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Particle Acceleration in Collisionless Magnetic Reconnection

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Abstract. We investigate the acceleration of charged particles in the framework of collisionless reconnection. A steady reconnection scenario is considered, with a two dimensional X-point magnetic field geometry having also a uniform field component transverse to the plane of the X-point field, and an inductive electric field generating an inflow of particles. Test particle trajectories are studied, and the energy spectra of the accelerated particles are determined.

1. Introduction

Magnetic reconnection is invoked as a mechanism for solar flares, and may also be involved in solar coronal heating. The acceleration of charged particles is an important signature of the reconnection process, and the energy spectrum of these particles may be observed and used in principle to infer details of the reconnection geometry. Here we are concerned with a collisionless scenario, in which the particle mean free paths are long compared with the scale length of the reconnection site. We consider steady two dimensional reconnection near an X-type neutral point in the magnetic field with a transverse electric field of inductive origin creating an inflow of plasma to the reconnection site. Since the plasma is collisionless, a first step is to consider test particle trajectories in such an electromagnetic configuration, ignoring the non linear effects of the particle motions on the fields [1]. Such self consistent effects, whereby the ions and electrons accelerated in opposite directions may produce a current, and the differing trajectories may also produce electric fields through charge separation, may be considered in future.

An exact magnetic neutral point is unlikely to be realised in astrophysical contexts. We thus consider the effect of adding a uniform magnetic field component transverse to the plane of the X point and hence parallel to the driving electric field. The aim is to bridge the gap between previous models such as [2] which have considered a pure X-point configuration and the results of [3] in which the tranverse magnetic field component is assumed to be very strong. The results are presented more fully in Ref [4].

2. The Model

The magnetic field is taken to be a potential X point configuration with scale length L

$$\mathbf{B} = -B_o\frac{y}{L}\hat{\mathbf{x}} - B_o\frac{x}{L}\hat{\mathbf{y}}l + \gamma B_o\hat{\mathbf{z}} \tag{1}$$

where γ is a dimensionless constant parametrising the magnitude of the component of magnetic field parallel to the electric field. The driving electric field is uniform $\mathbf{E} = \mathbf{E}\hat{\mathbf{z}}$. It has been shown [1,2] that particles of charge e and mass m are strongly magnetised on a global scale if $\epsilon << 1$, where $\epsilon = \frac{mE}{eB_o^2L}$, and we focus on this regime, which is appropriate for solar coronal configurations. In the case of $\gamma = 0$, there is a small region near the X point within which the particles are effectively unmagnetised and are thus directly accelerated by the electric field (corresponding to the narrow resistive dissipation region in conventional MHD reconnection models) [1]. If the transverse magnetic field component is sufficiently strong, the particles are magnetised everywhere, and it can be shown [4] that this occurs when $\gamma > \epsilon^{(1/3)}$. We consider here only the adiabatic motion of particles, so that our model is restricted to the outer region for weak transverse fields.

Following [2], it can be shown that the parallel speed of particles is governed by

$$\frac{dv_{||}}{dt} = v_{||}\mathbf{v}_E \cdot (\mathbf{h} \cdot \nabla\mathbf{h}) + \mathbf{v}_E \cdot (\mathbf{v}_E\nabla)\mathbf{h} - \frac{\mu}{m}(\mathbf{h} \cdot \nabla)B + \frac{e}{m}E_{||} \tag{2}$$

where $\mathbf{v}_E$ is the electric drift speed, $\mathbf{h}$ is the unit vector along the field and μ is the magnetic moment. The first two terms on the right hand side represent, respectively, the generation of parallel motion from the electric drift due to the curvature of the magnetic field lines and due to the associated curvature of the electric drift streamlines [2]. The third term represents the diamagnetic force, which is a minor effect in this study, since we are concerned with fast reconnection in which the electric drift velocity is strong; the fourth term, proportional to the magnitude of the component of the magnetic field transverse to the X-point, represents direct acceleration by the electric field. We solve this equation numerically, together with the motion perpendicular to the field given by the drift velocity, for particles entering along the upper boundary of the reconnection site which is taken to be a square of side L in the xy plane.

3. Results and conclusions

The parallel motion is affected both by the motion generated from electric drift (due to the curved field lines) and by direct acceleration (due to the component of the electric field parallel to the magnetic field) when γ is of similar size to ϵ. There is a critical entry position at the upper boundary for which particles approach close to the origin and are ejected from the reconnection site with a high parallel speed due to the strong electric drift motion when passing near the origin. As γ increases, it is observed that the bulk of particles are accelerated mainly directly by the parallel electric field although a small group of particles

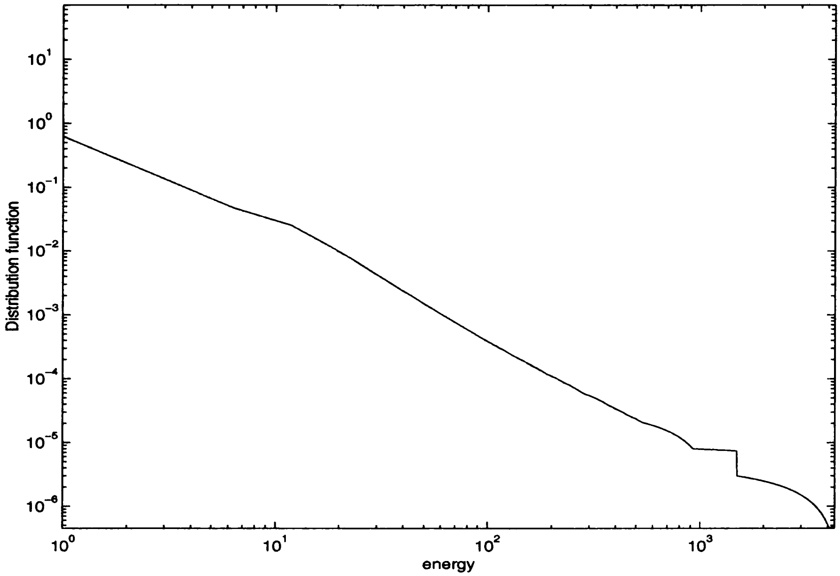

Figure 1. The distribution function f(K) (arbitrary units) of parallel kinetic energy (K) for particles ejected from the reconnection site assuming a uniform inflow at the upper boundary for $\epsilon = 0.001$, $\gamma = 0.003$

are still accelerated to significantly higher energies due to the electric drift until γ is of the order $\epsilon^{1/3}$.

In order to calculate the energy spectra, we assume that particles enter with no parallel velocity at the upper boundary y = L and calculate the parallel kinetic energy $K = (1/2)mv_{//}^2$ of particles leaving the reconnection site as a function of their entry position x_0. Then, assuming a uniform influx of particles at the upper boundary y = L, a distribution function may be derived, as shown in Figure 1. This typically takes the form of a broken power law, where for the higher energy range $f \sim K^{\alpha}$ with an index α in the range around $-1.7 - -2.0$, steepening as γ increases.

The highest energy which can be acquired by the processes discussed here is of the order $\epsilon^{-2/3}$, since there is a cut off for particles entering the non adiabatic region near the origin. For typical solar parameters [4], this allows acceleration up to energies of a few MeV for ions and hundreds of keV for electrons.

References

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