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Formation of secondary islands during magnetic reconnection

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[1] Full particle simulations are presented that suggest that the strength of an ambient guide magnetic field controls whether magnetic reconnection, once it is established, remains steady or becomes bursty. Specifically during anti-parallel (component) reconnection the electron current layers that form near the magnetic x-line are short (long) and therefore stable (unstable) to the formation of secondary magnetic islands. The implications for understanding magnetic reconnection and the formation of Flux Transfer Events at the magnetopause are discussed. **Citation:** Drake, J. F., M. Swisdak, K. M. Schoeffler, B. N. Rogers, and S. Kobayashi (2006), Formation of secondary islands during magnetic reconnection, *Geophys. Res. Lett.*, *33*, L13105, doi:10.1029/2006GL025957.

1. Introduction

[2] Magnetic reconnection is the dominant mechanism for converting stored magnetic energy in plasma systems into high velocity flows and energetic particles. The Hall reconnection model [*Birn et al.*, 2001] yields rates of energy release consistent with observations in the solar corona, the Earth's magnetosphere and in the laboratory. Whether magnetic reconnection, once established, forms a single large x-line or generates secondary magnetic islands remains an open scientific question that has important implications for understanding issues ranging from particle entry into the magnetosphere to the mechanisms for energetic particle production. Early satellite observations at the magnetopause suggested that reconnection was bursty and periodically formed flux ropes termed "Flux Transfer Events" (FTEs) [*Russell and Elphic*, 1978]. Others [*Gosling et al.*, 1982] suggested that reconnection at the magnetopause could be steady although such conclusions are complicated by the short residence time of spacecraft within the magnetopause proper. More recently images of the proton aurora from the IMAGE satellite suggest reconnection can remain steady for many hours [*Frey et al.*, 2003]. These IMAGE observations, however, were signatures of anti-parallel reconnection, in which the local ambient guide field was small. The conditions under which bursty or steady reconnection can take place are not well understood.

[3] Theoretical explanations of FTE observations were based on the magnetohydrodynamic (MHD) model, in which the extended Sweet-Parker current layers that form during reconnection at low resistivity break up into magnetic islands [*Lee and Fu*, 1985; *Raeder*, 2006]. However, the current layers that characterize the Sweet-Parker model do not exist in the essentially collisionless magnetosphere [*Cassak et al.*, 2005]. In the case of anti-parallel reconnection the structure of the late-time current layer near the x-line has been extensively explored [*Pritchett*, 2001; *Hesse et al.*, 2001; *Shay et al.*, 2001; *Zeiler et al.*, 2002]. Its width is several times the electron skin depth c/ω_{pe} with a length to width ratio of around five. The length of the current layer is determined by the effective Larmor radius of the accelerated electrons in the reconnected magnetic field downstream from the x-line. Once reconnection of anti-parallel fields has fully developed the electron current layer is too short for secondary islands to form and reconnection remains steady until the magnetic free energy is depleted.

[4] Thus, the kinetic reconnection models seem to suggest that steady reconnection should be the norm, leaving no simple explanation of the FTE observations. Here we suggest that reconnection with a guide field displays a very different time evolution than the anti-parallel case. The current layers that form during reconnection with a guide field differ greatly from those that form during anti-parallel reconnection, the width of the current layer scaling with the electron Larmor radius, which can be much narrower than c/ω_{pe} [*Hesse et al.*, 2002]. Further, the current layer develops a pronounced tilt as electrons accelerated parallel to the magnetic field stream preferentially outward along two of the four separatrices connected to the x-line [*Tanaka*, 1996; *Pritchett and Coroniti*, 2004; *Drake et al.*, 2005]. Here we show that the resulting current layer is much longer than in the case of anti-parallel reconnection and forms secondary islands as a result of the tearing instability. These secondary islands grow to finite size before merging with the main magnetic island and form strong core fields similar to those seen in the satellite observations [*Russell and Elphic*, 1978]. Guide fields of the order of 0.5 (a shear angle of 127°) of the reversed field are sufficient to produce secondary islands.

2. Computational Details

[5] Our simulations are performed with the particle-in-cell code p3d [*Zeiler et al.*, 2002]. The equations are written in normalized units: the magnetic field to the asymptotic value of the reversed field, the density to the value at the center of the current sheet minus the uniform background density, velocities to the Alfvén speed v_A, lengths to the ion inertial length $c/\omega_{pi} = d_i$, times to the inverse ion cyclotron frequency Ω_{ci}^{-1}, and temperatures to $m_i v_A^2$. We consider a system periodic in the $x - y$ plane where flows into and away from the x-line are parallel to $\hat{\mathbf{y}}$ and $\hat{\mathbf{x}}$, respectively. The guide magnetic field and reconnection electric field are parallel to $\hat{\mathbf{z}}$. The initial equilibrium consists of two Harris

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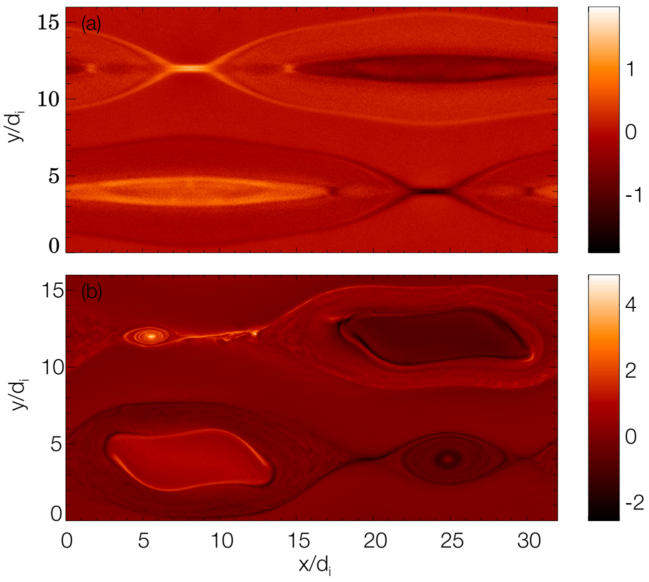

Figure 1. The electron out-of-plane current j_{ez} at late time from two runs with (a) $B_g = 0.0$ and (b) $B_g = 1.0$. Note the absence of secondary islands for the case with no guide field and the presence of large secondary islands for the case with a guide field.

current sheets superimposed on a ambient population of uniform density. The reconnection magnetic field is given by $B_x = \tanh[(y - L_y/4)/w_0] - \tanh[(y - 3L_y/4)/w_0] - 1$, where $w_0 = 0.5$ and L_y are the half-width of the initial current sheets and the box size in the $\hat{\mathbf{y}}$ direction. The electron and ion temperatures, $T_e = 1/12$ and $T_i = 5/12$, are initially uniform as is the guide field B_g. The initial density profile is the usual Harris form plus a uniform background of 0.2 so that the density at the center of each sheet is 1.2 at $t = 0$. To assure a sufficient separation of spatial and temporal scales, we take the electron mass to be 0.01 and the speed of light to be 20. The electron inertial (d_e) and Larmor (ρ_e) scale lengths are 0.1 and 0.029, respectively. The simulations presented here are two-dimensional, that is, $\partial/\partial z = 0$, and have $L_y = 16.0$ with $L_x = 32.0$ or 64.0 with the grid in both directions given by 1/64. The particle timestep is 1.0×10^{-3}. Reconnection is initiated with a small initial magnetic perturbation that produces a single magnetic island on each current layer. The essential results are not particularly sensitive to the size of this perturbation.

3. Results of Simulations

[6] In Figure 1 we show the electron out-of-plane current j_{ez} at late time from simulations with $B_g = 0.0$ in (a) and 1.0 in (b). In the case of no guide field the aspect ratio of the current layer is around five, as discussed earlier, and there is no evidence for the formation of secondary islands. Reconnection once established continues at a constant rate until each of the islands intersects the adjacent current layer.

[7] For the case of $B_g = 1.0$ there are secondary islands on both current layers. As discussed earlier, the current layers are tilted and the current extends along two of the four separatrices connecting to each x-line. Indeed the current on the lower x-line with $x \sim 20d_i$ wraps completely around the secondary island as the high-velocity, current-carrying electrons stream along the magnetic field away from the x-line. Thus, the short current layers that characterize anti-parallel reconnection give way to extended current layers that can be unstable to the tearing mode. To see this more clearly in Figure 2 we present the electron current j_{ez} at four times from a simulation with $B_g = 1.0$ but $L_x = 64.0$. In (a) at $t = 11.0$ each current layer is dominated by a single large island and an associated x-line where an intense but extended current layer has formed. In (b), at $t = 14.0$, secondary islands have formed on these intense current layers. In (c) at $t = 20.0$ these secondary islands have grown to finite size and some are in the process of merging with the dominant island on their respective current layers. On the lower current layer in (c) the two small secondary islands on the right have merged into a single island that is moving to the right to merge with the main island. Meanwhile the leftmost island is moving to the left to merge with the main island. At $t = 24.0$ in (d) the x-line around $x = 48d_i$ on the lower current layer has spawned another secondary island. Thus, the formation and merger of secondary islands is an ongoing process and not simply a result of a transient response to the initialization of the simulation.

[8] An important question is whether the growth of secondary islands as shown in Figure 2 results from the traditional tearing mode. The half width of the current layer at the upper x-line just prior to the formation of the two magnetic islands and the wavevector k_x of the islands just after they are visible on the current layer are 0.13 and 4.0, respectively. The product is 0.5, which is less than unity, as required for the tearing mode to be unstable.

[9] The growth of secondary islands as discussed here, however, differs significantly from the growth of a normal

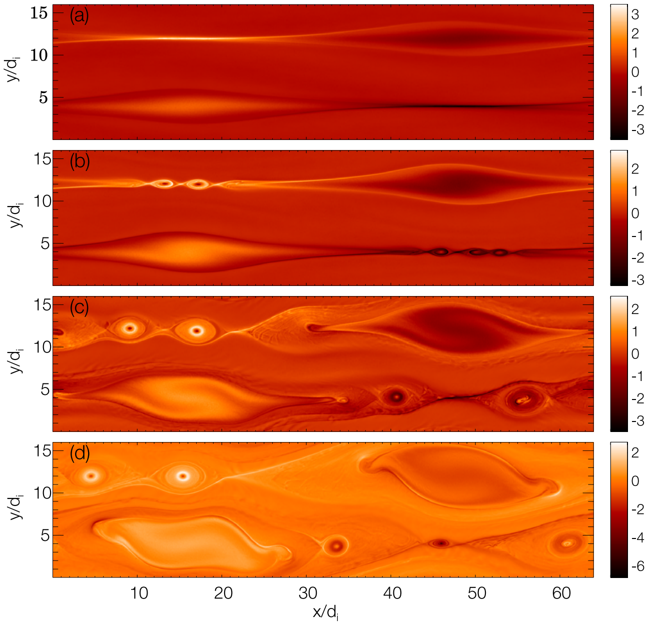

Figure 2. The electron out-of-plane current j_{ez} at four times ($t = 11.0$, $t = 14.0$, $t = 20.0$ and $t = 24.0$) from a run with $B_g = 1.0$ and other parameters as in Figure 1 but $L_x = 64.0$. (a) Note the large island growing on each current layer and the intense current layer driven at each of the x-lines. (b–d) Note the formation, growth and merger of magnetic islands is an ongoing process.

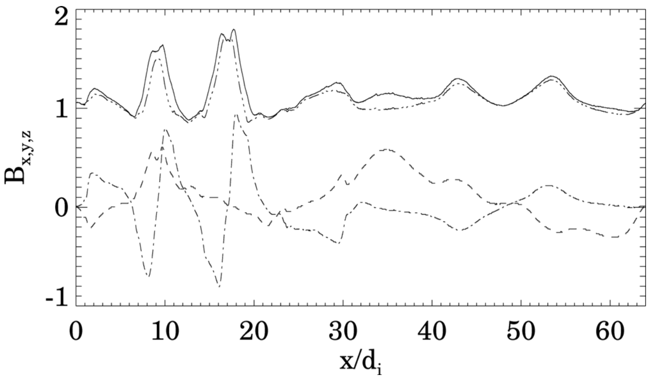

Figure 3. Shown are B_x (dashed), B_y (dot-dashed), B_z (dot-dot-dot-dashed) and B (solid) along a cut through the upper current layer in Figure 2c. Note the strong enhancement of B_z within the two secondary magnetic islands. Similar enhancements are seen in the plasma density.

tearing mode. In the growth of a conventional tearing mode the width of the island grows with time while the length of the island remains fixed. In the case of the secondary islands in Figure 2, both the island width and length grow with time. This is because the flow away from the x-lines of the secondary islands is not symmetric. The flow is stronger away from the secondary island than into it. As a result adjacent x-lines have a relative velocity that causes them to move away from each other so that the island between them grows.

[10] In the process of forming, secondary islands compress the ambient out-of-plane magnetic field and therefore evolve into flux tubes with strongly enhanced "core" fields. This is shown in Figure 3 where all three components of the magnetic field and the total field are plotted in a cut through the upper current layer in Figure 2c. Seen is the enhancement of B_z (the dot-dot-dot-dashed curve) by a factor of 1.7 over the ambient value in one of the secondary islands. Similar strong enhancements were seen in earlier MHD [*Ma et al.*, 1994] and hybrid simulations [*Karimabadi et al.*, 1999]. The strong compression of these fields within secondary islands occurs because these islands are largely filled with low pressure plasma from outside of the original current layer. Magnetic reconnection weakens the in-plane magnetic field within the secondary islands so force balance with the outside plasma and magnetic pressure can only be maintained by compressing B_z. Such enhanced core fields are widely observed in FTE structures at the magnetopause [*Russell and Elphic*, 1978] and in plasmoids in the magnetotail [*Slavin et al.*, 1995]. The loss of plasma within islands by jetting from the ends of flux tubes produces a similar compression of the core fields [*Hesse et al.*, 1996].

4. Summary and Discussion

[11] We have shown that the presence or absence of an ambient out-of-plane magnetic field has a major impact on the long-time behavior of magnetic reconnection. Specifically our focus is on late times after reconnection is already well developed and not on the initialization of reconnection, where the initial equilibria may play the dominant role. Understanding this late time behavior is essential to explaining how reconnection can continue for hours as is suggested by recent satellite observations [*Frey et al.*, 2003]. We propose that the late-time behavior is controlled by the structure of the current layer that forms in the vicinity of the magnetic x-line. In the case of anti-parallel reconnection the aspect ratio of the current layer remains modest and the current layer remains stable to the formation of secondary islands. Reconnection, once established, proceeds at a nearly constant rate. With a modest guide field the structure of the current layer becomes highly elongated, with a width that scales like the electron Larmor radius [*Hesse et al.*, 2002] and a length that extends far from the x-line along two of the four separatrices intersecting the x-line [*Pritchett*, 2001]. These elongated current layers repetitively spawn secondary islands that grow to finite amplitude, producing well developed flux tubes with enhanced core fields. In the simulations shown in Figure 2 the secondary islands cause the rate of reconnection to drop by around 50% so that secondary island formation does not cause reconnection to stop (see Figure 4a). The flux of ions streaming from the x-line/island region is very bursty (see Figure 4b). As magnetic islands and enclosed high density plasma are ejected from the x-line and merge with the main island there is a large transient increase in the ion mass flux. This bursty ion outflow is a clear signature of secondary island formation and should be visible in satellite data. The critical guide field defining the transition between these two distinct regimes has been bracketed: for a guide field of 0.2 (a magnetic shear of 157°) the current layer at late time is similar to the anti-parallel case and remains stable while with a guide field of 0.5 (magnetic shear of 127°) secondary islands form.

[12] Our findings appear to be consistent with some previous magnetospheric satellite observations. The intensity of the proton aurora linked to anti-parallel reconnection at the magnetopause reported by *Frey et al.* [2003] varied by no more than 50% during several hours of observations, consistent with our finding of steady reconnection without a guide field. If secondary islands had formed, much stronger modulation of ion fluxes should have been visible in the data (e.g., Figure 4b), a prediction that could be tested in future observations. The common presence of enhanced core fields in FTEs [*Russell and Elphic*, 1978] also strongly suggests that FTEs are formed as a result of secondary island formation during reconnection with a guide field.

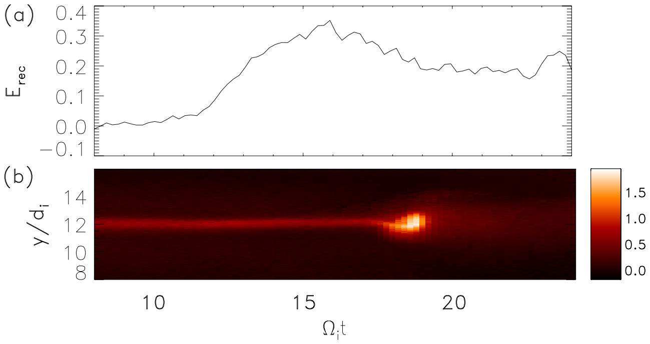

Figure 4. Shown are data from the upper current layer in the simulation in Figure 2: (a) the time dependence of the reconnection electric field at the dominant x-line; and (b) the time dependence of the x-directed ion flux from the x-line along a cut at $x = 28.1$. The burst of flux at $t \approx 18$ was associated with the flux from the remnant island at $x, y = 31, 12$ in Figure 2c.

[13] We are not able to address many important issues related to the spatial structure and time dependence of reconnection on the basis of the present simulations. Since the simulations have a limited spatial extent (at the magnetopause $64c/\omega_{pi}$ corresponds to around 3000 km, less than 0.5 of an Earth Radius (R_E)), we cannot make predictions of the spatial size of secondary magnetic islands. FTEs have characteristic scales of several R_E. Similarly the full cycle of secondary island formation, merging and reformation has not been carried out because of the limited magnetic flux available in the present simulation geometry. The present simulations also do not include a realistic asymmetry in the density and magnetic field such as exists at the Earth's magnetopause. The present simulations therefore do not include the effects of diamagnetic stabilization that were previously found to be important at high values of the ratio of the plasma to magnetic field pressure, β [*Swisdak et al.*, 2003]. We are currently exploring whether a Hall MHD model can reproduce these results and would therefore facilitate the simulation of larger spatial scales.

[14] The present results have important implications for understanding particle acceleration. The results suggest that magnetic reconnection in a large-scale system with a guide field will not occur at a single large x-line but will break up into many islands. Moreover, since guide field reconnection, unlike anti-parallel reconnection, is not limited to a single surface, we expect these islands to form in a finite volume. Particle acceleration due to reconnection in large systems such as the solar corona or perhaps even in the magnetotail [*Øieroset et al.*, 2002] may result from the interaction of particles with many x-lines and many magnetic islands.

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