The Significance of Tail Instabilities in Triggering Substorm Onset

M. I. Sitnov[1], A. S. Sharma[1], A. T. Y. Lui[2], P. H. Yoon[3], and P. N. Guzdar[4]

[1]Department of Astronomy, University of Maryland, College Park, MD 20742;
sitnov@astro.umd.edu, sharma@astro.umd.edu

[2]Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Rd Laurel, MD 20723-6099;
Tony.Lui@jhuapl.edu

[3]Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742;
yoonp@Glue.umd.edu

[4]Institute for Research in Electronics and Applied Physics, University of Maryland,
College Park, MD 20742; guzdar@glue.umd.edu

Abstract. Geomagnetotail is the main reservoir where the energy from the solar wind is accumulated and then suddenly released during substorms. Consistent with the modern results of the nonlinear data processing of the substorm activity, this release is described in terms of the appropriate plasma instabilities. It is shown that the tearing mode, resulting in the formation of the X-line, can be unstable for realistic ion-to-electron temperature ratios if the tail current sheet is long enough so that the electrons leaving it may be considered as transient particles. Closer to the Earth, where the change of the magnetic field topology is not favorable energetically, the perturbation of the current sheet may result in the formation of the Y-line, which does not change the original topology. The kinetic structure underlying the MHD Y-line is the thin current sheet (TCS). The corresponding Y-line reconnection is provided by the anomalous resistivity in TCS, which arises from instabilities with the perturbations primarily along the dawn-dusk direction. The kinetic nonlocal stability analysis of a class of such instabilities, including the drift-kink and lower-hybrid drift instabilities, shows that the onset of the Y-line reconnection is possible for some self-consistent TCS models, which are different from the Harris equilibrium.

1. Introduction

There are many models of substorm instabilities. However, none of them can determine if the substorm onset is actually an instability or it is just directly driven by the solar wind changes. This can be determined only on the basis of the experimental data in the form of some data-derived analog of the substorm dynamics. One such analog [*Sitnov et al.*, 2000a, 2001] has been recently derived from the Bargatze data set [*Bargatze et al.*, 1985] using the singular spectrum analysis (SSA) of the combined AL-vB_s data. In this technique a time delay is introduced to construct a multidimensional space from the original time series. Then the resulting extended set of the time series data is sorted to reveal their linear combinations, which are most essential to reproduce the dynamics of the system. SSA can be characterized as a multidimensional generalization of conventional linear filters [*Bargatze et al.*, 1985]. The first three principal SSA components represent roughly the solar wind parameter vB_s integrated over ~1 hour (I_1), its time derivative with similar time resolution (I_2), and time-integrated AL index (O). The substorm dynamics in these coordinates can be approximated as the motion on a two-level surface, which has a fold as shown schematically in Fig.1 (top panel). This averaged substorm dynamics resembles the motion of a point on the cusp catastrophe manifold [e.g., *Gilmore*, 1993] governed by the equation

$$dO/dt = -(d/dO)U(O, I_1, I_2)$$

while the folded surface is given by the equation $(d/dO)U(O, I_1, I_2) = 0$, where the potential *U(O)* may have two minima as shown in Fig.1 (bottom panel). The fast unloading process is represented in this model either as a disappearance of the upper local minimum in the process of the quasi-static loading or as a jump over the potential barrier under the action of the external trigger.

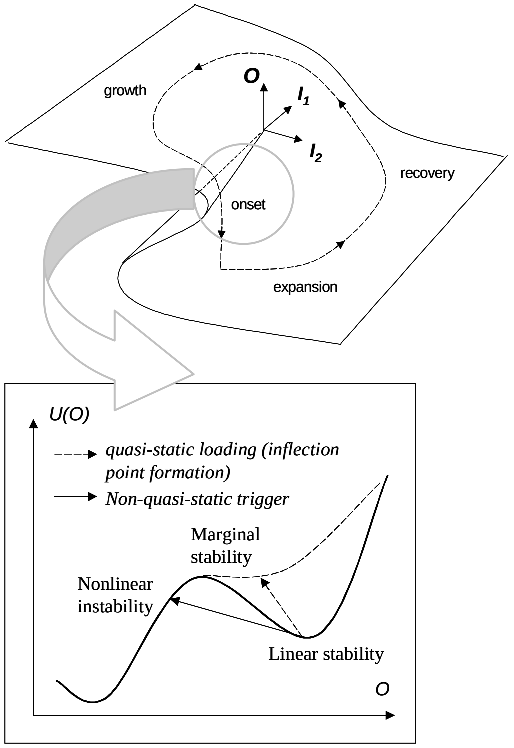

Figure 1. Sketch of the averaged evolution of the magnetosphere in the space of three principal SSA components (top panel), and the appropriate unloading regimes (bottom panel).

The evolution of the magnetosphere in the space *(I_1, I_2, O)* reveals both types of unloading. In particular, the *hysteresis* phenomenon near the onset [*Sitnov et al.*, 2000a, 2001] indicates that the magnetosphere during the growth phase may reach the "overheated" state, when the trigger amplitude is small. This means that it actually approaches the unstable branch of some plasma eigenmode, and the conditions of the transition to instability can be inferred from the linear theory. However, the linear growth rate may not reflect the unloading time scales as it approaches zero near the transition.

The above global dynamical image appears from the data as a mean-field picture, where many small-scale fluctuations are filtered out. They become essential however near the cusp point, where the deviations from the simple catastrophe model can be described in terms of the critical exponents [*Sitnov et al*, 2001], similar to those of the second order phase transitions [*Stanley*, 1971]. Note that the cusp catastrophe model, which had been first proposed for interpretation of substorms by *Lewis* [1991], is equivalent to the mean-field dynamical Ising model of nonequilibrium phase transitions [e.g., *Zheng and Zhang*, 1998]. Similar models of small-scale instabilities are used to describe the scale-invariant features of substorms in terms of the self-organized criticality [*Klimas et al*., 2000]. Thus the analysis of correlated input-output data indicates that the substorm onset does involve instabilities. The next question is whether these instabilities can be described using the present day equilibrium and stability models of magnetospheric plasmas.

2. Substorm instabilities and reconnection

During the growth phase of the substorm the magnetosphere accumulates the energy from the Sun mainly in the form of the magnetic field energy of the stretched tail. The release of this energy is known as magnetic reconnection. Magnetic reconnection is often associated with the formation of an X-line. This is however not the only possible scenario. Another one, current sheet or Y-line reconnection, which is also known as magnetic annihilation or merging, was proposed by *Syrovatsky* [1971] and later advocated by *Biskamp* [1986] (Fig.2). Y-line reconnection preserves the initial topology of the magnetic field, but violates the continuity of the system due to the formation of thin current sheet (TCS), which appears as the tangential discontinuity on the MHD level as its thickness is comparable or even less than the thermal ion gyroradius in the field outside TCS.

Both reconnection scenarios involve instabilities. In particular, the tearing instability provides the

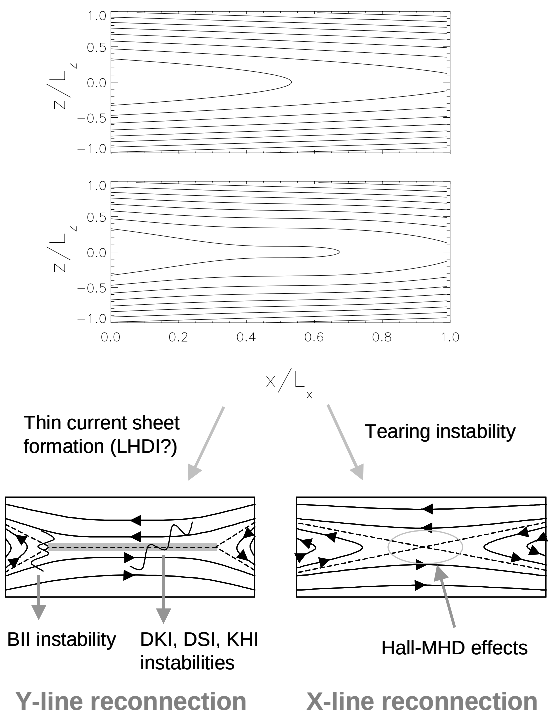

Figure 2. Different reconnection scenarios and some of the related substorm instabilities.

formation of the X-line in the initial stretched magnetic field. Its free energy source arises from the mutual attraction of parallel current filaments. The current-driven instabilities such as the drift-kink, drift-sausage, lower-hybrid drift and Kelvin-Helmholtz instabilities (DKI, DSI, LKDI, and KHI, respectively) describe the perturbations in the TCS along the dawn-dusk direction. Thus they preserve the initial magnetic field topology and are most relevant to the Y-line reconnection. Their main energy source is the kinetic energy of counter-streaming flows of ions and electrons as well as different motions of various populations of the same species including such effects as the bulk flow velocity shear. Another family of instabilities related to the Y-line reconnection is the ballooning interchange instability (BII) driven by the strong pressure gradient along the tail axis.

Below we describe some new results in the stability analysis of the tearing and current-driven instabilities, which show that both X- and Y-line reconnection onsets can be provided by these instabilities. The contemporary stability analysis has two distinctive features. It is now recognized that most of the substorm instabilities require very thin current sheets with the thickness *L* comparable to the ion gyroradius in the field outside the sheet ρ_{oi}. It is found also that the characteristic wavelength of the most unstable perturbations across the current sheet is often comparable to its thickness *L*. Both these features strongly complicate the stability analysis which has to be *kinetic* and *nonlocal*. One of the most appropriate tools for this analysis is the finite element method [*Sharma*, 1983; *Chen and Lee*, 1985; *Burkhart and Chen*, 1989; *Brittnacher et al.*, 1995, 1998; *Daughton*, 1998, 1999; *Sitnov et al.*, 2002].

3. Tearing instability

This instability, responsible for the onset of the X-line reconnection in tail-like magnetic field, was first considered for the collisionless plasma case relevant to Earth's magnetotail by *Coppi et al*. [1966] in the simplest geometry with antiparallel magnetic field lines [*Harris*, 1962]. Later it was found that prior to the substorm onset the tail magnetic field lines are not antiparallel but rather sharply curved due to the finite component B_n of the magnetic field normal to the sheet plane [*Fairfield and Ness*, 1970]. Then, assuming all the electrons were magnetized and trapped inside the current sheet, *Lembege and Pellat* [1982] obtained the sufficient stability criterion for the tearing mode in an isotropic current sheet to be $kLB_0 / B_n > 4/\pi$, where *k* is the wave number, *L* is the thickness of the sheet, and B_0 is the magnetic field outside it. This criterion is very restrictive as it coincides with the WKB approximation used in the stability analysis. The matter is that the magnetic field line tension in the isotropic current sheet equilibria with stretched magnetic field lines must be balanced by the pressure gradient along the direction of stretching, and the appropriate inhomogeneity scale $L_x \sim LB_0/B_n$ must exceed the WKB tearing wavelength. Attempts to explain tearing destabilization by the external diffusion or by dynamical chaos in electron orbits failed to do so [*Pellat et al*., 1991; *Quest et al*., 1996].

All authors, advocating the tearing stability in the case $B_n \neq 0$, considered electrons as a single fluid. Meanwhile, such an approach is not quite correct because the appropriate isotropic current sheet models, with the plasma density being constant along the field line, require the existence of a population of transient electrons. They can shield the stabilizing electrostatic potential created by differences in the motions of ions and trapped electrons. The effect strongly modifies the stability criterion $(3T_e/T_i)^2 kLB_0/B_n > 4/\pi$, making it much less restrictive [*Sitnov et al*, 1998]. The role of transient electrons was strongly underestimated earlier, based on the assumption that their number density is small. Indeed, the ratio of the local density of transient electrons and the total plasma density, $n^{(trans)}/n$, is small at the center of the sheet $n^{(trans)}/n \sim B_n/B_0$. However, tearing is a nonlocal mode, perturbing the entire current sheet. The simple estimate, valid for isotropic distributions and adiabatic electrons, gives the result $n^{(trans)}/n = 1 - \cos\theta_{\min}$, where $\theta_{\min}$ is the minimum pitch angle of trapped electrons and $\sin^2\theta_{\min} = B(z)/B_0 \approx \tanh(z/L)$. It shows that the ratio $n^{(trans)}/n$, averaged over the current sheet thickness $L<z<L$, is approximately constant, independent of B_n/B_0.

Attempts to resolve the tearing stability problem in configurations with $B_n \neq 0$ using particle simulations [e.g., *Pritchett*, 1994; *Pritchett et al*., 1997] are beset with problems such as the spurious temperature anisotropy at $T_i/T_e > 1$ and unrealistic mass ratios ($m_i/m_e \leq 64$). Besides, the simulation boxes in most simulations and the closely related linear stability analysis [*Brittnacher et al*., 1998] were too short to model transient particles, and the use of reflecting or reintroducing particle boundary conditions artificially made all electrons trapped.

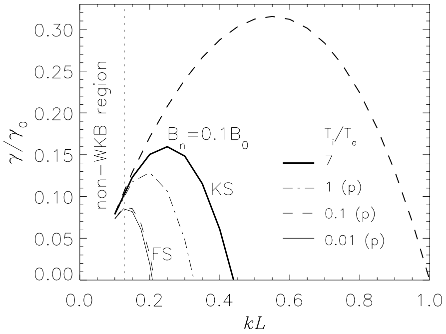

Figure 3. Tearing growth rate for isotropic current sheet with $L=\rho_{oi}$. *KS* and *FS* denote the solutions for realistic B_n and T_i/T_e and that in the fluid limit modeling the result of *Lembege and Pellat* [1982]. Dashed line corresponds to the solution by *Pritchett et al.* [1991].

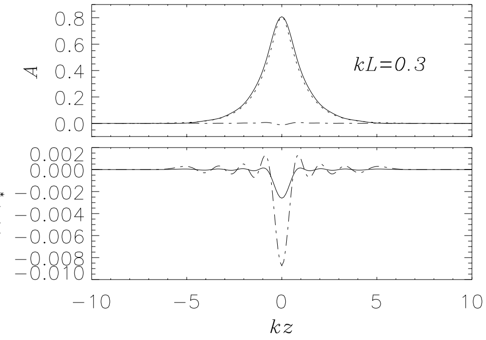

Figure 4. Real (solid line) and imaginary (dash-dotted line) parts of tearing eigenmodes for the case $L = \rho_{oi}$. $B_n = 0.1$, and $T_i/T_e = 7$. Dashed line represents the analytical solutions by *Pritchett et al.* [1991]. $\phi_* = (B_0/B_n)u_i/c$, where u_i is the ion drift velocity.

Thus, until recently the tearing stability problem remained open. The result of *Sitnov et al.* [1998], relaxing the criterion derived by *Lembege and Pellat* [1982], was still based on a sufficient stability condition and a simplified energy principle, and it did not reveal the actual stability threshold. The explicit solution of the problem using the finite element approach and taking into account transient electrons, has been proposed by *Sitnov et al.* [2002]. The main results of this nonlocal kinetic stability analysis are shown in Figs.3 and 4 in terms of the tearing growth rate and eigenfunctions. Fig.3 shows in particular that the tearing mode can be unstable within the WKB region $kLB_0/B_n>4/\pi$ for the temperature ratio $T_i/T_e = 7$ typical for the geomagnetotail current sheet. The unstable solutions are compared in Fig.3 with the earlier result of the TCS stability analysis of *Pritchett et al.* [1991], where the stabilizing effect of trapped electrons was completely neglected: $\gamma = \gamma_0 kL(1 + kL/2)(1 - kL)$, where $\gamma_0 \approx (2/3\sqrt{\pi})\omega_{oi}(\rho_{oi}/L)^3$, and ω_{0i} is the ion gyrofrequency in the field B_0 outside the sheet (similar estimate for thick current sheets was obtained earlier by *Schindler* [1974]). Previous results of *Lembege and Pellat* [1982] for the case $B_n \neq 0$ were mimicked in this analysis by reducing the parameter T_i / T_e in the Poisson's equation (index (p) in Fig.3). It has been found that in the limit $T_i / T_e \rightarrow 0$ the unstable region is actually reduced down to the non-WKB one. Note that the eigenmodes shown in Fig.4

$$A_y(x,z) = A(z)e^{\gamma t+ikx}, \phi(x,z) = \phi(z)e^{\gamma t+ikx}$$

are consistent with similar nonlocal solutions found in the fluid model [*Harrold et al.*, 1995] for the case of finite resistivity (their Fig.4), which in our case is provided by the ion Landau dissipation.

To unveil the nature of the destabilization mechanism responsible for the onset of the X-line reconnection, the results of the stability analysis have been compared to the earlier two-fluid analysis [*Galeev*, 1984]. This comparison shows, that the onset is controlled by the Hall effect and its entirely kinetic analog arising from different responses of trapped and transient electrons to the tearing perturbation.

The above results are not at variance with the alternative Y-line reconnection scenario and the corresponding models of substorms, with the emphasis on the processes in the transition region between the dipole and tail-like magnetic fields. The key issue is that the length of this transition region is comparable to the current sheet thickness. As a result, all particles, which leave the current sheet, will be reflected right away from the dipole field region and thus be effectively trapped. This is exactly the situation where the assumptions of the model [*Lembege and Pellat*, 1982] are valid and the change of the topology is forbidden. In this case, according to *Syrovatsky* [1971], *Kulsrud and Hahm* [1982], and *Schindler and Birn* [1993] any perturbations of the tail current sheet should result in the violation of continuity, that is, the formation of TCS. This picture is consistent with spacecraft observations. Geotail measurements showed that the formation of the near-Earth neutral line during substorms usually starts in the premidnight sector of the magnetotail between $X_{GSM} = 20R_E$ and $X_{GSM} = 30R_E$ prior to an onset signature identified with Pi 2 pulsations on the ground [*Nagai et al.*, 1998]. On the other hand, thin current sheets are detected as a distinctive feature of the near-Earth magnetotail between $X_{GSM} \sim 7R_E$ and $X_{GSM} \sim 18R_E$ prior to and during substorms [e.g., *Sergeev et al.*, 1998 and refs. therein]. Thus it appears that both types of the reconnection, involving the formation of X- and Y-lines happen in the Earth's magnetosphere.

4. Current-driven instabilities

The first most extensively studied instability of this class is the lower-hybrid drift instability (LHDI) [*Huba et al.*, 1981]. However, LHDI is most unstable at the edge of current sheet and it can hardly affect the central region. Later *Lui et al.* [1991] and *Yoon and Lui* [1996] proposed another class of instabilities, the cross-field current instabilities (CFCI), driven by different dynamics of unmagnetized ions and magnetized electrons at the center of the current sheet. At the same time, simulations [*Pritchett and Coroniti*, 1996; *Zhu and Winglee*, 1996] revealed the drift kink instability, which strongly distorted the main equilibrium current like the CFCI does. *Lapenta and Brackbill* [1997] also found the drift-sausage instability, which had the opposite parity with respect to DKI (even profile of the dawn-dusk component of the electromagnetic potential). However, *Daughton* [1998, 1999], having performed the nonlocal kinetic linear stability analysis of DKI, DSI and LHDI modes, reported no evidence of DSI. This analysis and later particle simulations [*Hesse and Birn*, 2000; *Pritchett and Coroniti*, 2001] revealed also a strong decrease of the DKI growth rate with the increase of m_i / m_e making this mode irrelevant for the realistic case with $m_i / m_e = 1836$. Trying to reconcile his finding with the other simulation results *Daughton* [1999] demonstrated that the cause of the high DKI growth rate might be the background population of ions. That finding was consistent with the earlier results [*Yoon and Lui*, 1996; *Yoon et al.*, 1996] that current-driven instabilities may survive for the realistic mass ratio due to the bulk flow velocity shear in the initial TCS equilibrium. Moreover, some recent simulations [*Hesse et al.*, 1998; *Horiuchi and Sato*, 1999; *Shinohara et al.*, 2001; *Lapenta and Brackbill*, 2002] revealed the formation of such current sheet profiles with the bulk flow velocity shear as a nonlinear effect of LHDI with subsequent excitation of DKI or KHI.

Deviations from the Harris-type TCS induced by LHDI may be consistent with some laboratory experiments [*Carter et al.*, 2002]. However, no such LHDI precursors are detected yet in the tail prior to substorms. One can propose however another model of the Y-line reconnection onset and related current-driven instabilities. It becomes possible due to a new class of self-consistent TCS equilibria, where the magnetic field line tension is balanced by the ion inertia of counter-streaming ion flows, in contrast to the modified Harris sheet with $B_n \neq 0$, where it is balanced by the pressure gradient. Such TCS, known as forced current sheets, may arise when the dawn-dusk electric field penetrates the sheet and accelerates ions. Strong evidence that such processes really occur in the near-Earth tail prior to substorm has been reported by *Ohtani et al*. [2000].

The self-consistent model of the forced TCS was recently elaborated by *Sitnov et al*. [2000b,c]. Its distinctive features, which are consistent with TCS observations, are the small thickness $L \sim \rho_{0i}$, the embedded structure and the corresponding bulk flow velocity shear. All these features must be favorable for the current-driven instabilities. Besides, forced current sheets have the characteristic bean-shaped distributions at the center of the sheet, which appear in the near-Earth tail prior to the onset of the current disruption [*Lui*, 2002]. Another advantage of this new class of TCS models is that their theory can be presented in the form similar to that of the Harris sheet (in particular, the magnetic field is presented in the form $B=(B_x,0,B_n)$, with $B_x=B_0b(z/L)$, where *b* is the universal function similar to the hyperbolic tangent one in the case of Harris), which is most suitable for the kinetic nonlocal stability analysis. The first results of this analysis are shown in Figs.5 and 6. The key parameters of the equilibrium model are the temperature ratio and the ratio between the bulk flow speed of counter-streaming ion flows outside the sheet and the thermal ion speed v_D/v_{Ti}. Fig.5 shows that the growth rate does not decrease with the increase of the mass ratio for such equilibria. A possible explanation of this effect may be the structure of the unstable eigenmodes

$$A_{y,z}(x,z) = A_{y,z}(z)e^{\gamma t+iky} ,$$

shown in Fig.6 (for this particular run we neglected the electrostatic effects and used the Coulomb gauge $ikA_y + \partial_z A_z = 0$). This figure shows that the unstable solution is a mixture of DKI and LHDI modes, and most likely, its free energy source is the bulk flow velocity shear of the ion species which is maximum outside the neutral plane z=0. These results are consistent with the fluid analysis of *Yoon et al.* [2002], indicating the domination of higher-order DKI modes for realistic mass ratio.

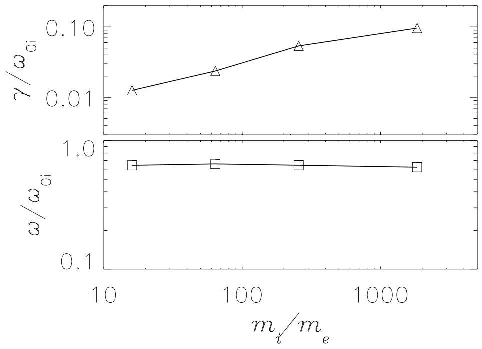

Figure 5. Growth rate and frequency of the current-driven instability of forced TCS as functions of the mass ratio. *kL=0.1*, $T_i/T_e=1$, $v_D/v_{Ti}=3$, $L=0.69\rho_{0i}$.

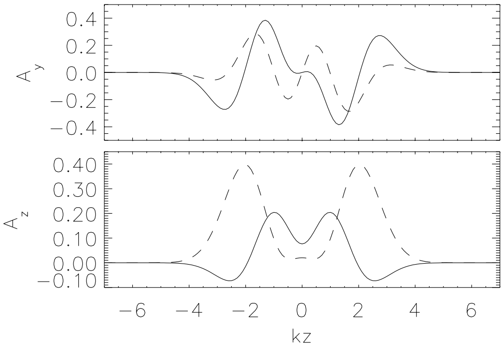

Figure 6. Real (solid line) and imaginary (dashed line) parts of the unstable plasma eigenmodes shown in Fig.5 for the case $m_i/m_e = 1836$, $\gamma/\omega_{0i} = (0.096,-0.62)$.

5. Conclusion

Thus, we have shown that the release of the energy accumulated in the magnetotail involves internal instabilities. This release, both in the form of the X-line reconnection onset with the change of the initial topology of the magnetic field and in the form of the Y-line reconnection onset with no topology changes can be described in terms of the appropriate instabilities of the collisionless plasmas. This description requires however taking into account fine kinetic features of the tail current sheet equilibrium and dynamics.

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