Inherently three dimensional magnetic reconnection: A mechanism for bursty bulk flows?

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[1] We examine the development of mesoscale structure during 3-D magnetic reconnection which initiates from random perturbations. Reconnection develops as multiple x-line segments with characteristic scale lengths of $\sim$1–4 R_e in the cross tail direction. For relatively wide initial current sheets (several c/ω_{pi}), these finite length x-lines remain spatially isolated and drive reconnection which is strongly reminiscent of bursty bulk flows (BBFs) in the magnetotail. In narrower initial current layers the x-line segments merge together to a state in which large scale magnetic energy release takes place. Thus, the degree of compression of the magnetotail may ultimately determine if energy is released in local bursts or globally as a substorm. *INDEX TERMS:* 7835 Space Plasma Physics: Magnetic reconnection; 2744 Magnetospheric Physics: Magnetotail; 2753 Magnetospheric Physics: Numerical modeling. **Citation:** Shay, M. A., J. F. Drake, M. Swisdak, W. Dorland, and B. N. Rogers, Inherently three dimensional magnetic reconnection: A mechanism for bursty bulk flows?, *Geophys. Res. Lett.*, *30*(6), 1345, doi:10.1029/2002GL016267, 2003.

1. Introduction

[2] Magnetic reconnection plays an important role in the dynamics of the magnetosphere, the solar corona, and laboratory experiments by allowing magnetic energy to be released in the form of heating and bulk acceleration of the plasma. Although much progress has been made in understanding reconnection in 2-D systems, physical systems have three dimensions and cannot form infinitely long x-lines. In the magnetotail, for example, bursty bulk flows (BBFs) are believed to be the primary means of energy and flux transport in the near-Earth neutral sheet (15–23 R_e) [*Angelopoulos*, 1996]. These flows, however, are not laminar like those seen in two dimensional simulations. Instead, BBFs are spatially and temporally limited, typically lasting about 10 minutes and being composed of minute-long bursts [*Baumjohann et al.*, 1990]. Significant differences in structure have been measured by satellites whose cross tail separation is from 3 R_e [*Angelopoulos et al.*, 1997] to 10 R_e [*Slavin et al.*, 1997]. If reconnection drives BBFs, magnetic x-lines must form with finite length in the cross tail direction.

[3] In this study we explore whether a one-dimensional Harris equilibrium can spontaneously develop and sustain collisionless reconnection with significant structure in the cross tail direction. In earlier full particle simulations reconnecton became nearly two-dimensional even when initialized from random perturbations [*Pritchett*, 2001; *Hesse et al.*, 2001]. These simulations, however, were carried out in relatively small systems with $L_y \sim 10\ c/\omega_{pi}$. The three dimensional structure of collisionless reconnection at larger spatial scales remains uncertain.

[4] Using a two fluid code we explore reconnection in a three dimensional mesoscale system with an initially uniform equilibrium current sheet. Here "mesoscale" denotes a system with an overall size much smaller than that of the magnetotail, but much greater than the microscales associated with 2-D reconnection. We find that spontaneous (starting from random noise) reconnection self-organizes into an inherently 3-D state, with multiple finite length x-lines which are localized in the cross tail direction *y*. In relatively wide current sheets (several c/ω_{pi} wide in which the growth of magnetic islands is weak), spontaneous reconnection occurs in relatively isolated x-line segments with a typical cross-tail length of 10 c/ω_{pi}. These "solitary x-lines" are strongly reminiscent of pseudobreakups or BBFs and are consistent with the inferred scale sizes of the latter from multisatellite observations [*Angelopoulos et al.*, 1997; *Slavin et al.*, 1997]. In narrower current sheets ($\leq c/\omega_{pi}$), the reconnection again develops 3-D structure but becomes global as closely packed finite-length x-lines merge together to produce extended overlapping regions of reconnection. To understand these results we have carefully explored the rate of spread and/or propagation of isolated nonlinear x-line segments in the *y* direction.

2. Simulations

[5] Simulations were completed using the two-fluid F3D code, which includes both the Hall term and the electron inertia in Ohm's law [*Shay et al.*, 2001a]. In the code time and space are normalized to $t_0 = \Omega_i^{-1} = (eB_0/m_ic)^{-1}$ and $L_0 = c/\omega_{pi} = \sqrt{c^2 m_i/(4\pi n_0 e^2)}$, with the magnetic field and density in the lobes initially B_0 and n_0. We make the isothermal assumption with $T = T_e + T_i = 1.0$. To prevent energy buildup at the grid scale, we have included fourth order ∇^4 dissipation in each of the equations.

[6] The initial equilibrium consists of a double current sheet with a magnetic field $B_x(z) = \tanh[(z + L_z/4)/w_0] - \tanh[(z - L_z/4)/w_0] - 1$. For $w_0 \ll L_z$ the system can be taken to be periodic in all directions. The density rises to 1.5 n_0 at the center of the current sheets to balance the magnetic pressure. All of the initial current is carried by the electrons.

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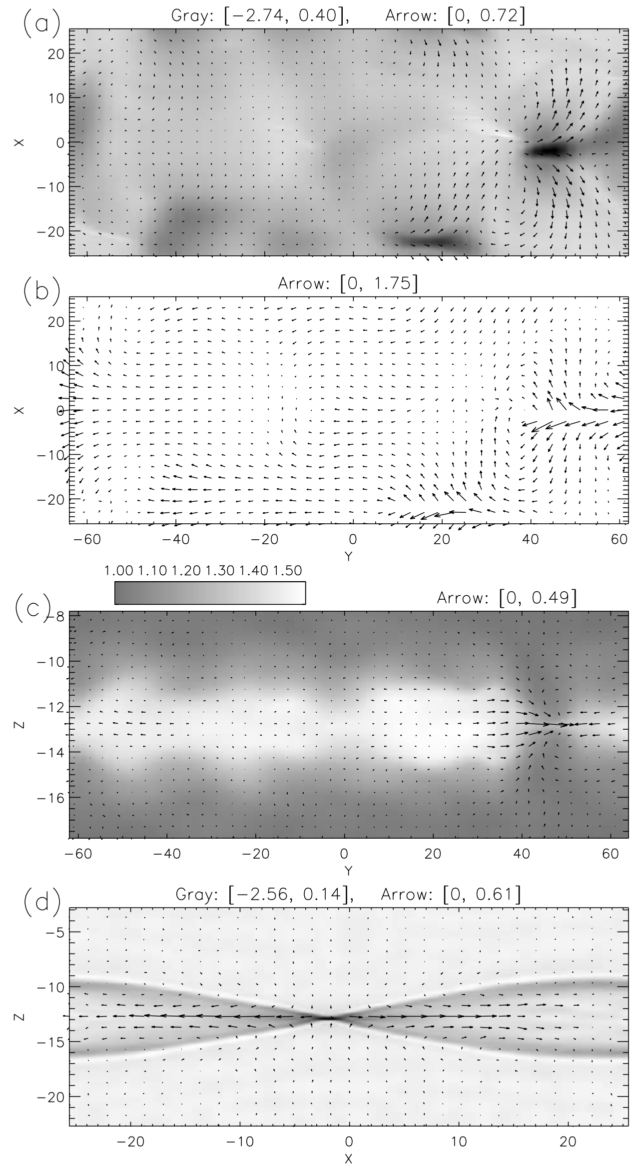

Figure 1. 3-D structure at $t = 212.0$ for a simulation with $w_0 = 2.0$. In (a) and (b) the (x, y) plane in a cut through one of the current layers ($z = -12.8$): (a) grayscale of $-J_y$ with ion velocity vectors; and (b) electron velocity vectors. Vectors in (a) and (b) are normalized the same. In (c) the density and ion velocity vectors in the (y, z) plane at $x = -2$. In (d) $-J_y$ and ion velocity vectors in the (x, z) plane at $y = 44$.

In the simulations presented $w_0 = 0.5$, 1.0, or 2.0, and the electron to ion mass ratio $m_e/m_i = 0.04$. The simulation size is $(L_x, L_y, L_z) = (51.2, 128, 51.2)$ with grid scale lengths $(\Delta_x, \Delta_y, \Delta_z) = (0.1, 2.0, 0.1)$. To ensure that the stretched grid in the y direction is not affecting the results of this paper, we have completed test runs with two different values of Δ_y and found no significant differences. At each grid point, random perturbations were added to each component of the ion current. Random perturbations to B_x and B_z were added using 3-D Fourier modes with a random phase and a $1/k$ amplitude dependence.

[7] For systems in which $L_y \gg 10\ c/\omega_{pi}$, the global reconnection dynamics ceases to be two dimensional. Finite length x-lines develop in time and nonlinearly interact. In Figure 1 are results from a simulation initiated with $w_0 = 2.0$ and random perturbations with $|\tilde{\mathbf{B}}|_{max} \approx 0.2$ and $|\tilde{\mathbf{J}}_{\rm ion}|_{max} \approx 0.2$. In a 2-D simulation the usual reconnection inflow and outflow directions are along z and x, respectively.

[8] An x-line is a boundary layer with $|J_y|$ large. In Figure 1a, the x-lines therefore appear as dark blobs or lines. At this time, two strong x-lines have formed, one centered at $(x, y) \approx (-23, 18)$ and the other at $(-2, 44)$. Both of these x-lines have coupled to the ions and therefore exhibit strong ion flows. The electrons in Figure 1b have been accelerated by the reconnection electric field at the two x-lines to super-Alfvénic speeds. For $y < 10$, no strong x-lines and associated ion flows have developed and the electron current has only modest perturbations. A cut through the right x-line in Figure 1a reveals the conventional current and flow patterns from reconnection (Figure 1d). Thus, for $w_0 = 2.0$ the release of energy is spatially localized rather than global, as inferred from observations of BBFs. The system appears to be marginally stable to x-line growth, and only in particular regions are the perturbations able to grow into nonlinear x-lines. For this case, when the size of the initial random perturbations are reduced significantly, no x-lines grow to finite amplitude for the limited duration of the simulation.

[9] If the current sheet width w_0 is reduced to 1.0, as shown in Figure 2, reconnection becomes global while retaining residual three dimensional structure. At early time x-lines form at apparently random locations and begin to lengthen in the y direction. By $t = 60.0$, nearly every y plane has only one well developed x-line whose outflows along the x direction have swept downstream and "defeated" the other x-lines in its y plane. At this point in time, the x-line segments have just started to interact with x-lines in neighboring y locations. X-lines close to one another in the y direction tend to join, and by $t = 96.0$, the x-lines located in the range $-40 < y < 0$ have merged together to

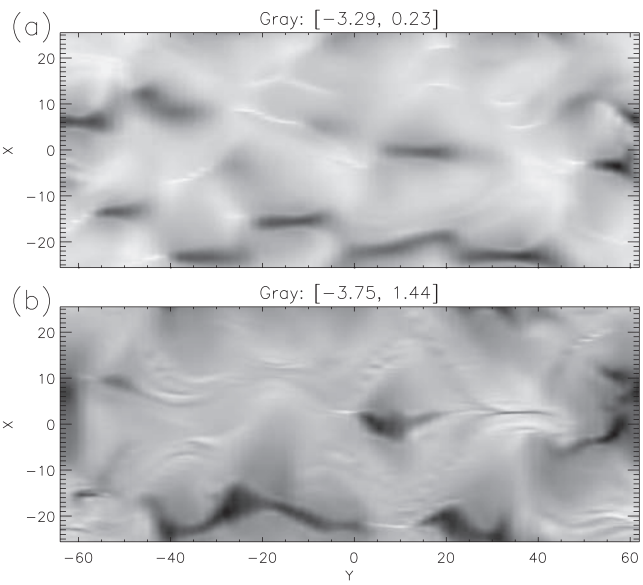

Figure 2. Results for the $w_0 = 1.0$ case. $-J_y$ at (a) t = 60 and (b) t = 96 in the (x,y) plane in a cut through one of the current layers ($z = -12.8.$).

form an extended x-line. The tendency of finite-length x-lines to merge along y is apparently a consequence of the continuity of the electron flow: electrons emerging from a current channel are diverted into a nearby channel to continue their high-speed flow, causing the two channels to merge.

3. Behavior of An Isolated X-Line

[10] Three dimensional x-line segments do not remain static, even after reconnection is strong enough to couple to the ions. They have a tendency to propagate and grow in length, usually in the direction of the electron flow, which generates the equilibrium current and which dominates the strong currents at the x-lines. Between Figure 2a and 2b, for example, the x-line segment centered at $(x, y) = (0, 14)$ grows in the negative y direction by about 5 c/ω_{pi}. This expansion is in the direction of the electron flow and is consistent with the electrons being frozen into the magnetic field except in a very narrow region of width c/ω_{pe} near the x-line. Similar results have been reported in previous two–fluid simulations [*Shay et al.*, 2001b; *Huba and Rudakov*, 2002].

[11] In order to gain more physical insight, we have studied the development of finite length (in y) x-lines growing on an otherwise uniform current sheet. The initial island is imposed from a conventional perturbation in the magnetic flux [*Birn et al.*, 2001] but localized in the y direction ($\sim\text{sech}^2(y/w_{0y})$) with $w_{0y} = 10.0$. This imposed x-line in all cases nonlinearly develops into a 3-D x-line which couples strongly to the ions. The dynamics of an isolated x-line depends strongly on the equilibrium current sheet width, w_0. To study the dynamics of finite-length x-lines, we define the "ends" of a developed x-line (in the y direction) by the locations where $|\mathbf{J}_y|$ falls below 2.5. The threshold 2.5 is half of the electron Alfvén speed, which is a measure of the peak electron flow speed during reconnection. The time dependence of the location of these ends, $y^{\pm}_{\text{end}}$ is plotted in Figure 3a for three values of w_0. The length of the x-line for $w_0 = 0.5$ (solid) grows the fastest, extending in both the negative and positive y direction. The rollover of lower end motion, y^{-}_{end}, after $t - t_i = 16.0$ is due to the interaction of the initially isolated x-line with other spontaneous x-lines that have formed from random noise. The $w_0 = 1.0$ case (dotted) shows substantial growth in the $-y$ direction, but very little growth along $+y$, except during an initial transitory phase. The case with $w_0 = 2.0$ exhibits pure convection in y with little or no net growth. The case with $w_0 = 2.0$ is therefore a constant-length, "solitary" x-line segment propagating along the current sheet in the cross tail direction.

[12] The time dependence of y^{-}_{end} is relatively straightforward to understand. In all the cases shown in Figure 3a this end propagates in the negative y direction (the direction of the electron flow). Near this end, where the reconnection is weak, the ions have not yet coupled with the electron flows and the magnetic perturbations are convected along y with the local electron velocity. Because the magnetic island has a width of several c/ω_{pi} along z, the convection velocity will be an average of the equilibrium electron flow, rather than simply the maximum electron velocity at the x-line. The magnitude of the initial electron velocity within the current sheet scales like $|V_{ey}| = J_y/ne \sim w_0^{-1}$. The average velocities

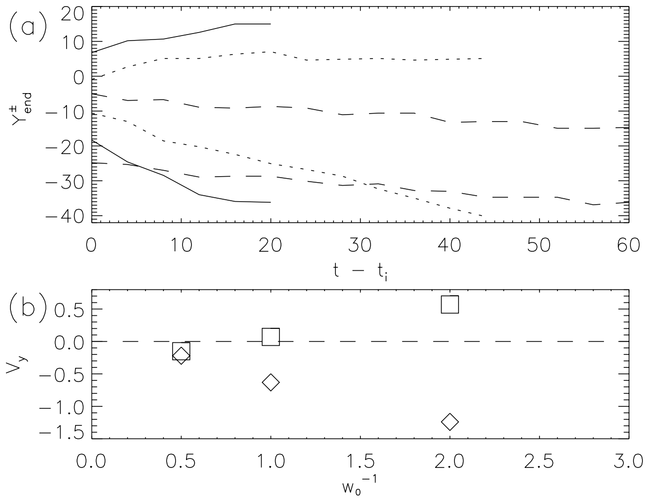

Figure 3. Expansion and propagation of finite length x-lines. In (a) the y positions of the ends of the x-line for differing w_0.: (solid) $w_0 = 0.5$, $t_i = 8.0$; (dotted) $w_0 = 1.0$, $t_i = 16.0$; and (dashed) $w_0 = 2.0$, $t_i = 96.0$, where t_i is the time required for the system to establish a strong x-line with $\mathbf{J}_y > 2.5$. In (b) the propagation velocities along y of the edges of the x-line for different w_0^{-1}: (squares) dy^{+}_{end}/dt and (diamonds) dy^{-}_{end}/dt.

of the ends of the x-line segments versus w_0^{-1} are shown in Figure 3b, and dy^{-}_{end}/dt is linear in w_0^{-1}, consistent with the dominance of electron convection. Consistent with this picture, the dynamics of the x-line segments in the simulations is insensitive to the electron to ion mass ratio since a variation of the electron mass only modifies the electron velocity very close to the x-line.

[13] The time dependence of y^{+}_{end} is less well understood. For small w_0, dy^{+}_{end}/dt is positive, opposite to the flow of electrons while for large w_0, dy^{+}_{end}/dt is negative. In the vicinity of y^{+}_{end} the ions are strongly coupled into the reconnection process, which can be clearly seen in the ion flows in Figure 1. As a consequence, the electrons and therefore the magnetic perturbations are anchored into the ion flows at large scales. For $w_0 \leq 1.0$ c/ω_{pi}, the coupling to the ions prevents the convection of y^{+}_{end} with the equilibrium electron current, and y^{+}_{end} either remains stationary or moves in the positive direction. The behavior of the case $w_0 = 2.0$ is distinctly different. y^{+}_{end} propagates in the negative y direction and therefore produces the constant length solitary structure. For $w_0 \geq 2.0$ a shock forms in the vicinity of y^{+}_{end}. This shock propagates in the negative y direction and convects the y^{+}_{end} edge of the x-line along with it, consistent with Figure 3a. Evidence for this shock can be seen in the ion flow patterns in Figure 1c which shows the plasma pressure and ion flow vectors in the yz plane in a cut through the right x-line ($x = -2$) of Figure 1a. The ions on the right edge of the x-line are flowing along negative y while those inside of the current layer are flowing in the positive y direction. There is a drop in the plasma pressure across the shock with the low pressure being in the region of the current layer. The shock has a dominant slow mode structure since the magnetic field pressure is out-of-phase with the plasma pressure. The shock is inherently three-dimensional and

apparently has no 1-D counterpart. Its structure has not yet been fully explored.

4. Discussion

[14] We have shown that in current layers which are near marginal stability spontaneous reconnection develops three dimensional structure corresponding to spatially isolated sites of reconnection with scale lengths around 10 c/ω_{pi}. These regions of reconnection propagate in the direction of the electron flow as "solitary" x-line segments of fixed length. These structures have not been previously identified in kinetic simulations because of their large spatial scale — simulations with computational domains well above 10 c/ω_{pi} in the direction of the equilibrium current are required to identify these mesoscale structures. In strongly unstable current layers, however, reconnection becomes a global process: multiple x-line segments form spontaneously and then merge to form extended, overlapping structures which can release magnetic energy over large spatial scales.

[15] These results suggest that bursty bulk flows observed in the magnetotail could be a consequence of the magnetotail being in a state of near marginal stability to reconnection such that external perturbations can cause reconnection to onset in a localized region but that reconnection will not tend to spread across the entire tail to cause a substorm. In the magnetotail, the density varies on average from about 0.33 cm^{-3} in the central plasma sheet to 0.01cm^{-3} in the lobes. The characteristic scale length of 10 c/ω_{pi} corresponds to 1–4 R_e. This spatial scale is consistent with current observations of BBFs, where correlation lengths of 3R_e [*Angelopoulos et al.*, 1997] to 10R_e [*Slavin et al.*, 1997] have been reported.

[16] In this picture of BBFs reconnection cannot organize and release energy over a large scale unless the current sheet is in a robustly unstable state. One can imagine, therefore, that if the magnetotail is only weakly driven by the solar wind, the release of energy through the formation of localized regions of reconnection would be sufficient to release the stress induced by the solar wind. The magnetotail, therefore, might not become strongly unstable and substorms would not occur. If the magnetotail is more strongly driven, BBFs would not provide enough dissipation of magnetic energy, the tail would evolve into a more strongly unstable state, and large scale reconnection could develop.

[17] The direction of x-line growth also has implications for magnetotail dynamics. In a Harris sheet model of the magnetotail, the ions carry the majority of the current. In a reference frame in which the ions carry most of the current a solitary x-line would propagate or grow primarily in the ion flow direction, which is dawn to dusk in the magnetotail. This is consistent with the stronger westward auroral expansion after substorm onset.

[18] This study represents an initial step towards understanding the structure and evolution of reconnection in 3-D mesoscale systems and its impact on the dynamics in the magnetosphere. Many unanswered questions remain. First, there are a variety of microinstabilities which coexist with the reconnection process, e.g., the lower-hybrid-drift, the kinetic kink and sausage modes [*Zhu and Winglee*, 1996; *Büchner*, 1998; *Horiuchi and Sato*, 1999]. Because of the focus on larger spatial scales (through the coarse grid), these instabilities were not dominant contributors to the dynamics. Second, the physics basis for understanding the onset of substorms in this study was incomplete because many kinetic effects as well as an equilibrium normal field B_z were not included. However, it is clear that reconnection in three dimensional mesoscale systems is much more dynamic and complex than that in two dimensions.

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