A simple model of core field generation during plasmoid evolution

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Abstract. Bipolar magnetic field signatures in the far magnetotail observed by the ISEE 3 spacecraft are commonly interpreted as signatures of a passing magnetic bubble, or plasmoid. A large number of such plasmoid-type variations in the north-south component of the magnetic field are accompanied by large core magnetic fields which are directed primarily in the cross-tail direction, indicating a flux rope-like structure. Similar signatures are also found in a recent examination of GEOTAIL deep tail data. The fact that more of these flux ropelike plasmoids are encountered in the far tail than closer to the Earth raises the question whether they are the result of an evolution from no or low core fields to high core fields or whether plasmoids without core fields and flux ropes are entirely different entities. We present a model which explains the evolution of a looplike plasmoid in the near tail to a thinner flux rope in the far tail. The transition is accomplished by magnetic reconnection, which progressively connects the plasmoid magnetic field lines to the colder plasma in the low-latitude boundary layer and magnetosheath. The connection leads to a draining of hot plasma from plasmoid field lines and a subsequent collapse due to the plasma pressure reduction. The collapse causes a strong enhancement of any preexisting cross-tail magnetic field component, until a quasi-force-free state is reached. We also present MHD simulations to demonstrate the process. Last, we show that this mechanism can produce core field enhancements beyond the ambient lobe field strength.

1. Introduction

Apart from theoretical investigations which predicted plasmoid-like structures as a result of a global magnetotail instability [e.g., Schindler, 1974], observational evidence of plasmoids was presented first by Hones [1977]. In his cartoon of substorm evolution, Hones depicted a plasmoid as a plasma sheet region which becomes disconnected from the geomagnetic field during the course of a substorm. Thus plasmoids consist of looplike magnetic field structures with hot plasma sheet plasma trapped inside. These initial observations used primarily the IMP satellites, which had apogees less than 40 RE. Therefore plasmoid observations during the IMP period were usually limited to investigations of the "trailing region," i.e., the part of the plasmoid volume closest to the Earth.

Ever after Hones's cartoon, plasmoids and their evolution in the far magnetotail have been a prime subject of interest for past and recent deep tail missions. Beginning with the ISEE 3 mission, typical plasmoid signatures such as north-south signatures of the $B_z$ magnetic field component have been identified in a large number of far-tail observations, ranging from $\approx 80$ RE to more than 200 RE downtail from the Earth [e.g., Hones et al., 1984; Baker et al., 1987; Richardson et al., 1987; Slavin et al., 1989, 1992; Moldwin and Hughes, 1991, 1992, 1993]. During periods spent in the magnetotail lobes, magnetic field observations often reflected remote signatures of plasmoids through the associated deformation of the magnetotail lobes: the so-called "traveling compression regions" (TCRs) [Slavin et al., 1984]. By identifying plasmoids directly through plasma sheet observations, or lobe observations of TCRs, it could be shown that each substorm is typically associated with one or more plasmoids which are being ejected down the tail [Slavin et al., 1992, 1993; Moldwin and Hughes, 1993].

Recent investigations of ISEE 3 and GEOTAIL data [Slavin et al., 1989; Fairfield et al., 1989; Moldwin and Hughes, 1991; Nagai et al., 1994; Machida et al., 1994; Frank et al., 1994; Lepping et al., 1995; Slavin et al., 1995] show that a considerable number of plasmoids observed in the far tail exhibit not only the usual bipo-
lar signature in the north-south magnetic field compo-
nent but also a very strong cross-tail \((B_y)\) magnetic field component. In some cases, referred to as "high field regions" (HFRs) by Slavin et al. [1995], the internal magnetic field, largely along the \(y\) direction, exceeds the ambient lobe magnetic field in magnitude. In the following we will denote such structures as "flux ropes," while plasmoids with no or small core \(B_y\) field enhancement will be referred to as "bubbles."

Several attempts have been made to model these flux ropelike structures. Moldwin and Hughes [1990] used an analytical model to fit the observed magnetic field variation. Birn [1991, 1992] developed a theoretical framework based on steady state MHD equilibrium for the self-consistent modeling of bubble-like plasmoid and flux rope structures. Lepping et al. [1995] employ a force-free magnetic field model adapted from the modeling of magnetic clouds in the solar wind. Slavin et al. [1995] combine a force-free magnetic field model with a kinematic model of the outer, not necessarily force free, regions of the plasmoid, and recently, Kivelson and Khurana [1995] employ a self-consistent equilibrium theory to model flux rope type magnetic signatures. While all of these models have advanced our understanding of the internal consistency of these structures, we presently lack knowledge of the formation process of flux ropes, and the relation between them and bubblelike plasmoids, which traditionally have been envisioned as closed magnetic loops with small cross-tail magnetic field components.

In this paper we present a simple model which attempts to answer these questions. In order to provide an explanation we will combine observational evidence with past modeling results pertinent to plasmoid formation and evolution. The combination of these results will lead to a possible evolutionary scenario, which is discussed in the following section. In order to support this qualitative scenario we will also present results of a simple MHD simulation of plasmoid formation, in which the evolution toward a force-free flux rope can be demonstrated. Owing to their simplicity, these MHD simulations are to be taken not as a final step of the investigation but rather as a simple model indicating that the qualitative scenario for flux rope formation may be viable.

2. Evolution of Plasmoids From Looplike Structures to Flux Ropes

To generate a scenario, we need to make use of some well-known observational facts. We list these here and discuss their consequences. The first is that the plasma temperatures in the plasma sheet and the magnetosheath are quite different, with a transition region of the low-latitude boundary layer (LLBL) [e.g., Schapke et al., 1981; Hall et al., 1990]. The fact that sheath ion and electron energies are in the range of 0.1–0.8 keV [e.g., Anderson and Fuselier, 1993] and 0.01–0.1 keV, respectively, while plasma sheet ion and electron energies lie in the range of 5–10 keV and 0.5–2 keV, respectively, indicates that usually there is no magnetic connec-
tion between the regions, since the field-aligned pressure or temperature gradient would immediately lead to the loss of hot magnetotail plasma through mass flow and/or heat flux.

Second, it has been pointed out recently [Lepping et al., 1995; Slavin et al., 1995] that the direction of the internal magnetic field component \(B_y\) in flux ropes correlates very well with the direction of the \(y\) component of the interplanetary magnetic field (IMF). This finding suggests a relation between the core field in these flux ropes and the prevalent small \(B_y\) component present in the magnetotail, which also correlates very well with the IMF \(B_y\) [Fairfield, 1979]. Third, observations of HFRs show that the core field can exceed in magnitude the ambient lobe field. The magnitude of the associated magnetic pressure is thus bigger than that in the lobes.

This finding implies that the internal magnetic field in such a flux rope in an otherwise high \(B = \mu_0 B^2/2\) plasma sheet is nearly force free. This feature suggests that mechanisms capable of reducing the plasma \(\beta\) may be of relevance for the explanation of flux rope formation. Along with the presence of strong core fields, recent observations of the electron temperature inside flux rope structures indicate a reduction below the ambient plasma temperature level [Moldwin and Hughes, 1992].

Finally, we utilize some results of prior modeling efforts. It has been known for some time that plasmoids forming in a magnetotail which exhibits a nonvanishing \(B_y\) magnetic field consist of helical, rather than looplike, magnetic fields [Hughes and Sibeck, 1987]. The evolution of these helical plasmoids has been studied in various tail MHD simulations [e.g., Ogino et al., 1990; Birn and Hesse 1990; Hesse and Birn, 1991]. While these simulations did exhibit plasmoid evolution and disconnection, they typically did not show \(B_y\) enhancements much beyond the initial magnitude. Therefore plasmoids modeled by Hesse and Birn appeared to be helical without a significant core field. The simulations did show, however, the establishment of magnetic connections between the flank regions and the interior region of the plasmoid via helical field lines undergoing reconnection during the disconnection of the plasmoid from the closed field line region [Birn and Hesse, 1990]. As an example, Figure 1, adapted from Birn and Hesse [1990], displays the evolution of a plasmoid in a three-dimensional MHD simulation. The top panel depicts an early stage of the evolution, where the entire plasmoid magnetic flux is still connected to the Earth, represented by the \(x = 0\) boundary in the model. At later times (bottom panel), various magnetic topologies have developed. Besides flux bundles which connect the Earth to the IMF (heavy shading), the plasmoid also includes flux which connects to the IMF region on both ends, including connections through the flank regions at \(y = \pm 10\) (light shading). Investigations by Hesse and Birn [1991] demonstrated that at later times the plasmoid consists entirely of magnetic flux with the latter topology. Similar connections have also been suggested by Moldwin and Hughes [1992] as an explanation of the variation of the average electron pressure and density with downtail distance.
Figure 1. Perspective view of a plasmoid flux rope developing in a three-dimensional MHD simulation. The top panel shows the flux rope at an earlier time \((t = 165)\), and the bottom panel displays the flux rope for \(t = 212\). During the earlier evolution, plasmoid field lines are connected solely to the Earth (or \(x = 0\) in the MHD model), whereas at later times, various magnetic topologies are found. For those times, heavy shading in the bottom panel indicates field lines which connect the Earth to the IMF, whereas light shading denotes completely open flux connected entirely to the IMF. (Adapted from Birn and Hesse [1990])

The combination of these observational and modeling results leads us to suggest the following scenario, illustrated in Figure 2. Initiating in a magnetotail with a net cross-tail magnetic field, three-dimensional magnetic reconnection generates helical field lines (panel a). As magnetic reconnection continues, additional flux is added to the plasmoid at outer, helical layers, while the inner helical field lines are extended to the flank regions by the progression of magnetic reconnection in the same direction (panel b). The continued expansion across the tail will ultimately lead to the establishment of a new magnetic connection of some plasmoid magnetic flux to the cold plasma of the magnetosheath or the LLBL, indicated by the shaded region in panel c. The pressure and/or temperature gradient along the magnetic field will cause mass flow and/or heat flux directed toward the flanks along the magnetic field, indicated by the black arrows. The ensuing pressure loss in the center of the tail causes a reduction of the diameter of the inner region of the plasmoid helix, until the remaining plasma pressure, enhanced by the volume reduction, is again sufficient to balance the ambient lobe pressure (panel d). Any pressure enhancement, however, will lead to an immediate additional drain to the flank regions. Therefore the only mechanism limiting the collapse is the buildup of the \(y\) component of the magnetic field and the magnetic pressure \(B_y^2/2\mu_0\), which assumes the role of the plasma pressure (see below). Thus a force-free flux rope begins to form in the center of the original plasmoid structure. Finally, continuing reconnection will connect outer layers of the original plasmoid to the flanks of the tail as well, causing plasma pressure reductions in those regions (panel e).

Assuming a collapse of the plasmoid diameter as described above, the magnetic field enhancement in the center of the plasmoid is easy to understand. Away
from the reconnection region the plasma flow velocity \( \mathbf{v} \), the electric field \( \mathbf{E} \), and the magnetic field \( \mathbf{B} \) are related via ideal Ohm's law,

\[ \mathbf{E} = -\mathbf{v} \times \mathbf{B} \]  

(1)

As long as (1) is valid, the magnetic flux inside any closed loop transported with the plasma flow is constant with time. If we pick a loop \( L \) circling some \( z-z \) section \( A \) of a plasmoid, then the magnetic flux through this loop, given by

\[ F = \int_A dF B_y \]  

(2)
do not change with time as long as \( L \) is convected with the plasma flow. In the frame moving with the plasmoid, the result is sketched in Figure 3. The plasma velocity in this frame is indicated by the black arrows. If the area enclosed by \( L \) decreases, the conservation of magnetic flux inside \( L \) necessarily implies an enhancement of \( B_y \). In our picture the reduction of plasmoid diameter will continue until the magnetic pressure inside the plasmoid balances the tension forces exerted by the ambient magnetic field. The resulting configuration resembles a force-free magnetic flux rope.

In summary, we suggest that helical plasmoid field lines generated by magnetic reconnection evolve until they extend to the flanks of the magnetotail. Since the inner regions of the resulting helical flux bundle are the most advanced, and the \( x \) and \( z \) components of \( \mathbf{B} \) are the smallest there, they should be first to be connected to the colder plasma of the LLBL/magnetosheath. The magnetic connection to colder plasma will lead to a pressure loss through heat flux or mass flow, or a combination of both. The pressure reduction will lead to collapse of the plasmoid cross section, initiating in the innermost regions, until the enhancement of the enclosed cross-tail flux is sufficient to balance the magnetic tensions of the ambient field. Therefore the highest \( B_y \) enhancements will be found in the center region of the plasmoid, followed by the outer regions as more flux becomes connected to the flank regions. Initiating in the core regions, the plasmoid will thus more and more resemble a force-free flux rope.

In the following section we will present results from a simple 2 1/2-dimensional resistive MHD simulation of plasmoid formation and evolution, in which we have attempted to include the effects of plasma pressure and density reduction in the form of an appropriate transport model.

3. Simulation Model and Initial Conditions

We initialize the simulation with a two-dimensional magnetotail equilibrium derived from the asymptotic theory of Birn et al. [1975]. The magnetic field lines are determined by the flux function

\[ A = \ln \cosh(f(x)z) - \ln(f(x)) \]

The magnetic field \( \mathbf{B} \) is then given by the derivatives of \( A \)

\[ B_x = -f(x) \tanh(f(x)z) \]  

(3)

\[ B_y = B_{yo} \]  

(4)

\[ B_z = df(x)/dx(z \tanh(f(x)z) - f(x)^{-1}) \]  

(5)
The \( y \) component of \( \mathbf{B} \) is set to a constant value \( B_{yo} \) initially, corresponding to a magnitude of 3% of the lobe field strength at \( x = 0 \).

The plasma pressure is determined by force balance

\[ p = \frac{1}{2} \cosh^2(f(x)z)) + p_0 \]

where \( p_0 \) is a constant offset value for the pressure. The initial temperature is chosen constant for simplicity.

The function \( f(x) \) models the variation of typical quantities along the tail axis. We choose

\[ f = (1 + x/x_0)^\alpha \]  

(6)

with \( x_0 = 60 \) and \( \alpha = -0.6 \). Similar choices were adopted by, for example, Birn et al. [1975]. This choice of a tail model corresponds to an equilibrium which represents the midnight meridional region of the magnetotail outward from about 15 \( R_E \).

Here all lengths are normalized with respect to a typical plasma sheet half thickness, e.g., \( L_z = 2 R_E \), at \( x = 0 \), where \( x = 0 \) defines the earthward boundary of the simulation region; the magnetic field is normalized with respect to a typical lobe magnetic field strength at \( x = 0 \), e.g., \( B_0 = 40 \) nT, and the velocity unit is a typical Alfvén speed (based on the lobe magnetic field and the plasma sheet density), e.g., \( v_A = 1000 \) km/s.

For the purpose of this investigation we integrate the resistive MHD equations in the form

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = j \times \mathbf{B} - \nabla p \]  

(7)

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta j) \]  

(8)
The resistivity, \( \eta \), is chosen spatially dependent initially, in order to speed up the evolution and determine the
Thus, on the time scales considered here, we can ignore plasmoid.

In order to model in a qualitative fashion the plasma loss due to the magnetic connection to the LLBL/sheath, both the energy and continuity equations need to be modified by loss terms. We assume that as soon as the magnetic connection between the interior of the plasmoid and the magnetosheath is established, magnetosheath plasma will enter the plasmoid, and plasma sheet plasma will leave the plasmoid, at their respective sound velocities. Because of the significantly higher density and typically lower pressure the sound velocity of the magnetosheath, however, is considerably smaller than the sound velocity of the hot plasma sheet plasma. Assuming plasma sheet densities around \(0.1 \text{cm}^{-3}\), and magnetosheath densities in excess of \(10 \text{cm}^{-3}\), the magnetosheath speed is less than \(c_s = 0.1\) in normalized units, even if sheath and sheet pressures are equal. Thus, on the time scales considered here, we can ignore the influence of the magnetosheath plasma entering the plasmoid.

Thus, to model the loss of plasma sheet plasma, we introduce the following modifications:

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) - \frac{5}{3} \rho \nabla \cdot \mathbf{v} + \frac{2}{3} \eta \mathbf{j}^2 + \frac{\partial p}{\partial t} \bigg|_{\text{loss}}
\]

For simplicity we here assume an adiabatic loss. Therefore the density changes according to

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \frac{3 \rho}{5} \frac{\partial p}{\partial t} \bigg|_{\text{loss}}
\]

The pressure reduction is modeled by a simple relaxation ansatz:

\[
\frac{\partial p}{\partial t} \bigg|_{\text{loss}} = \frac{1}{\tau} (p_0 - p)
\]

Here \(p_0 = 0.03\) represents a pressure offset value, chosen to be greater than zero in order to avoid numerical problems associated with very small pressures. The actual value of \(p_0\) does not change the evolution appreciably as long as \(p_0 \ll 1\).

In order to model the pressure loss we assume that the loss timescales depend on the geometry as well as on the magnetic connectivity, which we model in an adhoc fashion. We assume a tail radius of about \(20 \text{RE}\) (corresponding to 10 units in this model) and an equilibrium timescale between plasma sheet and sheath/LLBL pressures determined by the sound speed in the plasma sheet, which is approximately equal to unity in our normalization. Further, the geometry of a helical field line will influence pressure reduction times. In the case of a simple helix with circular cross section this geometry is determined by the angle between the magnetic field and the \(y\) direction. In a simple approximation we adopt this scaling locally in our simulation. In order to model the time evolution of a three-dimensional plasmoid qualitatively we also do not initiate pressure relaxation before the plasmoid has advanced to \(x > 22.5\) and \(B_y\) exceeds \(|B_y| = 0.04\) locally. These parameters are arbitrary, modeling the fact that magnetic connection to the IMF appears to be established at some later time of plasmoid evolution and that some enhancement of \(B_y\) above the initial magnitude can be expected when a connection to the IMF is established. Changing these parameters only influences the quantitative evolution, not its qualitative properties.

Thus we choose the time scale \(\tau\) as

\[
\tau = 10 \frac{B_y}{B_y^*} \quad \text{if } |B_y| > 0.04
\]

\[
\tau = \infty \quad \text{else}
\]

For comparison, we also perform a run without the simulated plasma exchange with the flank regions of the magnetotail.

The numerical scheme consists of a modified leap-frog method [e.g., Birn and Hesse, 1990]. The integration of equations (1)-(6) is performed in a rectangular box \(0 \geq x \geq 120\) and \(0 \leq z \leq 10\) on a \(67 \times 37\) grid with variable grid spacing in the \(z\) direction. Symmetry boundary conditions are employed at the \(z = 0\) boundary. At all other boundaries the normal magnetic field component is held fixed, except at the tailward boundary, where it is allowed to change. The velocity boundary condition is \(\mathbf{v} = 0\) at all non-equatorial boundaries, modeling a highly conducting, solid reflecting wall, except at the far-tail boundary, which is open. There we use a convective condition \(\partial \mathbf{B}_t / \partial t = 0\) for the tangential magnetic field components, whereas at the other side and top surfaces the normal derivative of these components is assumed to vanish.

4. Results

The evolution of the magnetic field and the plasma flow for the run with plasma contact (run 1) is demonstrated in Figure 4. The figure shows that the evolution transforms the initial condition (bottom panel) into a dynamical state of magnetic reconnection and plasmoid formation, accompanied by fast earthward and tailward flows. The results in Figure 4 appear quite similar to earlier two- and three-dimensional MHD simulations [e.g., Birn and Hesse, 1990].

The evolution of the \(B_y\) and \(B_z\) components of the magnetic field on the tail axis is displayed for both runs in Figures 5 and 6, respectively. The solid lines denote quantities from run 1, whereas the dash-dotted lines indicate the magnetic fields taken from the run without plasma contact (run 2). The figures show that the magnetic field evolution for the two runs is identical until \(t \approx 120\), when run 1 has developed a \(B_y\) enhancement at the center of the bipolar \(B_z\) signature associated with a
plasmoid. The upper panels exhibit the same features, albeit more pronounced. The magnitude of $B_y$ in the center of the bipolar signature of $B_z$ in run 1 has reached the ambient lobe magnetic field. It is noticeable that the maximum value of the $B_y$ enhancement is found right at the $B_z$ reversal, as found in the observations [e.g., Slavin et al., 1995].

It is also evident that the $x$ gradients of $B_z$ have steepened considerably in comparison with run 2, indicating a substantial reduction of the plasmoid scale size in run 1. This reduction of the scale size in the $x$ direction is associated with the collapse of the plasmoid. Investigations of the scale size in the $z$ direction show similar behavior. The evolution of the plasma pressure, plotted along the $x$ axis, for the two runs is shown in Figure 7. The upper panels demonstrate that a substantial plasma pressure reduction has occurred inside the plasmoid region. The pressure reduction is compensated by the increase in $B_y$ shown in Figure 5.

Thus our self-consistent simulation with a simple ad hoc transport model for plasma contact with the flanks of the magnetotail demonstrates that our qualitative model may be a viable explanation of flux rope formation. We note that if our explanation is correct, plasmoids and flux ropes are the same objects, only seen at different stages of their evolution.

5. Summary and Outlook

The formation of bipolar, plasmoidlike signatures accompanied by large enhancements of the cross-tail magnetic field component as observed in the deep tail by both ISEE 3 and GEOTAIL spacecraft [Fairfield et al., 1989; Moldwin and Hughes, 1991; Slavin et al., 1995; Nagai et al., 1994; Machida et al., 1994; Frank et al., 1994; Lepping et al., 1995], has been investigated in a simple model based on observational and previous mod-
Simulation also demonstrated the collapse of the plasma sheet and colder magnetosheath plasma along magnetic field lines, which necessarily leads to an exchange process. In case of a field-aligned pressure gradient, as one would expect at downtail distances where the magnetotail is still flaring, an exchange of plasma by mass flow and heat flux is to be expected. Further down the tail, beyond flaring distances, the exchange will most likely involve primarily heat flux directed from the plasmoid interior to the magnetosheath. In either case a reduction of plasma pressure inside the plasmoid will result.

Owing to the magnetic tension forces exerted by the ambient magnetic field, the loss of interior plasma pressure will lead to a collapse of the plasmoid magnetic helix. The collapse in turn enhances the y component of the magnetic field, until the magnetic pressure associated with the enhanced $B_y$ balances the magnetic tension forces. Since magnetosheath temperatures are substantially below plasma sheet temperatures [e.g., Schopke et al., 1981; Hall et al., 1990], the final state of this evolution necessarily resembles a force-free flux rope.

We have used a modified 2 1/2-dimensional MHD simulation with a transport model for the pressure and density reductions to provide an example of a self-consistent evolution leading from a plasmoid with no core field enhancement to a force-free flux rope by the mechanism discussed above. We found the expected core field enhancements up to values comparable to and in excess of the local ambient lobe field strength. The simulation also demonstrated the collapse of the plasmoid in its comoving frame, as evidenced by a significantly reduced $x$ distance between the two $B_z$ peaks associated with the bipolar signature. Along with the core field enhancement the model exhibited a pressure reduction inside the plasmoid proper.

On the basis of our proposed scenario we can explain a number of observations. First, our model explains in a natural way the formation of a force-free flux rope from a plasmoid. Second, the fact that the enhanced $B_y$ necessarily exhibits the same sign as the $B_y$ present in the equilibrium, which in turn is assumed to be correlated with IMF $B_y$, matches observations which find good correlation between the sign of the IMF $B_y$ and the sign of the core $B_y$. Third, the observed electron temperature reduction [Moldwin and Hughes, 1992] during plasmoid encounters is explained by the establishment of a magnetic connection between the inner plasmoid region and the flanks of the magnetotail. Last, some observations indicate that flux ropes tend to have smaller dimensions than plasmoids [e.g., Slavin et al., 1995]. This feature is explained by the contraction of the plasmoid diameter due to the pressure loss as the magnetic connection to the flanks is established.

The scenario predicts a somewhat different behavior for plasmoids connecting to the magnetotail flanks in the region earthward and tailward of the cessation of magnetotail flaring, which appears to occur at radial distances of about 100 $R_E$. In the former case, the plasma sheet pressure most likely exceeds magnetosheath pressures. In this case, a magnetic connection between the two regions will most likely lead to a reduction of the internal plasmoid pressure as well as of the total mass. In the latter case, however, the pressures could be more equal, leading to a plasmoid pressure loss primarily through heat flux, and less through mass flow. In this case, plasma density enhancements along with temperature drops might be expected. We note that equal pressures in the plasmoid core and the magnetosheath are not a necessity if the plasmoid is located in the far tail, because magnetic tension forces as well as dynamical effects might still maintain plasmoid plasma pressures in excess of the ambient plasma sheet pressures. Further, reconnection in a region tailward of 15-20 $R_E$ but earthward of 100 $R_E$ will establish a plasmoid-flank connection where the plasmoid is still in the flaring region of the tail. Therefore the first scenario is somewhat more likely, although a continuous transition between the two is possible as the plasmoid propagates down the tail after magnetic connection to the flanks is established. Finally, during the late stages of the plasmoid evolution, effects of magnetosheath plasma entering the plasmoid may become important.

Clearly, not all plasmoids will undergo this transition. In case of a small substorm which might be localized in a narrow local time sector, reconnection would not proceed sufficiently far to the flanks to establish the necessary magnetic connection. In this case, far-tail observations will still show the usual bipolar signature without strong enhancements of the core $B_y$. On the basis of this reasoning we would expect that substorms involving larger local time sectors should produce flux ropes, whereas otherwise, bubblelike plasmoids should be encountered. Since large extension in local time usually translates into larger substorms, one might expect a preference for flux rope production in larger substorms.

In summary, we have presented a simple model of plasmoid-to-flux rope transition as the result of new magnetic connections to the flanks of the magnetotail. The suggested scenario has been used to explain pertinent observation, as well as to predict some further observational evidence.

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