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Explosive Energy Release by Disruption of Current Sheets

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Abstract

Current sheets can occur in almost all cosmic plasmas like planetary magnetospheres, stars, and galaxies. The disruption of current sheets releases the excess magnetic energy stored in the plasma system via magnetic reconnection. Ion tearing mode instability can cause spontaneous disruption of the forced current sheets. It is found that trapped electrons have a strong stabilizing effect on the excitation of this instability. The presence of background turbulence can effectively lead to the untrapping of the electron orbits and thus, facilitate excitation of ion tearing instability. The role of current sheet disruptions in magnetospheric substorms, solar flares and coronal transients are discussed.

1. Introduction

The geospace environment is dominated by disturbances produced directly by the Sun, like solar flares and coronal mass ejections which are responsible for large geomagnetic storms [1] and interplanetary Alfv́en waves which are linked to substorms [2] occurring within the magnetosphere that are ultimately caused by the solar wind variations. A large portion of the energy extracted from the solar wind is stored in the form of excess magnetic flux in the magnetotail region, which subsequently is explosively released in the form of energetic particles and strong plasma flows [3] and dissipated in the near-Earth nightside region; this phenomenon is called a magnetospheric substorm. During substorm activity, the cross-tail current is disrupted and diverted towards the ionosphere as field-aligned current, and a part of the plasma sheet is severed from the earth, forming a "plasmoid" that flows out tailwards. There is an enhancement in the ring current and westward electrojet current, and in the auroral activity. Frequent occurrences of the substorms can give rise to geomagnetic storms. Magnetospheric substorms and major geomagnetic storms can produce intense, highly disruptive surges in energetic particle populations in the magnetosphere and rapidly-varying ionospheric-magnetospheric currents that can either completely paralyze or adversely affect the functioning of modern satellite and large power distribution grids on the ground [4].

Current sheets, similar to the plasma sheet at the center of the Earth's magnetotail, play a crucial role in many astrophysical situation requiring intense dissipation of magnetic energy into thermal and flow energy of the plasma. The process by which this conversion of energy is achieved is known as magnetic reconnection. During the reconnection process the magnetic field configuration is changed as the plasma attains a new equilibrium having less free energy than before. A prototype of spontaneous reconnection is the tearing instability of the planar neutral sheet. Current sheets can occur in almost all cosmic plasmas. For example, the current sheets in the bipolar magnetic regions on the sun and other stars could arise simply because of the continual mixing and swirling of the foot points of the magnetic field line in the subphotospheric/photospheric convection. The current sheet are expected to be created in magnetic field of galaxies and within cluster of galaxies.

Explosive energy released during a disruption of the Earth's plasma sheet can lead to magnetosphere substorms [5–6]. Similarly, 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 [7] has suggested that the X-ray corona and much of the region of a steller flare could be due to a 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 [8], coronal mass ejections [9], solar flares [10], microwave solar bursts [11], and comet-tail disconnection events [12–13].

It is customary to treat the current sheets as tangential discontinuities without any flow. However theoretical analyses and simulation studies show that when topologically different parts of a magnetic configuration are pushed together either due to convection, slowly changing boundary conditions, or vortex flows induced by some macroscopic instability, a thin forced current sheet may form in the center of the ambient current sheet [14]. The forced current sheets carry strong currents, have a thickness of the order of an ion Larmor radius, and are characterized by a finite B_n, the component of the magnetic field normal to the current sheet, as has been observed during the growth phase of the substorm in the earth's magnetotail [15]. Similar forced thin current sheets are likely to be formed in the solar atmosphere and in other astrophysical plasmas. Once the forced current sheets are formed, they would play crucial roles in the process of energy release. Hence it is of practical interest to investigate the stability of the forced current sheets in order to understand the processes of substorm onset, solar flares energy release etc.

2. Ion tearing instability of a forced current sheet

The tearing mode instability is believed to play an important role during substorms onset [16–22]. The thin current sheet observed during the growth phase of a substorm in the magnetotail (cf. Fig. 1) is characterised by a half-thickness, a, which is much smaller than the half thickness of the plasmasheet L. The strong current within this embedded sheet in

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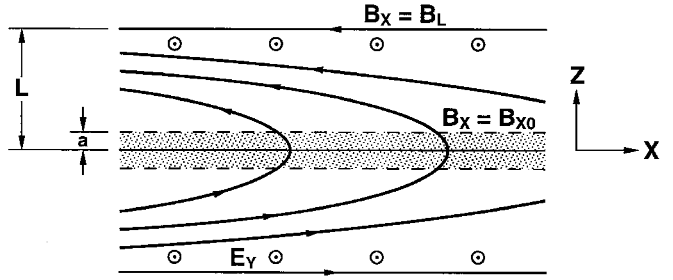

Fig. 1. Schematics of the two dimensional configuration of the earth's plasma sheet with an embedded forced current sheet at the center. The plasmasheet has a characteristic dimension of $2L$ and the forced current sheet (hatched region) has a half thickness of a. The x-component of the magnetic field 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 (taken from Lakhina [21] with permission from American Geophysical Union).

not due to a 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.

One can model the forced current sheet by assuming a self-consistent equilibrium, i.e., z-dependent current sheet with a constant normal component of the magnetic field, $B_z = B_n$, and a constant uniform dawn-to-dusk electric field, E_y [14]. The entire forced thin current sheet can be treated as an inner layer, and the rest of the region as an outer layer (see Fig. 1).

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 [21–23]. The dispersion relation is given by

$$\frac{\omega}{kv_D} = \frac{iX}{(1 - X^2)^{1/2}}. \tag{1}$$

where

$$X = (G + Q) \pm [(G - Q)^2 + (32\eta a_i^2 \varepsilon^{5/2}/15a^{5/2}k^{1/2})]^{1/2}, \tag{2}$$

and

$$G = \frac{\bar{a}_i^2(1 + T_e/T_i)}{\pi\bar{k}\bar{\lambda}_0 \operatorname{sech}^2 \bar{z}_0}\left[\frac{\operatorname{sech}^2 \bar{z}_0}{(1 + \tanh \bar{z}_0/\bar{k})} - \bar{k}^2(1 + 2\bar{k}\bar{a}) - \left(\bar{k}\bar{a}(1 - \eta) + \frac{8^{1/2}\eta}{15(\bar{k}\bar{a}\varepsilon)^{1/2}}\right)\frac{\pi T_e \bar{k}^2 \lambda_0 \operatorname{sech}^2 \bar{z}_0}{T_i \varepsilon^2 a(1 + T_e/T_i)}\right]. \tag{3}$$

The parameter Q is defined by $Q = (1 - T_i P_1/T_e)$, where

$$P_1 = \frac{k^2 a_e^2}{2\varepsilon^2} + \eta\left[1 + \frac{2^{1/2}\varepsilon^{5/2}}{3(ka)^{3/2}}\right], \tag{4}$$

and $v_D = cE_y/B_n$ is the $\boldsymbol{E} \times \boldsymbol{B}$ drift speed due to the dawn–dusk electric field, $\bar{a}_i = a_i/L$, $\bar{\lambda}_0 = \lambda_0/L$, and $\lambda_0 = c/\omega_{pi}$ being the ion inertial length outside the inner current sheet. Further, $\varepsilon = B_n/B_{x0}$, $a_e = (V_{te}/\Omega_e)$, is the electron gyroradius, $\Omega_e = (eB_{x0}/cm_e)$ is the electron gyro-frequency, $V_{te} = (2T_e/m_e)^{1/2}$ is the electron thermal speed, and η is the fraction of trapped electron population in the inner layer. The parameter $\bar{z}_0$ is determined by the relation

$$\tanh(\bar{z}_0) = B_{x0}/B_L, \tag{5}$$

Furthermore, we have used the appropriate relations, to correlate the equilibrium ion density in the inner region with that of the outside region [16, 18].

The ion tearing instability exists (i.e., $\gamma = \operatorname{Im} \omega > 0$) provided $X > 0$. In Figs 2 and 3, we have shown the normalized growth rate $\bar{\gamma} = (\gamma L/V_{ti})$ of the ion tearing instability against the normalized wave number $\bar{k}$ as calculated from eq. (1).

2.1. *Application to substorms*

Some typical substorm plasma parameters are: plasma sheet half-thickness $L \approx 0.5R_E$, $B_L = 20\,\mathrm{nT}$, and protons with energy $E_p \approx 10\,\mathrm{keV}$, giving $\bar{a}_i = 0.23$. Also, $n_0 = 0.1$–$0.4\,\mathrm{cm}^{-3}$, and $\bar{\lambda}_0 \approx 0.1$–$0.2$; $\bar{z}_0 = 0.3$, then $B_{x0} \approx 6\,\mathrm{nT}$, $\varepsilon = 0.1$ and $B_n = 0.6\,\mathrm{nT}$; and $v_D = (2$–$5)V_{ti}$ which corresponds to nominal values of $E_y \approx 2.0$–$6.0\,\mathrm{mV/m}$.

For these parameters, and for $v_D/V_{ti} = 2.0$, eq. (1) predicts the maximum ion tearing mode growth rate $\gamma = 7.0 \times 10^{-2}\,\mathrm{rad\,s^{-1}}$ (occurring at $\bar{k} \sim 0.2$), $8.4 \times 10^{-3}\,\mathrm{rad\,s^{-1}}$ (occurring at $\bar{k} \sim 0.03$), and $2.4 \times 10^{-3}\,\mathrm{rad\,s^{-1}}$ (occurring near $\bar{k} \sim 0.01$) respectively for $\eta = 0.0$, 0.05 and 0.1. Further, the range of unstable $\bar{k}$ is also reduced as η increases. Hence the presence of trapped electrons in the inner current sheet has a strong stabilizing effect on the ion tearing modes. Another interesting effect arising out of the presence of trapped electrons is evidenced by the change in behaviour of the parameter (v_D/V_{ti}) from de-

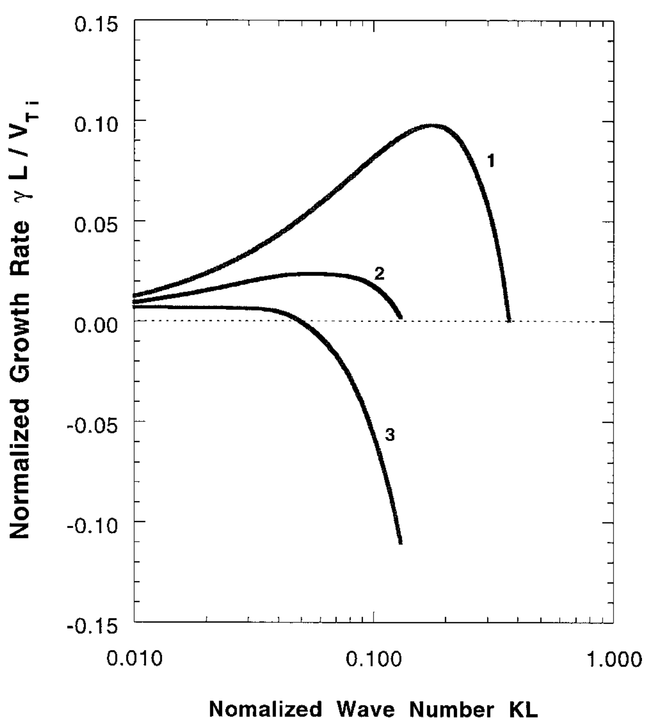

Fig. 2. Variation of normalized growth rate $\gamma L/V_{ti}$ versus normalized wave numbers $\bar{k} = kL$ for ion tearing instability of the two dimensional magnetotail with an embedded current sheet. The plasma parameters are $\bar{a}_i = a_i/L = 0.25$, $v_D/V_{ti} = 2.0$, $T_i/T_e = 10.0$, $\varepsilon = B_n/B_{x0} = 0.1$, $\bar{z}_0 = z_0/L = 0.3$ and for $\eta = 0.0$, 0.05, 0.1 for the curves 1, 2 and 3 respectively. In Figs 2 and 3, η represents the fraction of trapped electron population in the inner sheet relative to the total electrons number density (after Lakhina [21] with permission from American Geophysical Union).

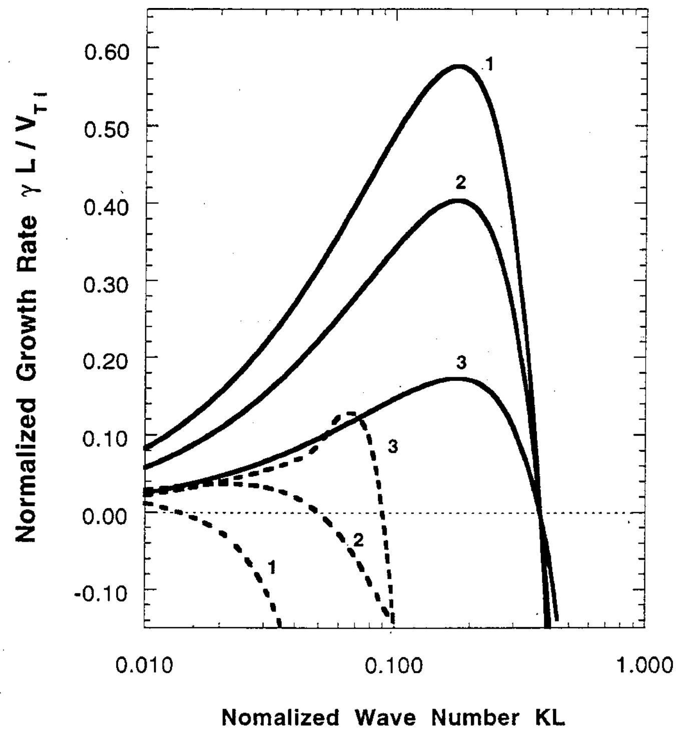

Fig. 3. Same as Fig. 2 and for $v_D/V_{ti} = 10.0$, 7.0 and 3.0 respectively for the curves 1, 2 and 3. The solid curves are for $\eta = 0.0$ and the dotted (⋯⋯) curves are for $\eta = 0.01$ (after Lakhina [21] with permission from American Geophysical Union).

stabilizing (when $\eta = 0$) to stabilizing (when $\eta \neq 0$) (cf. Figs 2 and 3).

The most unstable situation for the ion tearing modes is realized when $\eta = 0$ (i.e., absence of trapped electrons), and $\bar{a}_i$ and (v_D/V_{ti}) are large. In such cases the imposed electric field will enhance the ion tearing instability of the plasmasheet having an embedded thin current sheet. A small trapped electrons population $\eta \sim 10$–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.

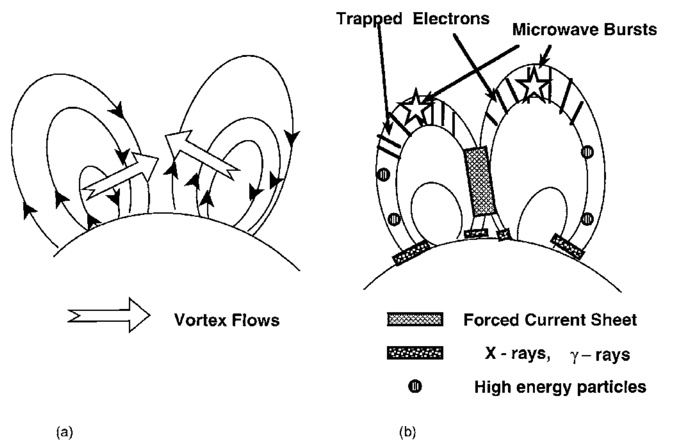

Fig. 4. Schematic model for impulsive release of solar flare from coalescence of two loops (a) which are deformed by the large scale vortex type flows to form strong forced current sheets (b). Disruption of the current sheets forms chain of islands which coalescence and release large amount of flare energy on the Alfvén time scale (∼1 minute or so) (taken from Lakhina [22]).

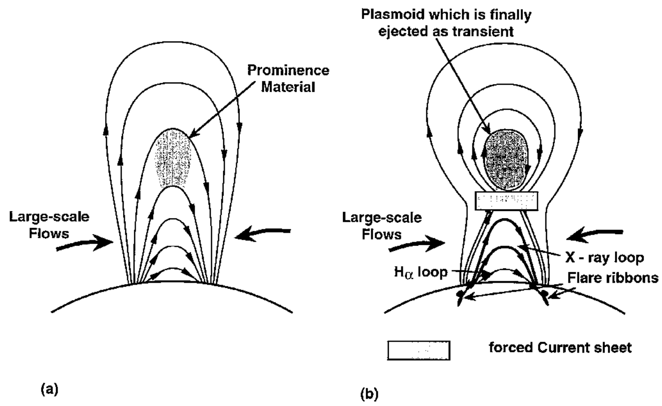

Fig. 5. Schematic model for coronal transients. The initial flaring coronal loop structure (a) is deformed and pinched by the large scale flows forming a forced current sheets (b). The disruption of the current sheet leads to the formation of inner fixed loop and a plasmoid. The latter is ejected as a coronal transient (after Lakhina [22]).

We can envisage the following scenario where the forced current sheet can become tearing unstable, leading to the formation of the near-earth neutral line and the diversion of current to the ionosphere. 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 of instability. These instabilities would generate turbulence which can scatter the electrons of the inner layer. (The background turbulence present in the central plasma sheet, for example low frequency turbulence, could lead to the same effect.) This would effectively result in all the electrons having untrapped orbits. Then the plasmasheet configurations with inner current sheet could easily become unstable provided the other parameters are favourable (cf. Figs 2–3). In such a case the onset of the expansion phase of the substorm could be identified with current sheet becoming tearing unstable.

2.2. *Application to solar flares*

Direct observation of interconnecting coronal loops in soft X-ray indicate that loop coalescence may be as an important process for solar energy release [24–25]. 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) $\simeq B_T$ (toroidal field) [26].

Following scenerio for solar flare energy release is proposed: Two nearby coronal loops [Fig. 4(a)] are distorted by large scale vortex flows; they are pushed against each other resulting in the formation a forced current sheet [Fig. 4(b)]. 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 much faster than the ion tearing instability growth rate (i.e., Alfvén time scale) and releases large amounts of energy.

2.3. *Coronal Transients*

Coronal transients are closely asssociated with two-ribbon flares. For a detailed description of the coronal transients and solar flare phenomena, one can refer to Švestka *et al.* [25]. Scenerio for coronal mass ejections (modified Pneuman [9] model as proposed by Lakhina [22]) is depicted below:

A single flaring loop [Fig. 5(a)] is distorted by the large scale flows suth that a current sheet is formed at a place where the loop is pinched [Fig. 5(b)]. Disruption of the current sheet initiates the magnetic reconnection process which leads to a two-loop structure, namely a lower loop connected to the solar surface (the flare loop), and an upper loop (plasmoid). The plasmoid finally gets disconnnected and pushed outwards, forming coronal transients or mass ejections.

3. Conclusion

We have shown that the excitaion of the ion tearing mode instability can lead to the disruption of the forced curreent sheets in space plasmas. It is found the trapped electrons have a strong stabilizing effect on the excitation of this instability. The presence of background turbulence can effectively lead to the untrapping of the electron orbits and, thus, facilitate excitation of ion tearing instability. Mechanism based on disruption of forced current sheet can provide new physical insight for the phenomena of magnetospheric substorms, solar flares and coronal transients.

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