Magnetotail dipolarization front and associated ion reflection:
Particle-in-cell simulations

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Received 23 February 2012; revised 23 March 2012; accepted 26 March 2012; published 25 April 2012.

[1] For the Earth magnetotail, the Svenes et al. (2008) statistical study infers the lobe density to be highly variable, in the range of 0.007–0.092 cm⁻³. Such lobe density variation modifies reconnection diffusion region physical processes and reconnection rate drastically. This letter addresses observable reconnection signatures in the vicinity of the X-line that are to be affected by the dynamic changes of reconnection. Using a 2.5D particle-in-cell (PIC) code, we find the dipolarization front (DF) a moving ram that pushes the initial equilibrium plasma sheet in front of it. The DF propagation velocity scales with the upstream Alfvén speed, leading to faster, steeper, and more compressed DFs with stronger $B_z$ at low lobe densities. These DFs reflect plasma sheet ions in a streaming manner. The streaming ions create a bipolar magnetic field straddling the central plasma sheet and can excite various instabilities. Citation: Wu, P., and M. A. Shay (2012), Magnetotail dipolarization front and associated ion reflection: Particle-in-cell simulations, Geophys. Res. Lett., 39, L08107, doi:10.1029/2012GL051486.

1. Introduction

[2] Although magnetotail reconnection has been the focus of intense scrutiny, no previous computational work has analyzed the effect of lobe density on the reconnection downstream region signatures. Recently, Wu et al. [2011] reported that a low lobe density drastically enhances the reconnection rate, affects diffusion region physical processes and leads to faster outflows. It is then natural to expect that such violent reconnections will also significantly modify the downstream signatures, particularly the observables such as the dipolarization front [e.g., Angelopoulos et al., 1992] and the suprathermal particles [e.g., Vaivads et al., 2011].

[3] Historically, the dipolarization front (DF) refers to the leading edge [e.g., Nakamura et al., 2002; Runov et al., 2009] of the earthward propagating magnetic flux pileup region (FPR) [e.g., Fu et al., 2011]. Earlier, magnetohydrodynamics (MHD) simulations [e.g., Hesse and Birn, 1994] and hybrid simulations [e.g., Hesse et al., 1998] found an increase of the normal magnetic field $B_z$ that propagates away from the X-line as a result of reconnection. Recently, particle-in-cell (PIC) simulations with open boundary conditions [Sitnov et al., 2009] measured the approximate propagation of the DFs that are in agreement with the observation by Runov et al. [2009]. The above works establish that the DF can be a generic and transient signature associated with reconnection, rather than a consequence of the compression of the Earth’s dipole field. A new feature is the recent observation of a plasma sheet ion population reflecting off the DF [Zhou et al., 2010] that has not been studied in previous simulations.

[4] The DF propagates away from the x-line which originally generated it. In this letter, we define “behind” the DF to be on the side nearest this x-line, and “in front” of the DF to be the opposite side. We perform large scale kinetic PIC simulations, systematically studying the DF at various lobe densities. A long history of the DF propagation is followed, allowing us to trace the DF propagation before the computational boundary can have an effect on the DF. We find that the DF propagates away from the reconnection site with a small initial speed (near zero). The speed soon increases and reaches a steady rate that scales, almost linearly, with the upstream Alfvén speed. At low lobe densities, the DF magnetic field $B_z$ is more compressed and in front of it, there is a sharp rise of plasma sheet density followed by a gradual decrease along X, corresponding to a rise of ion flow velocity in front of the DF that has been observed by Runov et al. [2009]. In addition, there is an X directional preferential heating for the ions in the region of flow velocity rise, as a consequence of their streaming away from the DF upon reflection, due to the lack of magnetic confinement in the central plasma sheet in the vicinity of the X-line. This streaming is different from the behavior of ions reflected off of a perpendicular shock, which gyrate and drift across a sizeable magnetic field. Further, we examine the ion phase space density to illustrate the streaming reflection processes and to reaffirm the localized feature of the DF. The DF is identified as a moving ram that pushes the initial equilibrium plasma sheet, as well as a separator between the sub-Alfvénic reconnection outflow and the super-Alfvénic reflected ion flow. Finally, we predict that the streaming of the reflected ions generates a bipolar magnetic field.

2. Simulations

[5] We analyzed the set of relativistic and electromagnetic 2.5D particle-in-cell (PIC) simulations as described in our other publication [Wu et al., 2011]. For completeness, we re-state the normalization scheme and the essential parameters. Normalization is based on the initial double Harris sheet maximum density $n_0$ and the asymptotic magnetic field $B_\infty = 1$. Therefore, lengths $(x, y, z)$ are normalized to an ion skin depth calculated from $d_\text{s} = c/\omega_p n_0$, where $\omega_p n_0$ is the ion plasma frequency calculated from $n_0 = 1$. Time $t$ is normalized to an inverse of ion cyclotron frequency $\Omega = 1$ calculated from $B_\infty$. The electric fields are normalized to $v_\text{e} B_\perp c$. The velocities are normalized to a referenced Alfvén speed $v_\text{A} = B_\perp (4\pi n_0 m_i)^{1/2}$. The electron mass is $m_e = 0.04 m_i$. The ion and electron temperatures are initially $T_i = 0.4167$ and $T_e = 0.0833$, where temperature $T$ is normalized to

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Figure 1. DFs overview. (a) Cuts of \( B_z \) along X through the X-line. (b) Cuts of ion density \( n_i \) along X through the X-line. Both Figures 1a and 1b only show two extreme background density simulations: \( n_b = 0.01 \) (red) and \( n_b = 1.0 \) (black). The other four simulation results (not shown) gradually transition from one extreme to the other. Dashed lines mark the DFs. (c) The propagation of the \( n_b = 0.01 \) DF. Note that the DF is undefined before reconnection starts and thus the discontinuities at \( t = 53, 55 \). At \( t = 77 \), the periodic boundary conditions begin to play a role and result in an unphysical velocity reversal. (d) DF propagation as a function of the upstream Alfvén speed. (e) Maximum dipolarization front magnetic field strength \( B_{DF} \) as a function of the upstream magnetic field \( B_{up} \), the upstream density \( n_{up} \), and the plasma sheet density \( n_{cs} \).

\[ T_0 = \frac{m_i v_{A0}^2}{e} \]  

The speed of light is chosen to be \( c = 15v_{A0} \). The simulations are 102.4\( d_0 \) \times 102.4\( d_0 \) in the X-Z plane. Double Harris plasma sheets are initiated with the width \( w_0 = d_0, B_x(z) = B_x \{ \tanh((z - L_x/4)/w_0) - \tanh((z - 3L_x/4)/w_0) \} - 1 \) and \( n_x(z) = n_0 (B_x^2 - B_x(z)^2)/(2(T_x + T_z)) \). To this Harris equilibrium is added a second non-drifting plasma population with density \( n_b \). Note that since the Harris equilibrium has a zero density in the lobes, the lobe density becomes \( n_b \). The six simulations analyzed have \( n_b = 0.01, 0.015, 0.03, 0.1, 0.2, \) and \( 1.0 \), respectively. There is no guide field. Small magnetic perturbations are included for reconnection to develop (through the tearing mode). The double Harris sheet with periodic boundary condition reproduces large values of the tearing mode stability parameter and does not exhibit artificial saturation due to conducting boundaries [e.g., Wu et al., 2011].

### 3. The Dipolarization Front and Ion Reflection

Using the PIC simulations described above, we analyze each dipolarization front (DF) at a time when the DF magnetic field \( B_{DF} \) reach a maximum. The DF is fully developed and the periodic boundary condition has not affected the DF yet. The general properties of the DF are illustrated in Figure 1. The two extreme density simulations shown both have X-lines near \( x \sim [25, 35] \). Focusing on the region to the right of these X-lines, the low lobe density simulation has a steeper and larger DF magnetic field magnitude \( |B_{DF}| \) relative to the higher density case. In front of the DF for the low density case, the reflected plasma sheet ions cause a density pileup (Figure 1b). Such a density pileup is not seen for the high density case which has too small a \( B_{DF} \) to reflect any ions visibly. Figure 1c traces the propagation of a DF by following the maximum \( B_z \) along X. During reconnection onset, the DF is forming in the diffusion region (DR) with an initial \( B_{DF} \) smaller than the DR fluctuating \( B_z \), as seen in the discontinuities at \( t = 53, 55 \). After reconnection onset, the DF is gradually accelerated to a maximum pressure balance \( P_{DF} \) is being converted into the plasma thermal pressure. Immediately in front of the DF, the conversion pressure is \( \sim 100\% \), \( P_{thermal, front} \sim P_{ram,cs} \). Integrating the curvature force along X across the DF yields an estimate for an effective “curvature pressure”: \( \delta P_{curv,DF} \sim B_z B_z \delta x/(4\pi\delta z) \sim B_z B_z \delta x/(4\pi\delta z) \). We have found in our simulations that the magnetic field lines in the vicinity of the DF are nearly circular, yielding \( B_z \sim B_z \sim B_{DF} \), and \( \delta z \sim \delta x \) because \( \nabla \cdot B = 0 \). Therefore, \( \delta P_{curv,DF} \sim B_{DF} \). Pressure balance requires \( P_{thermal, front} \sim 8\delta P_{curv,DF} + P_{B,DF} \), which now can be written as \( P_{ram,cs} \sim 2P_{B,DF} \). This estimate gives \( 2B_{DF}^2 = m_i n_i (0.3 v_{A,up})^2 \sim 0.3^2 m_i n_i (B_{up}^2/(4\pi m_i n_i)) \). Re-arranging the equation, we find \( B_{DF}/(B_{up} \sim 0.3(n_b/n_b)^{1/2}) \), which matches Figure 1c’s systematically shown relation: \( B_{DF} \sim 0.3B_{up}(n_b/n_b)^{1/2} \). The scaling indicates that the DF is a moving ram that pushes the initial equilibrium plasma sheet ahead of it. The scaling also provides a way to predict the maximum DF magnetic field in the reconnection vicinity using upstream conditions. It should be noted that our simulations only address the reconnection vicinity where the Earth’s pre-existing dipole field and other thermalization processes such as betatron and Fermi accelerations [e.g., Wu et al., 2006] are not affecting the \( P_{thermal, behind} \) (neglected above) behind the DF. Observational studies of DF events [e.g., Li et al., 2011] are necessary for understanding the DF pressure balance in the near Earth region.
Another piece of evidence of ion reflection is the rise of ion flow in front of the DF, as seen in the Figure 2a (left). The over-plotted Alfvén speed illustrates an interesting feature of the DF. The reconnection outflow behind the DF is sub-Alfvénic relative to the local Alfvén speed, while the flow in front of the DF is super-Alfvénic owing to the small plasma sheet magnetic field. This super-Alfvénic flow is created by a reflected beam of ions streaming away from the DF. This beam coexists with the ambient plasma sheet population, which is manifested as an increase in $T_{ixx}$ in front of the DF.

Another interesting feature present in the $T_{ixx}$ (Figure 2a) is that behind the DF, there is a region of heating ($x = [43,53]$) created as the high speed outflowing ions decelerate and compress behind the DF. The high speed outflowing ions are sub-Alfvénic, however, so this left hand edge of the compression region is not a fast shock. Furthermore, it does not match any other known discontinuity criteria (contact, tangential, intermediate shock). This structure steepens with time, reaching a peak density compression ratio of 2 and an associated deceleration of about $1 v_{ixx}$ at $t = 69$.

The presence of streaming ions in front of the DF is not limited to the lowest density case, and is evident for even the $n_b = 0.2$ case. To further understand these reflected ions, we examine phase space densities (PSDs) of the $n_b = 0.1$ case at $t = 93$ when the DF magnetic field is maximum (Figure 3). Figure 3c shows the spatial scope of the DF as a reference to the PSD panels. In the PSD panels (Figure 3a), there are two populations of plasma sheet plasmas in front of the DF, one with a small averaged $v_{ix}$ (population 1, as highlighted by an orange dashed rectangle) and one with a larger averaged $v_{ix}$ (population 2, as highlighted by a green dashed rectangle). Near the DF, the two populations are close enough to mix in velocity space and create a elongated oval. Slightly far away from the DF, the two populations clearly separate in $v_{ix}$. Population 2 fades out as we move away from the DF. Hence, population 1 is the ambient plasma sheet ions. Population 2 is the DF reflected plasma sheet ions. Due to the relatively modest size of these simulations, these reflected ions originate from both the growing and steady phase of the DF. Simulating realistic reflected ion dispersion will require a future study with much larger simulation sizes.

The scope of reflection is examined in Figure 3b, which shows that slightly off the central plasma sheet, the number of reflected ions is greatly reduced. About $5d_0$ above and below the central plasma sheet, there is no ion reflection at all. Comparing with Figure 3a, we find that the ion reflection is closely associated with the DF and therefore is rather localized, like the DF itself as shown in Figure 3c. Figure 3d shows a current $j_y$ generated by the streaming ions. Despite being partially counter-balanced by an electron current $j_x$, this leads to the net current $j_y$ which induces a bipolar magnetic field straddling the central plasma sheet (Figure 3d, bottom) in front of the DF. Such a feature is not seen in the highest density simulation where the DF is too weak to reflect ions.

4. Summary and Discussions

Particle simulations performed here focus on the specific topic of the dipolarization front (DF) in the vicinity of the X-line. At small lobe density, the dipolarization front propagates faster at a speed that scales with the upstream Alfvén speed. The fast propagating DF has a larger $B_{DF}$ due to compression. We find that $B_{DF}$ can be evaluated using upstream conditions and a scaling relation. A large $B_{DF}$ has the characteristic of a moving ram that pushes the plasma sheet in front of it, creating a population of reflected ions. Recall that for a perpendicular shock, reflected ions will gyrate and drift around the magnetic field and form a gyrotropic population [e.g., Wu et al., 2009]. The DF reflected ions are, on the contrary, initially unmagnetized and streaming strongly in $X$, resulting in: (1) The DF marks a boundary of the sub-Alfvénic reconnection outflow and the super-Alfvénic reflected ion flow. (2) The reflected ions are preferentially accelerated in $X$ initially. The highly anisotropic ions excite various instabilities inside the primary island, a topic of future investigations. (3) A strong current along $X$ induces a bipolar magnetic field straddling the central plasma sheet, as is evident in a Cluster observation (L.-J. Chen, personal communication, 2010).

In the simulations reported here, for simplicity, there is no guide field. In reality, events with a small guide field $B_y$...
n_b = 0.1 @ t=93

Figure 3. Ion phase space densities (PSD), v_{ix} versus v_{iz} and v_{ix} versus v_{iy}, (a) along the X-axis and (b) above the X-axis in front of the n_b = 0.1 DF. The orange and green dashed rectangles mark two distinct populations (see text). The physical location (x, z) of each PSD plot is marked on top of the images. (c) For comparison with the PSD panels, the intensity and physical domain of the DF are shown. (top) 1-D cut of B_z along X through the X-line. (bottom) 2-D illustration of the DF domain. (d) (top) A cut of j_{ix}, j_{ex}, and j_x along X through the X-line. (bottom) 2-D illustration of the bipolar magnetic field straddling the symmetric line. The solid vertical lines mark the dipolarization front and the dashed lines mark the X-line. Note in Figures 3c and 3d that there is a secondary island between the X-line and the DF. This island does not affect the DF physical processes due to its long distance from the DF: \( \sim 15d_i \).

Acknowledgments. This work was supported by NSF grant ATM-0645271 and NASA grants NNX08AM37G and NNX08AO83G. Simulations were performed at the NCAR Computational Information Systems Laboratory, sponsored by NSF. PW thanks Tai Phan, Marit Oieroset, Mitsuo Oka, Dan Winske, S. Peter Gary, William Mattheaus, Mikhail Sitnov, Andrei Runov, Michael Hesse, Thomas Moore, Vassilis Angelopoulos, and Xuzhi Zhou for discussions.

References


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