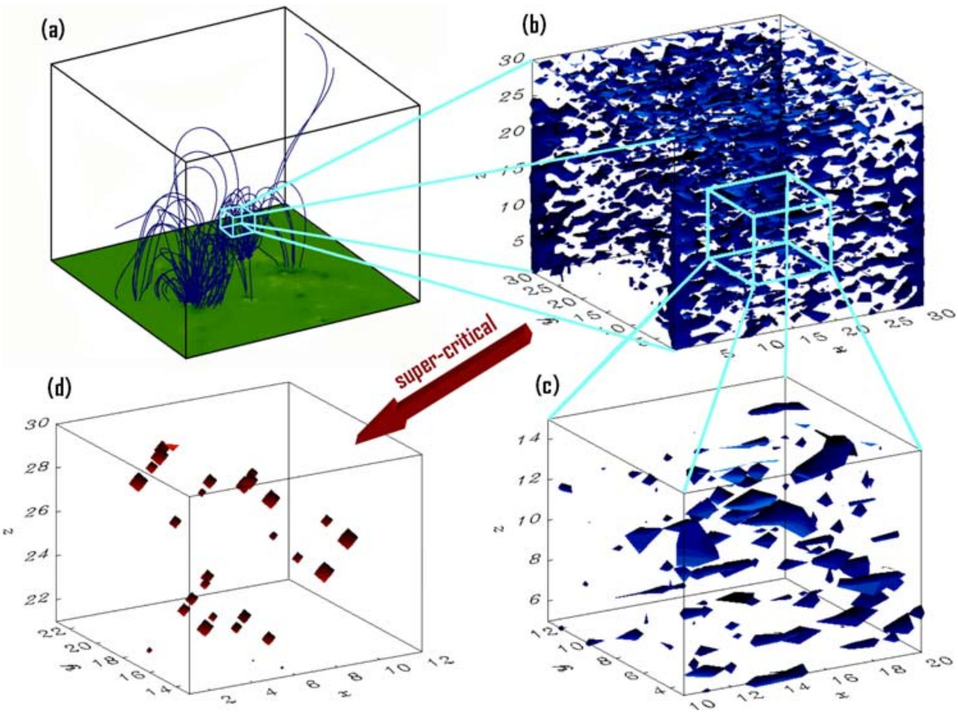

Figure 1. (a) A simulated magnetogram of a photospheric active region and associated coronal force-free magnetic field lines (generated by the model of Fragos *et al*., 2004). (b) Sub-critical current iso-surfaces in space determined by a X-CA model. (c) An expanded view of panel (b). (d) A temporal snapshot of the X-CA model during a flare, showing the spatial distribution of the UCS (supercritical current iso-surfaces) inside the complex active region. [From Vlahos *et al*., 2004].

in the monolithic current sheet approach. The acceleration is determined by three probability densities: one defining the distance between a pair of accelerators, one the electric field strength at each accelerator, and a third either the time spent in the UCS, or the length of the UCS. The first two are assumed to be power laws, and the third is taken to be a Gaussian. Note that this model only addresses acceleration by direct electric fields since that can be simply parameterised at the dissipation sites. We return to this point in Section 4. In the example shown in Figure 3, the distance between accelerators ranges from 10^4 to 10^{10} cm, the particle moves in a box of size 10^{10} cm, but the magnetic fields may be such that they are partially trapped and the trajectory is complex. The upper limit of the free travel distances is set to a value larger than the coronal volume in order to allow particles to leave the coronal region without undergoing any interaction with electric fields, besides the initial one (note that for the maximum time of 1 sec for which the system is monitored these escaping particles will move at most a distance 3×10^{10} cm, which is of the order of the length of the coronal volume). The electric field varies between the

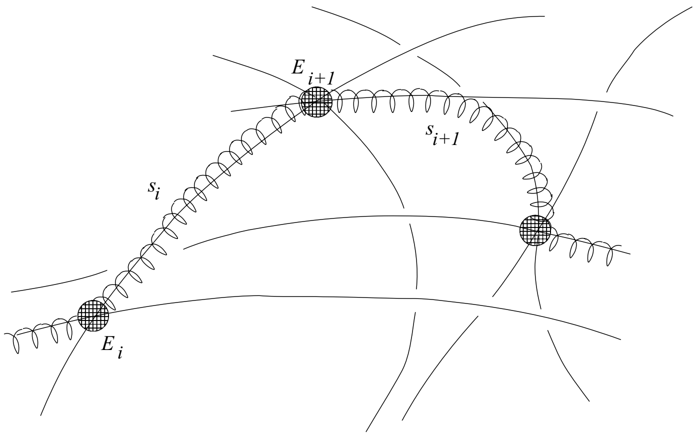

Figure 2. A sketch of particle motion in the coronal X-CA model of Vlahos *et al.* (2004). A particle (the spiraling line) essentially follows the magnetic field lines (solid lines), although also undergoing drifts, and travels in this way freely a distance s_i, until it enters a UCS (filled circles), where it is accelerated by the associated effective DC electric field E_{i+1}. The particle then moves freely again until it meets a new UCS.

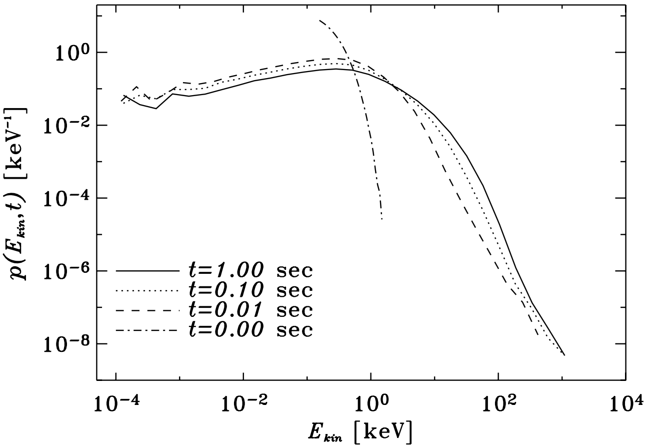

Figure 3. The kinetic energy distributions $p(E_{\mathrm{kin}}, t)$ (probability density function, normalized to 1) at times $t = 0$, 0.01, 0.1, 1 s, for the case in which the acceleration times are prescribed in the X-CA acceleration model of Vlahos *et al.* (2004).

Dreicer field and 10^8 times larger, and the acceleration time has a mean value of 2×10^{-3} s.

A large number of test particles are then tracked through this coronal geometry using the relativistic equation of motion. The details of the acceleration can be found in Vlahos *et al.* (2004), but we note here that most of the particles undergo multiple interactions with UCS, with acceleration taking place very rapidly ($\ll$1 s).

Figure 3 shows the distribution function of electrons at four different times. The initial distribution is a Maxwellian with a temperature of 100 eV (dash-dot line). We see that (a) prompt acceleration to energies well in excess of 100 keV takes place, (b) just under half of the particles end up in the high energy tail and (c) the tail is a power law with approximate slope of -4. When the test particles are protons, it is found necessary to allow for much longer acceleration times to attain similar energies when the acceleration time is prescribed.

4. Acceleration in Self-Consistent MHD Models

The CA models are simple to run, and do not have the limitations that often make MHD models difficult to run (e.g. timestep, number of grid points, numerical stability, artificial Reynolds number). On the other hand, when modelling the large-scale corona, the MHD approach is likely to be valid, and so it is important to address particle acceleration in such a framework. There is considerable evidence from 2.5 dimensional MHD simulations that driving the corona leads to complex magnetic geometries with multiple dissipation sites, as is found in the SOC/CA models (e.g. Buchlin *et al.*, 2003). Although the extension of these results to 3-D is difficult, primarily for computational reasons, it is essential that this be carried out to both conduct a comparison with the CA models and to correctly address loss of accelerated particles from the corona to the photosphere.

Recently Turkmani *et al.* (2005, 2006) have addressed the issue of particle acceleration in a 3-D coronal MHD model. The MHD model was developed by Galsgaard and Nordlund (1996) and Galsgaard (2002), and considers the response of the corona to random photospheric driving. The initial magnetic field extends between the two photospheric ends of a "straightened" coronal loop, and a turbulent cascade develops as energy is injected. This leads to the formation of multiple current sheets in the corona, which appear and disappear over short times, but overall give rise to a continually turbulent coronal state. Figure 4 shows the resistive coronal electric field distribution at one time during such a simulation. In this case the MHD model has a scale of 1.5×10^9 cm between the photospheric ends, and a transverse dimension a factor 20 less. It is clear that current sheets are distributed throughout the corona. The distribution of current sheets will change when different snapshots are considered, giving rise to the possibility of very bursty particle acceleration.

To study particle acceleration, the MHD simulation is "frozen" in time, and test particles are followed through the electromagnetic fields using the relativistic equations of motion. [Since the acceleration time is short compared to the MHD time, we are able to look at a fixed field profile.] A range of particle motions are seen to occur. Some particles undergo rapid and systematic energy gain, and leave the computational box with relativistic energies. Other particles undergo trapping in the corona, gaining some energy, and some do not interact with the current sheets, gaining no energy at all. The model also allows particles to be lost from the

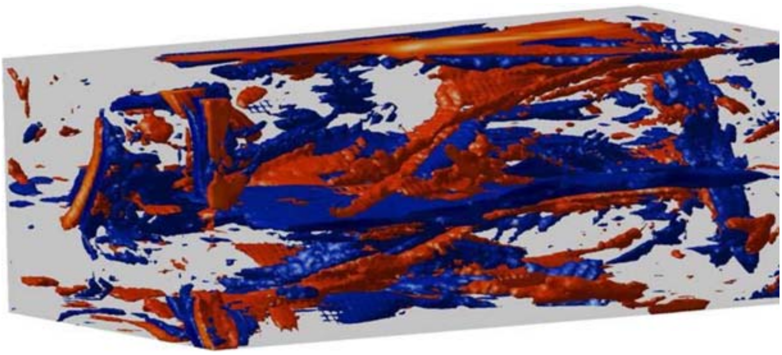

Figure 4. Snapshots of the resistive electric field configurations within the coronal volume, as calculated from the global MHD model. The blue and red regions represent electric field regions that point towards the left and right foot points respectively. [From Turkmani *et al.*, 2005].

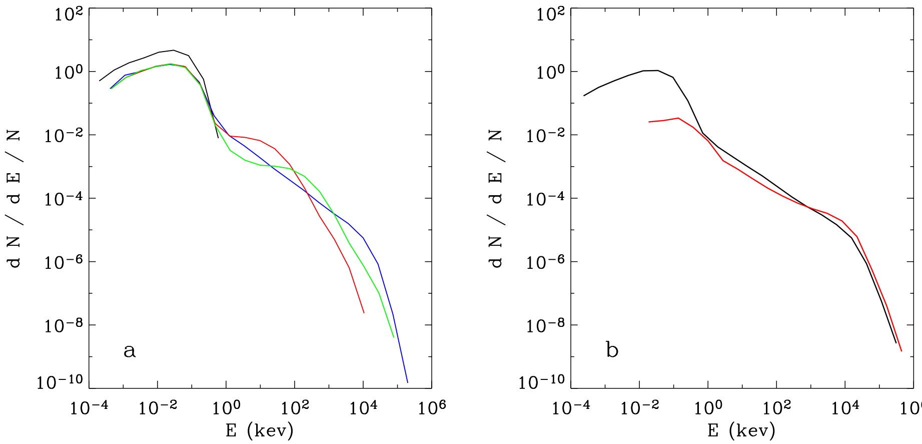

Figure 5. Distribution function obtained by running 40,000 electrons in the MHD model for a coronal volume with $L = 1.5 \times 10^9$ cm. (a) The time evolution of the distribution functions taken at $t = 0$ (black; the curve terminates at $E = 1$ keV), $t_1 = 0.0125$ s (red), $t_2 = 0.025$ s (green), and $t_3 = 0.05$ s (blue). (b) The final distribution function at $t = 0.1$ s from the above model when we consider only the resistive component of the electric field (black) compared to that of a similar model that considers both the resistive and the inductive components on the electric field (red).

computational domain, hence limiting their energy gain. The results show that (a) the resistive electric field is the principal means of energisation: the inductive field plays little role; (b) the particles gain (and lose) energy through multiple interactions with different current sheets; (c) acceleration to relativistic energies is very rapid for both electrons and ions and (d) a large fraction of the particles are accelerated. Figure 5 shows the distribution function of electrons at a number of times during a model run. The distribution has a clear two-part power law structure, with a thermal component at low energies.

It is interesting to briefly compare the two classes of models. The MHD one gives higher particle energies in somewhat faster times than the CA one when the acceleration time is prescribed. This is likely to be due to different choices in the basic parameters, especially the magnetic field strength and density. The same MHD snapshot accelerates both electrons and protons without any need to adjust the electric fields, contrary to the CA based model. It is unclear why this difference arises. The two-part power law does not arise in the CA model, and may be due to the loss of particles in the MHD one. But despite these differences, both approaches show that a fragmented coronal environment is an excellent particle accelerator.

5. Discussion

In this paper we have discussed some of the problems in understanding particle acceleration in the corona, and some ways that these problems may be addressed. In particular, we have demonstrated that a turbulent corona with multiple current sheets is an excellent environment for particle acceleration (see also Dmitruk *et al.*, 2003, 2004). But it is clear that we are still a long way from solving “the flare problem”. In particular the following points need to be noted:

– The fact that a large fraction of the flare energy goes into energetic particles suggests that the test particle approach is unlikely to be valid at all times. Instead, feedback needs to be considered on the evolution of the coronal magnetic fields. Also, the influence of energetic particles on the spreading of dissipation may be of importance.
– The present generation of test particle models in coronal fields consider only direct electric field acceleration. Other mechanisms need to be considered.
– Are simplified approaches to coronal magnetic field dynamics such as SOC valid, and what are their limitations?
– Particle transport in the corona, and from corona to chromosphere, is believed to be influenced by scattering, probably due to small-scale turbulence. This is of importance in determining distribution functions entering the chromosphere.

We now address these points in turn. Regarding point (1), theories for current sheet structure do not consider what happens if there is significant particle acceleration. For example, if much of the plasma in the vicinity of the diffusion region is accelerated, and leaves the current sheet rapidly, does this have an effect on the reconnection rate? What happens if beams of charged particles from one acceleration site pass through a current sheet that is not undergoing dissipation? Can such an interaction lead to destabilisation of another current sheet, and so trigger a spreading of dissipation? We have not even the simplest of possible answers to such questions.

Point (2) requires the development of suitable parameterisations of the acceleration processes. This is relatively simple with a DC electric field, since that is a quantity that is "outputted" from an MHD code, but even in this case collective effects influencing the distribution function are ignored. Acceleration by MHD turbulence has been well-studied in isolation (e.g. Miller *et al.*, 1997), but the relationship with coronal dissipation has never been properly established. The difficulty is relating the presence of the required level of turbulence to coronal reconnection. One can make conjectures though. It is well known that magnetic reconnection leads to plasma jets with a velocity at approximately the Alfvén speed based on the reconnecting field components. One can argue that such a jet will be unstable to hydromagnetic instabilities, leading to the generation of plasma eddies, and ultimately a turbulent cascade which can then accelerate particles.

How can one include such a process into a corona with multiple dissipation sites? Clearly it is essential to parameterise the turbulent acceleration, in particular the magnitude of the field fluctuations, in terms of the properties of the reconnection site. One then needs to parameterise the energy gain attained when a particle of given energy interacts with this region of turbulence. These are not unattainable goals, but they do require considerable thought. Similar thoughts apply to diffusive shock acceleration, and we note here that some ideas for drift acceleration have already been considered by Anastasiadis and Vlahos (1991).

The viability of simplified models is an open question. Future work must address in an interactive way the relationship between MHD simulations (including current sheet particle dynamics) and the recovery from MHD codes of the basic rules of the SOC theory (e.g. Isliker *et al.*, 2000, 2001). Moving away from two-dimensional MHD is essential here: many simulations of 3-D MHD processes show turbulent small-scale structures forming that are not present in simulations with reduced dimensionality. It seems essential to abandon once and for all the concept of the monolithic current sheet.

The issue of transport is in many ways not quantifiable given the many possible wave modes that could be responsible for particle scattering. But this is an issue that could be addressed either by introducing a random scattering operator into the equation of motion, or another parameterisation, and so this cannot be regarded as a problem of the same magnitude as the other points.

The material presented above, and in the rest of this paper, offers an alternative approach to solar flares that abandons the monolithic current sheet approach in favour of distributed energy release as suggested by many models of the corona. In fact, the two approaches are related when one realises that the current sheets in the fragmented models are no different from the monolithic ones, but the presence of multiples sheets introduces new dissipation and acceleration scenarios. But the outstanding problem of linking kinetic physics with large-scale MHD in a consistent way with feedback remains of key importance.

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