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Particle acceleration at 3D magnetic reconnection sites

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Abstract. It is proposed that the direct electric fields associated with magnetic reconnection may be responsible for accelerating high energy charged particles which are observed in solar flares. We investigate charged particle acceleration using a test particle approach, with electromagnetic fields arising from a simple model of magnetic reconnection at a 3D magnetic null point for both spine and fan modes of reconnection.

Key words. Acceleration of particles – Sun: flares – Sun: particle emission

1. Introduction

Magnetic reconnection is believed to be the fundamental energy release process in solar flares, as well as occurring in many other astrophysical situations. During flares, significant populations of high energy (non thermal) charged particles, both ions and electrons, are produced. Reconnection in flares is associated with super-Dreicer electric fields (typically 1000 V/m in 2D geometries). Are these strong direct electric fields responsible for generating the high energy particles?

Nature is inevitably 3D, which should be taken into account in models. 3D null point configurations have been observed in flares (Aulanier et al. 2000), and it is likely that 3D nulls are common in the corona due to the complex nature of photospheric magnetic flux sources. Thus, we model particle acceleration in 3D reconnection configurations. The aim is to determine how charged particles are accelerated in 3D configurations and how this differs from 2D results. We describe here test particle studies in 3D reconnection geometries; see Dalla & Browning (2005) and Dalla & Browning (2006) for details.

The test particle approach takes magnetic and electric field configuration representative of reconnection, neglecting the fields generated by the test particles themselves (valid if number of accelerated particles is small compared with background plasma). Usually collisions of test particles are neglected. The equation of motion (without gyroaveraging) is integrated numerically. Much effort has focussed on studying particle acceleration during 2D reconnection (e.g. Browning & Vekstein 2001; Hamilton et al. 2003; Wood & Neukirch 2005). But 2D configurations are unrealistic in many respects (e.g. infinite extent in invariant direction); reconnection in 3D may differ quite fundamentally.

The simplest 3D reconnection configuration, used here, is a current-free magnetic null:

$$\mathbf{B} = B_0 \frac{R}{L}\mathbf{e}_R - 2\,B_0 \frac{z}{L}\mathbf{e}_z \qquad (1)$$

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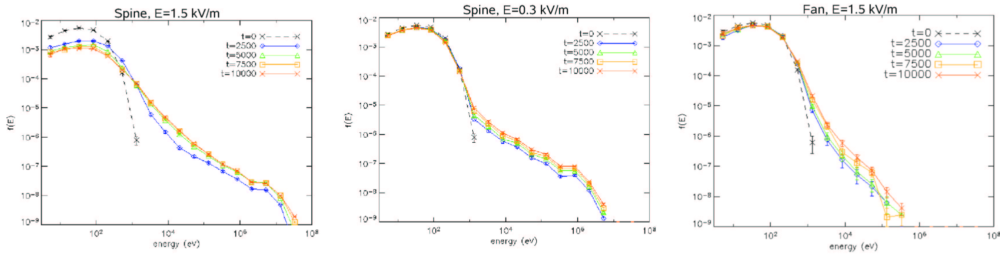

Fig. 1. Calculated proton energy spectra showing evolution to steady state. Left: Spine reconnection, standard conditions. Centre: spine reconnection, electric field reduced by factor 5 ($E_0 = 0.3kVm^{-1}$). Right: fan reconnection, standard conditions.

where L is the size of the reconnection region and B_0 is the magnitude of **B** at R=L and z=0. Analytic expressions for the electric field are taken from a kinematic model of reconnection at a 3D null (Priest & Titov 1996); this describes the outer ideal reconnection region. Two regimes are possible: spine and fan reconnection. In the former, there is a singularity (a current filament) along the spine and plasma flow is within planes through the spine; in the latter, the singularity is in the fan plane and the flow has a swirling pattern.

Analysis of single particle trajectories in spine reconnection showed that efficient particle acceleration can take place, in the case of strong electric fields (magnitude of the electric drift velocity $\frac{E}{B}$ exceeds the particle thermal speed (Dalla & Browning 2005)). We then inject a population of particles randomly distributed on a spherical boundary at a distance $r = L$ from the null point. The initial velocity of each particle is randomly generated according to a Maxwellian distribution.Here we present results for injecting 10000 protons, with an initial temperature T=86 eV (=10^6 K). Standard conditions are taken to be B_0 =100 gauss, E_0 = 1.5 kV/m and the region scale length L = 10 km, representative of the solar corona. Trajectories are integrated for 10000 gyroperiods (64 ms), sufficient for the energy spectrum to reach a steady state.

2. Results for spine and fan reconnection

First, spine reconnection is considered. The flow field is such that all particle trajectories move inwards towards the spine, where they can be strongly accelerated. Individual trajectories are discussed in (Dalla & Browning 2005), where it is shown that the final energy depends on the injection position. The energy spectrum is power law for nonthermal particles $f \propto W^{-0.9}$ with bump at high energies (particles closely approaching null) (see Fig. 1). Most strongly accelerated particles enter near the region of weak electric field, exiting in the opposite quadrant or along the spine. The highest energy particles are trapped ($v_\perp > v_\parallel$), bouncing in mirror field these do not reach large distances from null. Another population of high energy particles are escaping these form jets along the spine fieldline (Dalla & Browning 2006).

It is interesting to investigate how the effectiveness the acceleration depends on the system parameters, in particular, the magnitudes of the electric and magnetic fields. We expect that the acquired energy should largely scale with the E/B drift speed, since acceleration is due to coupling between the drift and the parallel motion (Browning & Vekstein 2001). The effect of varying the electric field can be seen from Fig. 1, showing that acceleration is reduced for weaker electric fields.

The case of fan reconnection is then considered, which in the model of Priest & Titov (1996) has the same magnetic field (eq. 1) but

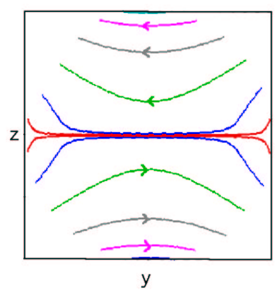

Fig. 2. Projections in the rz plane of streamlines for fan reconnection.

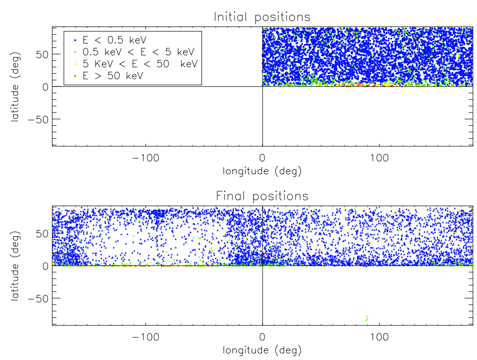

Fig. 3. Particle angular positions colour coded according to final energy, showing initial positions (top) and final positions (bottom) for fan reconnection.

a different electric field and flow pattern. The flow has both an azimuthal component and a component of inflow (in some regions) towards the fan plane where the electric field is strong. It can be seen from the streamline pattern (Fig. 2) that only particles which start very close to the fan plane are brought towards this plane. This suggests that acceleration may be less effective than spine reconnection, which is indeed the case. The energy spectrum, for the standard set of parameters, can be seen in Fig. 1 (right panel); the spectrum is steeper, and the maximum energy gain is much less. No jets of high energy particles are created in fan reconnection; see Fig. 3, which shows particles emerging positions colour coded by their energy.

3. Conclusions

Magnetic reconnection in flares and elsewhere may take place in 3D configurations. We have modelled test particle trajectories in outer ideal region of magnetic reconnection near 3D null points. Energy gain depends strongly on the entry position to reconnection site. In the case of spine reconnection, populations of trapped and escaping energetic particles can be generated; particle jets escape along spine. For fan reconnection, preliminary results suggest it is more difficult for particles to reach the strong electric field region; acceleration is much weaker and no jets are found.

Our results are relevant to other astrophysical/space plasmas where reconnection may occur: for example, the Earths magnetosphere, extra-galactic jets, pulsars. In future this work will be extended in a number of ways. We will study particle trajectories using more self-consistent 3D reconnecting field configurations. Electron trajectories will be calculated (using a guiding centre code, except near the spine, due to the much smaller Larmor radius). Calculated particle spectra will be compared with data, in particular from RHESSI.

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