Plasmoid-like structures in multiple X line Hall MHD reconnection

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[1] Driven by a waveform inflow, multiple X line reconnection is initiated in a long current layer, and the plasmoids are bound between two neighboring reconnection sites. We investigate the behaviors of the plasmoid-like structures in the absence and presence of an initial guide field $B_{x0}$ normalized by $B_0$ ($B_0$ is the initial intensity of $B_x$ field at the top and bottom boundaries of the simulation domain) using a Hall magnetohydrodynamic (MHD) code. For the case with $B_{x0} = 0$ the profiles of the out-of-plane $B_y$ component are the bipolar signature or the bipolar wave-like signature which is caused by Hall effect and independent of the external mechanism. Such $B_y$ features are in line with the observed signature of a closed-loop-like plasmoid in the magnetotail. The bipolar and fluctuation signatures of $B_x$ have an asymmetric feature in the presence of a small $B_{x0}(= 0.1)$, and the $B_y$ profile becomes a positive signature as $B_{x0}$ reaches or exceeds 0.3. In the case of $B_{x0} = 0.5, a B_y$ bulge appears in the $B_x$ signature when the enhanced $B_y$ regions caused by Hall effect take place in the plasmoid. The $B_y$ bulge evolves into a peaking signature, whose maximum ($B_{y \text{max}}$) is quickly raised and approaches the lobe magnetic field strength. Such a significant enhancement of the $B_y$ component in the central region of the plasmoid might be representative of the observed strong core field in the magnetic flux rope. The present results indicate the following implications: (1) Hall effect and a pre-existing cross-tail component $B_x$ are two important factors controlling the occurrence of various plasmoid-like structures in the magnetotail. (2) In the later phase the nonlinear interaction between Hall effect and the $B_x$ flux added by the plasma inflow makes a most important contribution to the growth of the core $B_y$ field.


1. Introduction

[2] Plasmoids have been observed in the magnetotail by a number of early spacecraft missions, for example, ISEE [Moldwin and Hughes, 1993; Slavin et al., 1989] and Geotail [Deng et al., 2004; Ieda et al., 1998; Zong et al., 1997]. A large number of plasmoids observed in the magnetotail exhibit not only the usual bipolar signature in the north–south magnetic field component $B_z$, but also a very strong cross-tail magnetic field component $B_y$ (core $B_y$ field) which can approach or exceed the ambient lobe magnetic field in magnitude. Such plasmoids with helical magnetic field structures were called “magnetic flux rope” (MFR) [Chen et al., 2007; Ieda et al., 1998; Slavin et al., 1995]. The dawn-dusk magnetic field $B_y$ in the magnetotail has been found to be well correlated with the interplanetary magnetic field (IMF) $B_y$ component. Lui [1984] suggested that about 50% of the IMF $B_y$ component exists in the neutral sheet region. In addition, the other kind of plasmoids detected in the magnetotail reveals the bipolar waveform signatures in both $B_z$ and $B_y$ components [Deng et al., 2004; Zong et al., 1997; Moldwin and Hughes, 1992]. They were considered to be plasmoid-like structures with closed-looped magnetic field lines. In the present work the term plasmoid is used for both of MFR and “closed loop” plasmoid.

[3] The formation of plasmoids in the magnetotail can be understood in terms of the multiple X line reconnection (MXR) model proposed to explain the helical magnetic structure in flux transfer events (FTEs) at the dayside magnetopause [Lee et al., 1985]. The Geotail spacecraft encountered an active reconnection diffusion region in the Earth’s magnetotail. Deng et al. [2004] provided evidence of multiple X line collisionless reconnection on the basis of the following observed features: quadrupole pattern of the out-of-plane $B_y$ component during the passage of a magnetic island, a direction reversal of the electron beams and plasma flow reversal. On 2 October 2003 the observation made by the four Cluster spacecraft showed that the variations of field and flow in the vicinity of magnetotail current sheet
are most consistent with a series of two active reconnection sites bounding an Earthward moving flux rope [Eastwood et al., 2005]. It indicated that reconnection can occur simultaneously at different points in the near-Earth magnetotail current sheet, providing (further) important experimental validation of MXR theories on the mesoscale (tens of ion inertial length) level [Eastwood et al., 2005]. The “time of flight” of the flux rope across the 4 Cluster spacecraft yielded \( V_x \approx 700 \text{ km/s} \) and a diameter of \( \sim 1 R_e \) [Slavin et al., 2003]. Lui et al. [2007] investigated an MFR observed by Cluster during a substorm, and found that the MFR was aligned with its principal axis closely along the dawn-dusk direction. A theoretical study [Drake et al., 2005] suggested that electrons gain kinetic energy by reflecting from the contracting “magnetic islands” that form as reconnection proceeds. Recently, Chen et al. [2007] provided evidence for the link between energetic electrons and magnetic islands during reconnection in the Earth’s magnetotail on the basis of the observation made by the four Cluster spacecraft.

[4] Many attempts have been done to explain the observed strong core field in plasmoids. Walker and Ogino [1996] studied the origin and evolution of MFR using a three-dimensional (3-D) global MHD simulation. When there initially was no IMF \( B_y \) in the plasma sheet, reconnection led to the formation of plasmoid composed of a quasi-2-D closed magnetic loop structure. For IMF \( B_y \neq 0 \) initially in the plasma sheet the reconnection immediately led to the formation of an MFR structure [Walker and Ogino, 1996]. Ma et al. [1994] proposed that the increase in the core magnetic field depends on both the property of the initial configuration and the particular reconnection geometry on the basis of the 2-D and 3-D simulations of various reconnection models. Somerup [1987] examined the basic properties and motions of flux tubes of the Russell-Elphic type for FTEs at the magnetopause and suggested that in the supercritical case the circumferential magnetic flux is continually fed into the flux tube from the surrounding magnetopause and the helical FTE field lines are formed. A 2.5-D MHD simulation of multiple-plasmoid-like structures in the course of a substorm was carried out by Jin et al. [2001]. The results indicated that the occurrence of various magnetic structures in the magnetotail might be related to the different initial distributions of \( B_y \) component in the driven reconnection processes. The evolution of the helical topology in the reconnected flux tube was investigated by Jin and Cui [2004] in terms of the principle of magnetic helicity. It was found that the concentration of the helicity density \( h \) in the core of a flux tube arises from the enhancement of the axial field \( B_y \) which is associated with the continuous addition of \( B_y \) flux to the domain. However, the above studies [Jin et al., 2001; Jin and Cui, 2004] based on MHD model did not include the effect of Hall current. Karimabadi et al. [1999] carried out 2-D and 3-D hybrid simulations that explained the large core field in terms of Hall-generated currents which can naturally lead to core field strength exceeding even the ambient lobe field magnitude. Ion beta and the presence of a preexisting guide field are two important factors controlling the Hall-generated field. Full particle simulations were presented by Drake et al. [2006] that suggested that the strength of an ambient guide magnetic field controls whether magnetic reconnection remains steady or becomes bursty. Specifically during antiparallel (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. A fully kinetic simulation showed that the length of the electron diffusion region is observed to increase with time resulting in the formation of an extended electron current sheet, and the electron layer becomes unstable and produces a secondary island in the reconnection with open boundary condition [Daughton et al., 2006]. Besides, the effect of the guide field on the electron acceleration was examined by a particle simulation [Fu et al., 2006].

[5] We derived a 2.5-D Hall MHD code from the multi-step implicit scheme [Hu, 1989] to study collisionless reconnection problems. For the quasi-steady reconnection with a single X line the following works have been carried out. The driven reconnection processes with various scales were investigated [Yang and Jin, 2004]. The single X reconnection with a quadrupolar \( B_y \) structure was exhibited in the cases with \( L_1/d_i \leq 1.0 \) (\( L_1 \) is the half-thickness of initial current layer, \( d_i \) is the ion inertial length). The reconnection rates \( \partial A/\partial t \approx 0.15 \) and 0.11 in the quasi-steady states for the cases of \( L_1/d_i = 0.5 \) and 1.0, and they are insensitive to different magnitude of the spatially uniform resistivity. The single X reconnection is transformed into the reconnection with an extended current sheet and the reconnection rate is dramatically reduced as the Hall effect weakens with increasing \( L_1/d_i \). The results from the reconnection process driven by the plasma inflow are compatible with those obtained from the reconnection initiated by magnetic perturbations in the GEM reconnection challenge [Birn et al., 2001]. Jin et al. [2005] examined the dependence of the Hall effect on plasma \( \beta \), and found that the openness of the magnetic separatrix angle is enlarged as \( \beta \) increases and the fine structures of \( B_y \) contours with reversed sign emerge as \( \beta > 2.0 \). The numerical results indicated that these fine structures are attributed to the reversed currents associated with the relative motions between electrons and ions [Jin et al., 2005]. The density depletion layers in magnetic reconnection were explored [Yang et al., 2006]. The simulation results showed not only the density depletions along the magnetic separatrices but also a density dip near the X line and indicated that the Hall effect is responsible for the phenomena of density depletion. On the basis of the comparison between simulation results and Wind observations we argued that the density dip observed by Wind would be distributed around the reconnection X line, rather than along the magnetic separatix [Yang et al., 2006]. The effects of the initial guide field \( B_{0y} \) on the reconnection dynamics were examined by Yang et al. [2008]. The openness of the magnetic separatrix angle is slightly reduced, and the features of the reconnection field are substantially altered in the presence of \( B_{0y} \). The reconnection rates(\( \partial A/\partial t \)) at the X line drops from 0.151 to 0.06 as \( B_{0y} \) increases from 0 to 4.0 (in unit of \( B_{0y} \), \( B_0 \) is the initial intensity of the oppositely directed field component \( B_z \) at the top and bottom boundaries), and \( \partial A/\partial t \) in the case of \( B_{0y} = 1.0 \) is about 75% of that in the case of \( B_{0y} = 0 \). This result is approximate to that in Huba’s [2005] simulation where the reconnection is initiated by magnetic perturbations.
In the present work we use a 2.5-dimensional Hall MHD code to investigate the dynamic features of the multiple X line reconnection. In $(x, z)$ plane the opposite-pointing magnetic field lines driven by the plasma inflow approach each other, and as a result the tearing mode instability is triggered and the multiple X line reconnection is initiated in a long current layer. It is found from 2.5-D Hall MHD simulations that the thin current sheet with a sufficient length facilitates the trigger of a tearing mode instability. The behaviors of the plasmoids to be bound between two neighboring reconnection sites, especially the evolving features of out-of-plane $B_y$ component associated with Hall effect are explored in the absence and presence of an initial guide field $B_y$. The numerical results exhibit the observed features of two types of plasmoid-like structures in the magnetotail. The factors controlling the occurrence of various plasmoid-like structures will be discussed.

2. Simulation Model

A magnetic flux function $A(x, z, t)$ is introduced by the equation

$$B = \nabla \times (A e_z) + B_x e_x.$$  

(1)

We assume that the $x$ coordinate of a right-handed Cartesian coordinate system is in the tailward direction, the $z$ coordinate is perpendicular (northward) to the plasma sheet, and $y$ coordinate is in the dusk-dawn direction. A Harris current sheet equilibrium solution is chosen as the initial state. At $t = 0$, the magnetic field is

$$B_x(x, z) = -B_0 \tanh(z/L_c), \quad B_z(x, z) = 0,$$  

(2)

the corresponding magnetic flux function is given by

$$A(x, z) = A_0 \ln(\cosh(z/L_c)).$$  

(3)

The static isothermal equilibrium state is given by $V_z(x, z) = V_A(x, z) = V_\perp(x, z) = 0$, $T(x, z) = T_0$ and $\rho(x, z) = \rho_0 + \rho_0 \text{sech}^2(z/L_c)$, and $\rho_0$ is determined by $RT_0 \rho_0 = B_0^2 / 8\pi$ ($R$ is gas constant) and $\rho_0 = 2.0 \rho_0$. To facilitate the trigger of a tearing mode instability and the formation of multiple X line reconnection, the half width of the initial current sheet $L_c$ was set as 0.04$L_0$ (i.e., $L_c = 0.04L_0$, $L_0$ is the half length of simulation domain in $z$ direction). The initial Harris current sheet is not modified by the addition of a uniform out-of-plane magnetic field component $B_y$, and so the cases with the guide field $B_y$ ranging from 0 to 1.2 (in unit of $B_0$, $B_0$ is the initial value of $B_z$ field at the top and bottom boundaries) are investigated in this simulation.

On the basis of the Hall MHD approximation, the generalized Ohm’s law, including the Hall current and scalar electron pressure gradient term, is combined with Faraday’s induction equation. The 2.5-D Hall MHD equations are written in dimensionless forms which are given by Jin et al. [2005] and Yang et al. [2006]. The length, magnetic field strength, density, temperature, magnetic flux function, velocity and time are scaled by $L_0$, $B_0$, $\rho_0$, $T_0$, $A_0 = B_0L_0$, $V_A = B_0/\sqrt{\rho_0}$ and $\tau_A = L_0/V_A$, respectively. And the factor $(4\pi)^{1/2}$ is involved in the unit of $B_0$, so that $1/4\pi$ does not appear in Lorentz force terms. The dimensionless parameters $\chi_m$, $K_{tt}$, $K_P$ are given by

$$\chi_m = \frac{\eta}{V_A L_0}, \quad K_{tt} = \frac{d_t}{L_0}, \quad K_P = \frac{\beta}{2L_0},$$  

(4)

where $\eta$ is the plasma resistivity and $\beta = P_y/(B_0^2/2)$ is the ratio of plasma pressure to magnetic pressure outside the current sheet. In the present study, the resistivity $\eta$ is assumed to be uniform and the Lundquist number $S = (\mu_0 L_0 V_A/\eta) = 1/\chi_m$ is set as 2500. The other parameters are taken as follows: $T_0 = 1.44 \times 10^7$K, $B_0 = 20$ nT, $\rho_0 = 3.34 \times 10^{-25}$ g/cm$^3$ (corresponding to $n_0 = 0.2$ protons/cm$^3$), $c = \omega_{pi} = \sqrt{\frac{4\pi n_0 m_p}{e}} = 509$ km, $L_0 = 5d_t$ and $\beta = 0.5$.

The numerical computation is carried out in the whole simulation domain which extends from 0 to $L_x$ in the $x$ direction and from $-L_z$ to $L_z$ in the $z$ direction. To examine the behaviors of multiple X line reconnection, the long domain ($L_x = 12$ in unit of $L_0$) is employed in the runs presented here. Along the left boundary ($x = 0$) and right boundary ($x = L_x = 12$), $\rho_0$, $V_x$, $V_y$, $V_z$, $B_x$ and $T$ are determined by linear extrapolation. For the magnetic flux function $A(x, z, t)$, we choose $\partial^2 A/\partial x^2 = 0$ (i.e., $\partial B_x/\partial x = 0$) at the left and right boundaries. Along the top boundary ($z = L_z = 1$) and bottom boundary ($z = -L_z = -1$), the parameters $\rho_0$, $T_0$, $V_x$, $V_z$ and $V_y$ are maintained at their initial values, and $\partial A/\partial z$ is chosen to be zero (i.e., $\partial B_z/\partial z = 0$). In order to simulate the situation of driven reconnection with multiple X line, the inflows $V_z$ (in unit of $V_A$) are imposed at the top and bottom boundaries,

$$V_z = \mp\left\{V_1 \cos\left[\frac{x}{L_{cx}} - 5/2\right] + V_0\right\}.$$  

(5)

Here $V_1 = 0.004$, $V_0 = 0.03$ and $L_{cx} = L_x/5$. As seen in expression (5), the waveform perturbation is superimposed on the uniform inflow $V_0$, and $V_z$ reaches the maximum and minimum at $x/L_{cx} = 5/2 = 0, \pm 2$ and $x/L_{cx} = 5/2 = \pm 1$, respectively.

The 2.5-D MHD equations are solved by a new Hall MHD code [Yang and Jin, 2004] derived from multistep implicit scheme [Hu, 1989]. In the present simulation, the computational domain is divided into $241 \times 61$ grid points. In order to allow adequate spatial resolution in the current sheet, the grid spacing in the $z$ direction from $z = 0$ to $z = \pm L_z$ increases according to a geometric series. In the $x$ direction, the computation from $x = 0$ to $x = L_x = 12$ is advanced by a uniform grid point spacing $\Delta x = 0.05$. To ensure computational accuracy and numerical stability, the time steps $\Delta t$ are required to satisfy the following Courant condition: $\Delta t \leq \Delta L/V_{max}$, where $\Delta L$ is the minimum grid spacing and $V_{max}$ is the maximum of the plasma velocity $V$ in the simulation box.

3. Simulation Results

The initial equilibrium state is driven by waveform inflows imposed at the top and bottom boundaries and three reconnection X lines are formed in the long current sheet. In the absence and presence of an initial guide field $B_y$, the
behaviors of the plasmoids bound between two neighboring reconnection sites are investigated using a Hall MHD code [Yang and Jin, 2004].

3.1. Case 1: $B_0 = 0$

The time evolution of Hall MHD reconnection with three X lines is shown in Figure 1 where the magnetic field lines (i.e., the contours of $A(x, z)$) and the contours of the out-of-plane magnetic field $B_y$ are expressed by the solid lines and the color plots, respectively. As seen in Figure 1a ($t = 16.5 \tau_A$), two flat plasmoids are bound between two adjacent X lines, and $B_y$ has the expected quadrupole structure at every one of three X lines. The picture of $B_y$ in a plasmoid consists of the quadrupole $B_y$ fields generated by two adjacent X lines. During the evolution phase shown in Figure 1 the size of the plasmoid in the z direction gradually increases and so the opennesses of the quadrupolar $B_y$ structures in the plasmoid are correspondingly extended. Some fine structures of $B_y$ contours with the reversed sign emerge and gradually grow within the original $B_y$ structures, as seen in Figure 1b ($t = 18.5 \tau_A$) and Figure 1c ($t = 19.0 \tau_A$). The plasmoids with a rather large extent in the z direction are composed of two distinct regions in Figure 1d ($t = 20.0 \tau_A$): The quadrupolar $B_y$ structures in the outer regions are determined by the neighboring X lines. The inner regions enveloped in the outer regions consist of the new emerging $B_y$ quadrupole structures which have the $B_y$ polarities as opposed to those in the outer regions. The plasma inflow does not transfer any $B_y$ flux to the reconnection region since $B_y$ is kept up the initial magnitude ($B_0 = 0$) along the top and bottom boundaries in Case 1. Consequently, the maximum and minimum of $B_y$ are maintained at about $\pm 0.3$ in the reconnection process as seen in the color bar of Figure 1, and the generation of the inner $B_y$ structures is independent of external mechanism. The $B_y$ picture including the inner and outer quadrupole structure in Figure 1 is somewhat similar to the intensity plot of out-of-plane field from the hybrid simulation by Karimabadi et al. [2004].

The velocity vector plots of the in-plane ion and electron flows at $t = 20 \tau_A$ are illustrated in Figures 2a and 2b, respectively. In Hall MHD the ion flow velocity $V_i \approx V$ and the electron flow velocity can be expressed as $V_e \approx V - K_i n/n$, where $n$ is the proton density (in a hydrogen
In order to clearly illustrate the distributions of ion and electron flow in a plasmoid, only the data for $0 \leq x \leq 36d_i$ are used in the Figure 2 plotting. The waveform inflow is imposed at the top and bottom boundaries and the jets are ejected from the X lines in Figure 2. When the flows toward the central part of the plasmoid run into each other, the flow with a positive $V_x$ runs head on to the flow with a negative $V_x$ and then the flows are deflected to the upper and lower sides. The outflows along the z direction are formed in the central region of the plasmoid and result in the extension of the plasmoid in the z direction. As seen in Figures 2a and 2b, the ion flow and electron flow are the symmetric patterns with respect to the x axis ($z = 0$) and the plasmoid center. The maximum speed of the electron flow ($V_e|_{\text{max}} = 2.66V_A$) is much larger than that of ion flow ($V_i|_{\text{max}} = 0.64V_A$). In particular, the electron flow is much faster than the ion flow near the X lines. It indicates that the motion of electrons and ions decouples in the vicinity of the X lines.

In order to get a better understanding of the time evolution in the magnetic signature within the plasmoid, at four different times ($t = 16.5, 18.5, 19.0$ and $20.0\tau_A$) we have plotted the profiles of the field components $B_x$ (dashed line), $B_y$ (solid line) and $B_z$ (dot-dashed line) along x at $z = -0.8d_i$ in Figure 3 (the cuts are marked by the white dashed lines in Figure 1). The component $B_x$ has the familiar bipolar signature which is first negative and then switches to positive. The amplitude of the $B_x$ bipolar signature increases and the interval between the bipolarity shortens as the time elapses. The $B_x$ component reaches the maximum at the edges of the plasmoid and becomes of the minimum at the center of plasmoid. The profiles of $B_x$ are the concave curves and the depth of the concave-down signature increases with time, as seen in Figure 3. Note that the profiles in Figure 3 are plotted along the cuts with same location at four separate times and so such developing behaviors in both $B_x$ and $B_y$ are related to the extension of the plasmoid in the z direction. In addition, there is a more notable time evolution in the profiles of the out-of-plane component $B_y$. At $t = 16.5\tau_A$ the $B_y$ profile is a bipolar signature ($-/+$) which is associated with the $B_y$ field generated by two neighboring X lines. The amplitude of the bipolar signature with ($-/+$) pattern enhances and a new bipolar signature, which is first positive and switches to negative, appears between the original ($-/+$) signatures at $t = 18.5\tau_A$. The inner ($+/-$) bipolar signature, which arises from the new emerging $B_y$ quadrupole structure in the plasmoid, grows with time and its amplitude is almost equal to that in the original bipolar signature at $t = 20\tau_A$. In Case 1 the $B_y$ profiles including inner and outer bipolar variations exhibit a wavelike fluctuation feature that is similar to the hybrid simulation by Karimabadi et al. [1999]. The bipolar and wavelike signatures of $B_y$ in Figure 3 are in line with the observed features of a closed-loop plasmoid in the magnetotail. The waveform features in both $B_y$ and $B_z$ were investigated using an MHD simulation without Hall effect [Jin et al., 2001]. Some of multiple plasmoids in the cases of Type II showed the bipolar variations of the $B_y$ component, but such signatures with very small amplitudes was not a good representation of the observed bipolar feature in the $B_y$ component [Deng et al., 2004; Zong et al., 1997;...
Moldwin and Hughes [1992] due to the absence of Hall effect.

3.2. Case 2: $B_{yo} = 0.1$

At $t = 16.5\tau_A$ and $t = 19.0\tau_A$ the magnetic field configuration and the $B_y$ contours are shown in Figures 4a and 4b, respectively. The reconnection configurations in Figure 4 are similar to those in Figure 1. The pictures of $B_y$ in Case 2 of $B_{yo} = 0.1$ have somewhat resemblance to those in Case 1 ($B_{yo} = 0$). However, due to the addition of $B_{yo} = 0.1$ the maximums and minimums of $B_y$ contours in Case 2 are larger than those in Case 1, as shown in the color bars of Figure 1. At $t = 19.0\tau_A$ the inner $B_y$ structure, in which the red areas with $B_y > 0.1$ are larger than blue areas with $B_y < 0.1$, has formed in the plasmoid. To compare with Case 1, the profiles of the field components $B_x$ (dashed line), $B_y$ (solid line) and $B_z$ (dot-dashed line) along $x$ at $z = -0.8d_i$ at four corresponding times are illustrated in Figure 5. The time evolutions of the $B_x$ and $B_z$ components in Figure 5 resemble to those in Figure 3. Some differences can be found by the comparison between the $B_y$ profiles in Case 2 and Case 1. At $t = 16.5\tau_A$ the $B_y$ profile is a bipolar variation with respect to $B_{yo} = 0.1$, which is first less than 0.1 and then switches to be larger than 0.1. The variation amplitude with $B_y > 0.1$ is obviously larger than that with $B_y < 0.1$ in the $B_y$ signature. A new bipolar variation about $B_y = 0.1$, which is first larger than 0.1 and switches to be less than 0.1, appears between the minimum and maximum associated with the original $B_y$ signature at $t = 18.5\tau_A$. The inner signature associated with the new emerging $B_y$ structure grows with time and a wavelike fluctuation signature of $B_y$ component occurs in Figures 5c and 5d. The fluctuation signatures have an asymmetric feature, namely, its amplitude and width in the $B_y > 0.1$ region are notably larger than those in the $B_y < 0.1$ region in Case 2 with a small guide

Figure 4. The magnetic field lines (solid lines) and the contours of out-of-plane magnetic field $B_y$ (color plots) for Case 2 with $B_{yo} = 0.1$ at (a) $t = 16.5\tau_A$ and (b) $t = 19.0\tau_A$. 

Figure 3. The profiles of three components, $B_x$ (dashed line), $B_y$ (solid line), and $B_z$ (dot-dashed line), of magnetic field along $x$ at $z = -0.8d_i$ for Case 1 with $B_{yo} = 0$ at (a) $t = 16.5\tau_A$, (b) $t = 18.5\tau_A$, (c) $t = 19.0\tau_A$ and (d) $t = 20.0\tau_A$. 

Figure 5.
Figure 5. The profiles of three components, $B_x$ (dashed line), $B_y$ (solid line), and $B_z$ (dot-dashed line), of magnetic field along $x$ at $z = -0.8d_i$ for Case 2 with $B_{y0} = 0.1$ at (a) $t = 16.5\tau_A$, (b) $t = 18.5\tau_A$, (c) $t = 19.0\tau_A$, and (d) $t = 20.0\tau_A$.

Figure 6. The magnetic field lines (solid lines) and the contours of out-of-plane magnetic field $B_y$ (color plots) for Case 3 with $B_{y0} = 0.5$ at (a) $t = 17.5\tau_A$, (b) $t = 19.0\tau_A$, (c) $t = 20.0\tau_A$, and (d) $t = 20.5\tau_A$. 
field \((B_{y0} = 0.1)\). The asymmetric behavior of the \(B_y\) signature becomes more notable as \(B_{y0}\) increases. The \(B_y\) profile is translated into a unipolar variation with \(B_y > 0\) when \(B_{y0}\) reaches or exceeds 0.3.

3.3. Case 3: \(B_{y0} = 0.5\)

[17] At four separate times \((t = 17.5, 19.0, 20.0\) and \(20.5\tau_A)\) the situations of multiple X line reconnection are shown in Figure 6, in which the magnetic field lines and the contours of the out-of-plane magnetic field \(B_y\) are marked by the solid lines and the color plots, respectively. The plasmoids are bound between two adjacent X lines and the basic behavior in the magnetic field configuration of Case 3 \((B_{y0} = 0.5)\) is similar to that of Case 1 with \(B_{y0} = 0\), as seen in Figure 6. However, the plot of \(B_y\) in Figure 6 is notably different from that in Figure 1. As seen in Figure 6, the \(B_y\) field changes from a quadrupolar to a unipolar structure with positive value at every one of the X lines due to the addition of the initial guide field \(B_{y0}(= 0.5)\). Such a unipolar \(B_y\) structure with four branches is referred to as the four-wing structure in the following. The intensity of \(B_y\) in the plasmoid is nearly a constant \((B_y / C25 = 0.55)\) until \(t = 17.5\tau_A\) as seen in Figure 6a. In this phase \((t \leq 17.5\tau_A)\) \(B_y\) in the plasmoid gradually increases due to the continuous addition of \(B_y\) flux which is carried from the lobe regions near the boundaries into the plasmoid-like regions by the plasma inflows imposed at the top and bottom boundaries where \(B_y\) is maintained at its initial value \((B_{y0} = 0.5)\). The size of the plasmoid in the \(z\) direction gradually increases and the opennesses of the \(B_y\) structures are correspondingly extended in Figure 6, which is similar to that in Figure 1.

There occur two red regions with enhanced \(B_y\) near the four-wing structures at two neighboring X lines in Figure 6b \((t = 19\tau_A)\). The enhanced \(B_y\) regions in Case 3 resemble to the inner quadrupole \(B_y\) structures in Case 1 \((B_{y0} = 0)\), but the regions with \(B_y < 0.5\) disappear in the new emerging structure at \(t = 19\tau_A\) due to the presence of the guide field \(B_{y0}(= 0.5)\). The additional \(B_y\) flux carried by the plasma flow result in the inward shift of two red regions with enhanced \(B_y\). An S-shaped region is formed within the plasmoids while the two red \(B_y\) regions connect each other, as seen in Figures 6c and 6d. The similar result from the hybrid simulation was obtained by Karimabadi et al. [1999]. In Figures 6a, 6b, and 6c the \(B_y\) pictures have evolved into the nonuniform patterns including the red regions with the enhanced \(B_y\) and the green (or blue) regions with the reduced \(B_y\) in the plasmoids. The blue and green regions with the reduced \(B_y\) extend while the \(B_y\) intensity in the red region enhances, as seen in Figures 6c and 6d. This indicates that the \(B_y\) field is transferred and concentrated onto the red regions after the occurrence of the enhanced \(B_y\) regions caused by Hall effect. As a result the maximum of \(B_y\) \((B_y / max)\) in the plasmoid rapidly strengthens. We suggest that the rapid growth of core \(B_y\) field in the plasmoid might be associated with the Hall effect since the concentration of \(B_y\) field takes place after the emergence of the enhanced \(B_y\) regions caused by Hall effect. As a result the maximum of \(B_y\) \((B_y / max)\) in the plasmoid rapidly strengthens. We suggest that the rapid growth of core \(B_y\) field in the plasmoid might be associated with the Hall effect since the concentration of \(B_y\) field takes place after the emergence of the enhanced \(B_y\) regions caused by Hall effect.
the plasmoid in the later phase might be attributed to the interaction between Hall effect and the additional $B_y$ flux in Case 3. A further discussion on the growth of core field can be found in section 4.

[18] The velocity vector plots of the in-plane ion and electron flows at $t = 20.0 \tau_A$, as illustrated in Figures 7a and 7b, respectively. The maximum speed of the electron flow ($V_{\text{e,max}} = 2.91 V_A$) is much larger than that of ion flow ($V_{\text{i,max}} = 0.59 V_A$) and so there is the decoupling of electron and ion in vicinity of the X line in Case 3 as well. As seen in Figure 7, the ion flow remains approximately symmetric with respect to the x axis ($z = 0$), but the electron flow becomes an asymmetric pattern. Near the edge of the plasmoid the electrons have a stronger flow pointing to the central region of plasmoid in the upper right and lower left quadrants, whereas they have a flow pointing to the X line in the upper left and lower right quadrants of the plasmoid. The initial magnetic field is a noncoplanar field due to the presence of guide field $B_{y0} = 0.5$ in Case 3. It can be found by comparing Figure 7 with Figure 2 that the outflow along the z direction in Case 3 is weaker than that in Case 1. Such a weaker flow in the z direction is attributed to a less deflection of the flow in the noncoplanar Case 3 as compared to Case 1. The plasma flows with positive and negative $V_z$ are displaced with respect to each other, as the situation interpreted by Karimabadi et al. [1999]. As a consequence the extension of plasmoid in the z direction in Case 3 is slower than that in Case 1. This feature is comparable to that in Hall MHD reconnection with a single X line [Yang et al., 2008] in which the openness of the magnetic separatrix angle is slightly reduced as a nonzero $B_{y0}$ is added.

[19] Figure 8 shows the profiles of the field components $B_x$ (dashed line), $B_y$ (solid line) and $B_z$ (dot-dashed line) of magnetic field for Case 3 with $B_{y0} = 0.5$ at (a) $t = 17.5 \tau_A$, (b) $t = 19.0 \tau_A$, (c) $t = 20.0 \tau_A$, and (d) $t = 20.5 \tau_A$ along the cuts which are marked by the white dashed lines in Figure 6.

The field component $B_x$ reaches the maximum at the edges of the plasmoid and becomes of the minimum at the center of the plasmoid and so the $B_x$ profiles also are the concave curves. However, the depth of the concave-down signature in the $B_x$ profile, which is made on the different location at the different time in Figure 8, does not have a regular development like that in Figure 3. It is worthy of note that the $B_x$ profiles of Case 3 display the distinct behavior from Case 1. At $t = 17.5 \tau_A$ (Figure 8a) the $B_x$ shows a valley and peak at $x = 8.4 d_i$ and $26.3 d_i$, which are associated with the $B_y$ four-wing structure at neighboring the X lines. The intensity of $B_y$ between the valley and peak is an approximate constant ($B_y \approx 0.6$). In the early phase ($t \leq 17.5 \tau_A$) the approximately uniform $B_y$ in the $B_x$ profiles gradually increases with time due to the inward transportation of the $B_y$ flux from the lobe region near the boundaries. There occurs a $B_y$ bulge associated with the red enhanced $B_y$ region in Figure 8b ($t = 19.0 \tau_A$). The $B_y$ bulge resembles to inner bipolar signature caused by Hall effect in Figure 3b, but the fluctuation with $B_y < 0.5$ disappears in the inner region of the $B_y$ profile due to the presence of the guide field $B_{y0} = 0.5$. The $B_y$ bulge grows into a peaking signature while the $B_y$ flux is transferred and concentrated onto the enhanced $B_y$ regions in the plasmoid. As seen in Figures 8b, 8c, and 8d, the maximum in the $B_y$ peaking signature enhances and the peak’s location shifts toward the center of plasmoid as the reconnection proceeds. At $t = 20.5 \tau_A$ the maximum of $B_y$ near the center of plasmoid approaches the lobe magnetic field strength. Such a substantial enhancement of the out-of-plane component $B_y$ in the central region of plasmoid might be representative of the observed strong core field in the flux rope structure.

4. Summary and Discussion

[20] The plasmoids have been observed by many spacecrafts in the magnetotail. A large number of plasmoids exhibit a strong core field and were called "magnetic flux...
rope,” and there also exist the plasmoids with closed-looped magnetic field lines in the magnetotail. As mentioned above, the numerical results in the cases with various guide field \( B_0 \) exhibit the features of the different plasmoid-like structures. The origination and evolution of the different features will be discussed in what follows.

4.1. Bipolar and Wavelike Signature of \( B_y \) in Case 1 \( (B_0 = 0) \)

[21] As seen in Figure 1, the picture of \( B_y \) in a plasmoid consists of the quadrupole \( B_y \) fields generated by two adjacent X lines in the early phase, and then it evolves into two regions with different quadrupole structures. The inner region is composed of the new emerging \( B_y \) having the opposite polarities from those in the outer region. The profile of \( B_y \) component correspondingly develops from a bipolar signature into a bipolar fluctuation signature. There is no addition of \( B_y \) flux since \( B_y \) is maintained at zero along the top and bottom boundaries; in other words, the formation of the bipolar and fluctuation signatures is independent of the external mechanism in Case 1 with \( B_0 = 0 \). As seen in Figure 2, the outflows along the \( z \) direction are formed in the central region of the plasmoid and result in the extension of the plasmoid in the \( z \) direction. The new \( B_y \) structures emerge within the original quadrupole structure when its openness is extended to large enough. This situation is rather similar to our previous result [Jin et al., 2005] in which the openness of the quadrupolar \( B_y \) structure is enlarged as \( \beta \) increases and the fine structures of \( B_y \) contours with the reversed signs emerge as \( \beta > 2.0 \).

[22] In order to get a better understanding of the inner \( B_y \) structures, at four separate times we have plotted the profiles of both \( x \) and \( z \) components in the electron velocity \( V_e \) and ion velocity \( V_i \) as well as the profiles of \( B_y \) component at \( z = -0.8d_i \) along \( x \) in Figure 9 where \( V_e \) and \( V_i \) are marked by the solid line and dashed line, respectively. In Figure 9 the profiles of \( V_e, V_{ix}, V_{iz} \) (first plot) and the profiles of \( V_{ex}, V_{iz} \) (second plot) display the time evolution of the decoupling motion between the electrons and ions: At \( t = 16.5 \tau_j \) the \( V_{ix} \) signature with a small amplitude is first positive and then switches to negative, but \( V_{ex} \) switches from negative to positive via a central range with zero magnitude, and so there exists the obvious separation of \( V_{ex} \) and \( V_{ix} \) in two regions of the profiles. In the second plot of Figure 9a \( V_{iz} \) only slightly separates from \( V_{ex} \). The profile of \( B_y \) in Figure 9a is a bipolar signature associated with the \( B_y \) quadrupolar structures at two neighboring \( x \) lines. It can be found comparing the \( B_y \) profile with the profiles of \( V_{ex} \) and \( V_{ix} \) that the \( B_y \) bipolar signature is corresponding to the decoupling regions of electrons and ions in Figure 9a. At \( t = 18.5 \tau_j \) the amplitude in the \( (+/-) \) bipolar signature of \( V_{ix} \) is notably larger than that at \( t = 16.5 \tau_j \). The original \( (+/-) \) bipolar signature of \( V_{ex} \) becomes narrower and a new \( V_{iz} \) bipolar signature with \( (+/-) \) pattern occurs inside the original \( (+/-) \) signature in first plot of Figure 9b. In second plot of Figure 9b the profile of \( V_{iz} \) still is a concave curve, but \( V_{ex} \) shows the bipolar variations with \( +/- \) and \( -/+ \) patterns at the left and right sides of the plasmoid. A new bipolar \( B_y \) signature with \( (+/-) \) pattern appears inside the original \( (+/-) \) \( B_y \) signature in third plot of Figure 9b. Interestingly, the new bipolar \( B_y \) signature coincides with the regions where later decoupling of the electrons and ions takes place. As seen in Figure 9c \((t = 19.0 \tau_j)\) and Figure 9d \((t = 20.0 \tau_j)\), the inner \( B_y \) bipolar signature grows up as the separation between \( V_{ex}, V_{ez} \) and \( V_{ix}, V_{iz} \) develops. Therefore, the reversal currents caused by the additional decoupling of electrons and ions might be responsible for the new bipolar signature corresponding to the inner quadrupole structure of \( B_y \) in Figure 1; in other words, the observed bipolar or waveform signature of \( B_y \) component in the closed-loop-like plasmoid might arise from the effect of Hall current. As mentioned in Case 2, the bipolar feature still exists in the \( B_y \) profile although the variation amplitude with \( B_y > 0 \) is considerably larger than that with \( B_y < 0 \) in the presence of a small guide field \((B_0 = 0.1)\) and the asymmetric behavior becomes more notable as \( B_0 \) increases. Such an asymmetric bipolar feature of \( B_y \) component could be comparable with a closed-loop plasmoid. The typical feature of a magnetic flux rope is shown in the cases with \( B_0 \) ≥ 0.3. The result in Case 2 with \( B_0 = 0.1 \) might exhibit the transition situation from the closed-loop plasmoid to magnetic flux rope.

4.2. Development of the Core Field Within the Plasmoid for the Cases With \( B_0 \) ≥ 0.3

[23] When \( B_0 \) reaches or exceeds 0.3, the \( B_y \) component is the positive everywhere, which is in line with the hybrid simulation by Karimabadi et al. [1999] and the Hall MHD simulations with a single X line by Yang et al. [2008] and Huba [2005], and the \( B_y \) profile becomes of a unipolar variation. As shown in Case 3 \((B_0 = 0.5)\), a \( B_y \) bulge appears as the enhanced \( B_y \) regions take place in the plasmoid, and then it grows into a peaking signature in the \( B_y \) profile of Figure 8. The maximum in the \( B_y \) peaking signature increases with time and approaches the lobe magnetic field strength. Such a substantial enhancement of the out-of-plane component \( B_y \) in the central region of plasmoid is consistent with the observed feature of strong core field in the flux rope structure.

[24] In order to get a better understanding of the growth of the core field, we investigate the cases with \( B_0 \) ≥ 0.3. Figure 10 shows the time history of the \( B_y \) component at the center of the plasmoid \((x = 18d_i, z = 0d_i)\), which is referred to as \( B_y^* \) in the following, for five cases with \( B_0 = 0, 0.3, 0.5, 0.7 \) and 1.0. As seen in Figure 10, the evolution of \( B_y^* \) can be divided into two stages: At the first stage the intensity of \( B_y^* \) gradually increases with time, while the \( B_y \) component is approximately uniform in the plasmoid. The gradual enhancement of \( B_y^* \) in the plasmoid is attributed to the continuous addition of \( B_y \) flux from the lobe regions near the top and bottom boundaries where \( B_y \) is maintained at its initial value \( B_0 = 0.5 \). In the first phase the mean increasing rates of \( B_y^* \) \( \Delta B_y^*/\Delta t \) increases with increasing \( B_0 \), namely, the growth of \( B_y^* \) becomes faster as \( B_0 \) increases. In addition, the \( B_y^* \) remains zero throughout the reconnection process in Case 1 \((B_0 = 0)\). The reason is that there is no the addition of \( B_y \) flux since the \( B_y \) component at the top and bottom boundaries is maintained at zero in Case 1. Interestingly, for four cases with a finite \( B_0 \) in Figure 10 the intensity of \( B_y^* \) is quickly raised at the second stage that starts from the occurrence of the enhanced \( B_y \) region in the plasmoid. The enhanced \( B_y \) regions resembling to the inner quadrupole \( B_y \) structures in Case 1, are also generated by Hall current associated with the
Figure 9. The profiles of both x and z components in the electron velocity $V_e$ (solid line) and ion velocity $V_i$ (dashed line), and the profiles of the $B_y$ component along x at $z = -0.8d_i$ for Case 1 with $B_{y0} = 0$ at (a) $t = 16.5 \tau_A$, (b) $t = 18.5 \tau_A$, (c) $t = 19 \tau_A$, and (d) $t = 20 \tau_A$. 
decoupling of electrons and ions. As is readily evident from Figure 10, the nonlinear development in the second phase can make a greater contribution than the simple superposition of the $B_y$ flux added by the plasma inflow to the growth of the core $B_y$ field in the cases with $B_{y0} \geq 0.3$. In the second phase an S-shaped region is formed, the $B_y$ field is concentrated onto the enhanced $B_y$ region and the maximum of $B_y$ rapidly strengthens while the $B_y$ is continuously translated into the plasmoid-like regions, as shown in Case 3 ($B_{y0} = 0.5$). In contrast, the enhancement of $B_y$ does not occur although there also exists the Hall effect in Case 1 ($B_{y0} = 0$). The reason might be that there is no the continuous addition of $B_y$ flux in Case 1. This implies that the nonlinear enhancement of the core $B_y$ field might arise from the interaction between the Hall effect and the continuous addition of $B_y$ flux. In the second phase $B_y$ is the enhanced $B_y$ intensity and its time evolution is representative of rapid growth of $B_y$ intensity in the enhanced $B_y$ region, but $B_y$ does not necessarily be the maximum of $B_y$ ($B_{y\text{max}}$, i.e., the intensity of the core field) and the location of $B_{y\text{max}}$ varies with time in the second stage. In order to illustrate the differences between $B_y$ and $B_{y\text{max}}$, we have plotted $B_{y\text{max}}$ and $B_y$ at $t = 20\tau_A$ as a function of $B_{y0}$ in Figure 11. As seen in Figure 11, $B_{y\text{max}}$ and $B_y$ are almost linearly raised, and $B_y$ gradually approaches $B_{y\text{max}}$ as $B_{y0}$ increases; in other words, the larger the initial guide field $B_{y0}$ is, the stronger the intensity of the core field is and the closer to the center of the plasmoid the core field is.

[25] The results mentioned above indicate that the strong core $B_y$ field in the plasmoid can be created in the presence of a sufficiently large guide field ($B_{y0} \geq 0.3$) and has the same direction as the initial guide field (preexisting cross-tail field). In order to understand the physics of the second stage, the profiles of $B_y$ component at $z = -0.02d_l$ and $z = -0.37d_l$ for Case 3 ($B_{y0} = 0.5$) and Case 1 ($B_{y0} = 0$) are plotted in Figures 12a and 12b, respectively. As seen in Figure 12a, the $B_y$ profiles in the plasmoid at $t = 14.0$, 15.5 and 16.5$\tau_A$ are approximate to the level lines. It indicates that there is a region with an approximately uniform $B_y$ in the plasmoid and the intensity of $B_y$ gradually increases with time due to the inward transportation of the $B_y$ flux from the lobe region at the early stage. At $t = 18.0\tau_A$ two $B_y$ bulges associated with the enhanced $B_y$ regions in the plasmoid emerge in the $B_y$ profile. The bulges of $B_y$ grow while they move inward, and coalesce into a peaking signature at $t = 20\tau_A$. The maximum in the $B_y$ peaking signature enhances with time. Such development of the $B_y$ profile corresponding to the second phase in Figure 10, starts from the occurrence of the enhanced $B_y$ region in the plasmoid. There are the following evolving features in the $B_y$ profiles of Figure 12a for $t > 18\tau_A$: (1) The increase in the $B_y$ intensity is accompanied by the contraction of the region with the enhanced $B_y$. (2) The region with $B_y < 0.6$ extends while $B_y$ in the region with $B_y > 0.6$ rises in Figure 12a, namely, the blue and green regions with the reducing $B_y$ extend while the $B_y$ intensity in the red region enhances, as seen in Figures 6c and 6d. It indicates that the transference and concentration of $B_y$ flux from the region with lower $B_y$ intensity to the red region. In Case 3 there is the continuous addition of $B_y$ flux which is carried from the lobe region into the plasmoid-like regions by the plasma inflows imposed at the top and bottom boundaries where $B_y$ is maintained at its initial value ($B_{y0} = 0.5$). The additional $B_y$ flux might result in the coalescence and compression of the enhanced $B_y$ region. The transference and concentration of $B_y$ flux toward the red regions with the enhanced $B_y$ lead to the rapid rise of the $B_y$ peaking signature in the second phase. In contrast to Figure 12a, the inner bipolar signature of $B_y$ component grows as the decoupling motion between the electrons and ions develops in Figure 12b. However, the inward shift and coalescence of positive and negative signatures do not take place; and there does not exist the transference and concentration of $B_y$ flux in the inner bipolar signature of Case 1. The distinction of Figure 12b from Figure 12a arises from that there is no any addition of $B_y$ flux since $B_y$ is maintained at zero along the top and bottom boundaries in Case 1. These results imply that the interaction between Hall effect and the $B_y$ flux added by the...
plasma inflow might be responsible for the rapid growth of the core \( B_y \) field in the second phase of the cases with a finite \( B_{y0} \) in Figure 10. Besides, as seen in the time histories of \( B_y^* \) of Figure 10, \( B_y^* \) decays and increases once more after it quickly grows to the maximum. Such a process is associated with the temporary extension and succedent contraction of the red enhanced \( B_y \) region in the plasmoid.

[26] As mentioned in section 2, the generalized Ohm’s law including the Hall current and scalar electron pressure gradient terms is combined in Faraday’s induction equation and the 2.5-D Hall MHD equations in dimensionless forms are formed [Jin et al., 2005; Yang et al., 2006]. In the Hall MHD equations the dimensionless parameters \( c_m, K_H \) and \( K_P \) are given by the expression (4) and the terms with \( K_H \) and \( K_P \) are attributed to the effects of the Hall current and pressure gradient in the generalized Ohm’s law. In order to investigate the important factor controlling the occurrence and development of the second stage, we take \( L_z = L_0 = 7d_i \) and \( L_x = 12L_0 = 84d_i \) and carry out the supplementary cases with \( B_{y0} = 0.3, 0.5 \) and 0.7. Obviously, \( K_H = d_i/L_0 = 1/7 \) in these cases is smaller than that (\( K_H = 1/5 \)) in the cases of Figure 10. The waveform inflows \( V_z \) imposed at the top and bottom boundaries is given by the expression (5). The initial equilibrium state is driven by the waveform inflows, and three reconnection X lines and the plasmoids bound between two adjacent X lines are formed in the simulation box of \( L_x/L_z = 12 \). In the supplementary case with \( B_{y0} = 0.5 \) (\( L_0 = 7d_i \)) the basic behavior of the magnetic field configuration is similar to that in Case 3 (\( B_{y0} = 0.5, L_0 = 5d_i \)), however, the emergence of the red regions with enhanced \( B_y \) in the plasmoids is notably postponed in comparison with Case 3. For the further comparison of the cases with \( L_0 = 7d_i \) with the corresponding cases (\( L_0 = 5d_i \)) in Figure 10 the histories of \( B_y^* \) (i.e., the \( B_y \) intensity at the center of the plasmoid) are plotted in Figure 13, in which \( d_i/V_A \) is used as the unit of time and the histories of \( B_y^* \) for the cases of \( L_0 = 7d_i \) and \( L_0 = 5d_i \) are marked by the dot-dashed lines and the solid lines, respectively. There are also two developing stages in the \( B_y^* \) histories marked by the dot-dashed lines, as seen in Figure 13. However, the beginning times of the second stage are substantially postponed and the rapid increasing amplitudes of \( B_y^* \) in the cases with \( L_0 = 7d_i \) are obviously smaller than those in the original cases (\( L_0 = 5d_i \)). The 2.5-D Hall MHD equations in dimensionless forms are numerically solved in the simulation boxes with same dimensionless length (\( L_x/L_z = 1.0 \) and \( L_x = 12.0 \) in unit of \( L_0 \)) and the same inflow and

Figure 12. The profiles of the \( B_y \) component along \( x \) (a) at \( z = -0.02d_i \) at seven different times for Case 3 (\( B_{y0} = 0.5 \)) and (b) at \( z = -0.37d_i \) at four different times for Case 1 (\( B_{y0} = 0 \)).

Figure 13. Time history of \( B_y^* \) (the \( B_y \) intensity at the center of the plasmoid) for the cases with \( L_0 = 7d_i \) (dot-dashed lines) and \( L_0 = 5d_i \) (solid lines) using \( d_i/V_A \) as the time unit.
By pressure gradient is negligible in the cases with the initial guide field. Comparative tests indicate that the reconnection dynamics is observed in islands, such as density compression, bipolar core and plasma density at \( t = 20.5 \tau_A \). This means that in the second stage are attributed to the reducing Hall effect in the cases with \( L_0 = 7d_i \). In consequence, Figure 13 reveals that the intensity of Hall effect has an influence over the generation and evolution of the second phase and it further demonstrates that the interaction between Hall effect and the additional \( B_y \) flux is responsible for the rapid growth of the core \( B_y \) field in the second phase.

[27] Chen et al. [2007] reported the features of the observed islands, such as density compression, bipolar \( B_y \) and single-peaked and double-peaked \( B_y \), and demonstrated that these features were the generic signatures of two-dimensional magnetic islands using a Hall MHD simulation with an initial guide field \( B_{yo} = 1.0 \) [Chen et al., 2007]. The region with a compressed plasma density is consistent with the accumulational region of electrons in the Hall MHD model based on the assumption of the electrical neutrality. In this section we investigate Case 4 with \( B_{yo} = 0.3 \), which might be comparable in magnitude to a preexisting cross-tail component in the magnetotail. The plots of \( B_y \) component and plasma density at \( t = 20.5 \tau_A \) for Case 4 are shown in Figures 14a and 14b, respectively. As seen in Figure 14, there are a compressed density area and an S-shaped region with the enhanced \( B_y \) in the plasmoids, but the S-shaped region does not coincide with the central area with the compressed plasma density in Case 4 (\( B_{yo} = 0.3 \)). It can be found from Figure 11 that the difference between \( B_y \) and \( B_y \) decreases with increasing \( B_{yo} \); in other words, the enhanced \( B_y \) region gradually approaches the central area of the plasmoid as \( B_{yo} \) increases. To compare with the observation, we have plotted the profiles of the \( B_y \) components (solid line), \( B_z \) component (dotted line) and plasma density \( \rho \) (dashed line) along cut 1 and cut 2 in Figures 14a and 14b, respectively. Cut 1 at \( z = -1.39d_i \) across the maximum of \( B_y \) and cut 2 at \( z = -0.06d_i \) cross over the central region of the plasmoid. The snapshot of cut 1 (Figure 15a) shows a bipolar \( B_y \) pulse, a compressed density region (\( \rho_{\text{max}} \approx 3.3 \)) peaked at the center of the plasmoid, a major peak of (\( B_y \) max \approx 0.8) near the plasmoid’s center and a secondary \( B_y \) peak related to the four-wing structure of \( B_y \) at the X line. Figure 15b illustrates a bipolar \( B_x \), a high density region (\( \rho_{\text{max}} \approx 3.6 \)) and a double peaked \( B_y \) in the central region of the plasmoid. The results illustrated in Figure 15a and 15b qualitatively resemble to Cluster observation [Chen et al., 2007], that might be an evidence for the development of core \( B_y \) field in the case with a small initial guide field. In order to get a better understanding for the development of compressed plasma density in the plasmoid. At four different times the profiles of plasma density \( \rho \) along \( x \) at \( z = -0.32d_i \) for Case 1 (\( B_{yo} = 0 \)) and Case 4 (\( B_{yo} = 0.3 \)) are shown in Figures 16a and 16b, respectively. In the plasmoid there is a high density region arising from that the current layer is a region with enhanced plasma density in the initial equilibrium state, as seen in Figures 16a and 16b. This region is compressed and the density in the compressed region increases with time. The similar feature in Figure 16a and Figure 16b might be related to the same inflow from the boundaries where \( \rho \) is maintained at the initial value \( \rho_0 \). The plasma flows from the boundaries and the two X lines compress the regions with higher densities and pile up the plasma within the plasmoids causing the plasma density to be enhanced. This means that the plasma inflow might play an important role in generating the link between compressed plasma density and magnetic islands during reconnection. It can be found by comparing Figure 16b with Figure 16a that the maximums of density \( \rho_{\text{max}} \) in Case 4 (\( B_{yo} = 0.3 \)) are about the same as...
those in Case 1 \((B_y^0 = 0)\) at \(t = 15\tau_A\) and \(17\tau_A\). However, \(\rho_{\text{max}} \approx 2.9\) and \(\rho_{\text{max}} \approx 3.5\) in Case 4 are lower than \(\rho_{\text{max}} \approx 3.2\) and \(\rho_{\text{max}} \approx 3.8\) in Case 1 at \(t = 19\tau_A\) and \(20\tau_A\), respectively, when \(B_y^*\) in Case 4\((B_y^0 = 0.3)\) is rapidly growing, as seen in Figure 10. And \(\rho_{\text{max}}\) decreases with increasing \(B_y^0\) in a series of cases with various \(B_y^0\) at a corresponding time of the second phase shown in Figure 10. Such results indicate that the compression of plasma density could be restricted due to the growth of core \(B_y\) field. Besides, as shown in Figure 16b, the central region of the plasmoid is a compressed density area and also a higher plasma pressure region in Case 4 with \(B_y^0 = 0.3\). Therefore, the plasmoid-like structure with a core \(B_y\) field in the cases with \(B_y^0 \geq 0.3\) could not be characterized as a force-free rope structure.

[29] The following conclusions can be drawn from the above results. (1) Hall effect and a preexisting cross-tail

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure15.png}
\caption{The profiles of the \(B_z\) component (solid line), \(B_z\) component (dotted line), and plasma density \(\rho\) (dashed line) for Case 4 with \(B_y^0 = 0.3\) at \(t = 20.5\tau_A\) along the two cuts which are marked by the white dashed lines in Figure 14.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure16.png}
\caption{The profiles of plasma density \(\rho\) along \(x\) at \(z = -0.32d_i\) at four different times (a) for Case 1 \((B_y^0 = 0)\) and (b) for Case 4 \((B_y^0 = 0.3)\).}
\end{figure}
component $B_y$ are two important factors controlling the occurrence of various plasmoid-like structures in the magnetotail. (2) In the second phase the nonlinear interaction between Hall effect and the additional $B_y$ flux can make a greater contribution than the simple accumulation of the $B_y$ flux fed by the plasma inflow to the growth of the core $B_y$ field. (3) The development of core $B_y$ field in the plasmoid could restrict the compression of plasma density.

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References


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