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Disruption of forced current sheets in astrophysical plasmas

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Abstract. Ion tearing mode instability of the forced current sheets is studied. The trapped electrons have a strong stabilizing effect on the excitation of the instability. The presence of background turbulence can effectively lead to the untrapping of the electron orbits and, thus, facilitate excitation of ion tearing instability. Respective scenarios for magnetospheric substorms, solar flares and coronal transients are discussed.

Key words : current sheets—astrophysical plasmas

1. Introduction

Current sheets can occur in almost all cosmic plasmas like planetary magnetospheres, stars, in the magnetic field of galaxies, and within cluster of galaxies. When topologically different parts of magnetic configuration are pushed together either due to convection, or slowly changing boundary conditions or because of some vortex flows induced by some macroscopic instability, a thin forced current sheet could form in the centre of the ambient current sheet (Burkhart *et al.* 1992a). The disruption of current sheets releases the excess stored magnetic energy via magnetic reconnection process and consequently the plasma system relaxes to a new equilibrium configuration with less free energy than before. Magnetic field configuration is changed during the reconnection process; a prototype of which is the tearing instability of the plane neutral sheet. The energy dissipation during disruption of current sheets could provide the necessary heat source responsible for the X-ray corona and the X-ray emission from almost all stars. Parker (1987) has suggested that the X-ray corona and much of the region of a stellar flare could be due to cloud of small reconnection events (nanoflares) in the ambient current sheets. Some other phenomena associated with the disruption of current sheets are the loop prominences (Kopp & Pneuman 1976), coronal mass ejections (Pneuman 1980), solar flares (Priest 1981), microwave solar bursts [Kundu 1985], magnetospheric substorms (Schindler 1974; Hones 1977) and comet-tail disconnection events.

2. Ion tearing instability of forced current sheet

The tearing mode instability is believed to play an important role during substorms onset (Coppi *et al.* 1966; Schindler 1974; Lakhina & Schindler 1983, 1988; Lakhina 1992a,b; Lakhina 1993). The thin current sheet observed during growth phase of a substorm in the magentotail (cf. figure 1) is characterised by a half-thickness, a, which is much smaller than the half thickness of the plasmasheet L (Mitchell *et al.* 1990). The strong current within this embedded sheet in not due to diamagnetic drift (i.e., the apparent drift due to the difference in the plasma populations on the adjacent field lines); rather it is due to the acceleration of "Speiser like" ions trajectories by a dawn to dusk electric field E_y. The entire forced thin current sheet can be treated as an inner layer, and the rest of the region as an outer layer (see figure 1).

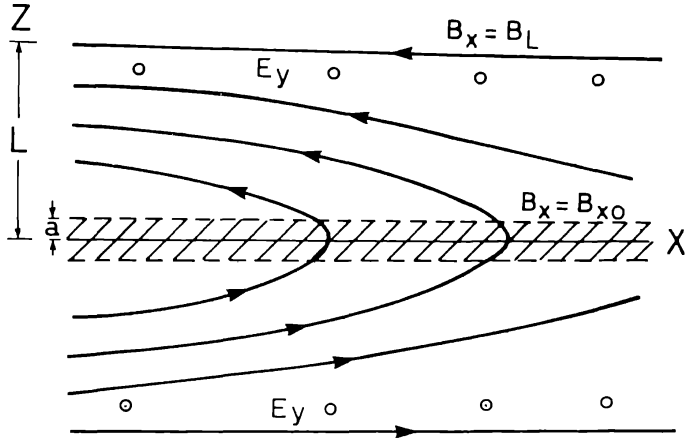

Figure 1. Schematics of the two dimensional configuration of the earth's plasma sheet with an embedded forced current sheet at the centre. The plasmasheet has a characteristic dimension of $2L$ and the forced current sheet (hatched region) has a half thickness of a. The x-component of the magnetic field has a value B_{x0} just outside the boundary of the inner current sheet (dashed horizontal line), and a value B_L in the lobe region. A uniform dawn to dusk electric field E_y is imposed on the plasma sheet. The forced current sheet has a finite B_n.

The dispersion relation for the ion tearing instability of a thin current sheet embedded in a thick plasma sheet, taking into account the effects of electron dynamics and the perturbed electric field potential Φ_1, can be derived by the matching of the inner and outer layer solutions at $z = \pm a$ which defines the boundary of the inner layer (Lakhina 1993; Burkhart *et al.* 1992b).

The analysis of the dispersion relation shows that the most unstable situation for the ion tearing modes is realized when $\eta = 0$ (where η is the fraction of the electron population trapped in the singular layer), and the parameters a_i/L is large. In such cases the imposed electric field, E_y, will enhance the ion tearing instability of the forced current sheet.

2.1. *Application to substorms*

For some typical parameters relevant to the substorms, ion tearing mode instability analysis predicts that $\eta \sim$ 10-20%, can either completely stabilize the mode or reduce its growth rate to such low value that for all practical purposes the forced current sheet can be considered as stable. Hence the disruption of the current-sheet and the formation of the substorm current wedge cannot occur under this situation. We can envisage the following scenario where the forced current sheet can become tearing unstable, leading to the formation of near earth neutral line and the diversion of current to the ionoshpere :

Let us have a situation where the current in the inner current sheet is locally strong enough to excite some plasma instabilities, e.g. lower-hybrid type instabilities. These instabilities would generate turbulence which can scatter the electrons of the inner layer (The same job could possibly be done by the background turbulence present in the central plasma sheet, for example low frequency turbulence). This would effectively result in all the electrons having untrapped orbits. Then the plasmasheet configurations with inner current sheet could easily become unstable. In such a case the onset of the expansion phase of the substorm could be identified with curent sheet becoming tearing unstable.

2.2. *Application to solar flare*

Direct observation of interconnecting coronal loops in soft X-ray indicate that loop coalescence may be an important process for solar energy release (Howard & Svestka 1977). Coalescence instability has been suggested as a likely cause for the impulsive release of solar flare energy. This process works only when B_p (poloidal field) $\geq B_T$ (toroidal field) (Tajima *et al.* 1985). Following scenario for solar flare energy release is proposed :

Two nearby coronal loops (figure 2a) are distorted by the large scale vortex flows; they are pushed against each other resulting in the formation of a forced current sheet (figure 2b). This current sheet becomes ion tearing unstable when the electron orbits become untrapped due to scattering from the background turbulence present in the solar atmosphere. A chain of magnetic islands are created, which coalescence at a rate (i.e., Alfven time scale) much faster than the ion tearing instability growth rate and release huge amount of energy.

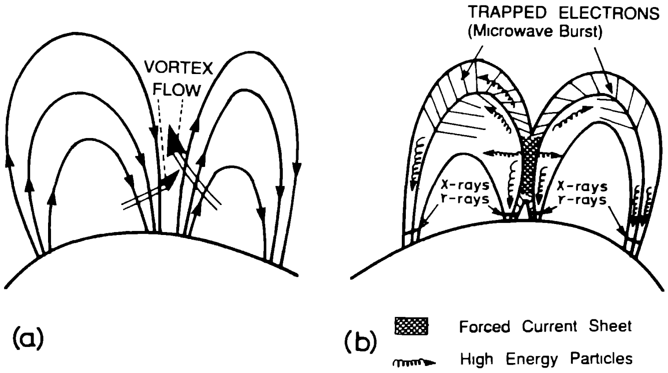

Figure 2. Schematic model for impulsive release of solar flare from coalescence of two loops (figure 2a) which are deformed by the large scale vortex type flows to form strong forced current sheets (figure 2b). Disruption of the current sheets forms chain of islands which coalescence and release large amount of flare energy on the Alfven time scale (~1 minute or so).

2.3. *Coronal transients*

Coronal transients are closely associated with two-ribbon flares. Scenario for coronal mass ejections [modified Pneuman (1980) model] is depicted below :

A single flaring loop (figure 3a) is distorted by the large scale flows so that a curent sheet is formed at a place where the loop is pinched (figure 3b). Disruption of the current sheet initiates the magnetic reconnection process which leads to two-loop structure, namely a lower loop connected to the solar surface (the flare loop), and an upper loop (plasmoid). The plasmoid finally gets disconnected and pushed outwards forming coronal transients or mass ejections.

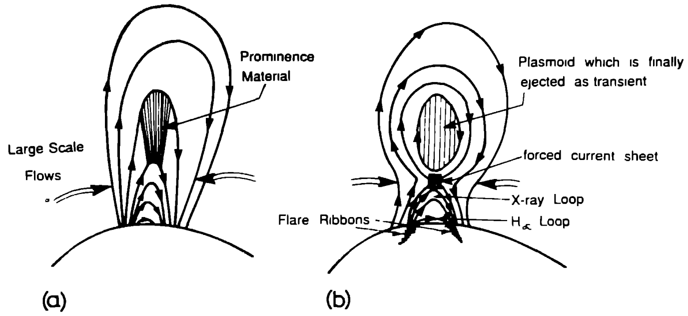

Figure 3. Schematic model for coronal transients. The initial flaring coronal loop structure (figure 3a) is deformed and pinched by the large scale flows forming a forced current sheets (figure 3b). The disruption of the curent sheet leads to the formation of inner fixed loop and a plasmoid. The latter is ejected as a coronal transient.

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