Complexities of a 3-D plasmoid flux rope as shown by an MHD simulation

N. L. Farr, D. N. Baker, and M. Wiltberger

Received 16 April 2008; revised 4 August 2008; accepted 5 September 2008; published 5 December 2008.

[1] The results of a global magnetohydrodynamic (MHD) simulation of a pair of magnetospheric substorms on 11 August 2002 are presented. Comparisons of data with simulation results reveal a good agreement regarding the sequence of events during substorm development. We give particular emphasis to results in the simulation of a flux rope formed during the second substorm. Unlike standard 2-D depictions of reconnection and plasmoid release during the substorm sequence, the simulation shows a highly complex structure that has considerable winding of both closed and open field lines. Additionally, the simulated flux rope does not move tailward uniformly, but rather it has asymmetric motion in which the dawn flank portion moves tailward prior to the dusk portion of the flux rope. This results in a skewed flux rope structure that runs almost parallel to the tail axis instead of perpendicular to it. The simulation compares well with both prior flux rope simulations as well as satellite observations of flux ropes. We use the global simulation to map flux tube properties to the ionosphere, which allows the complexity of the mapping of the magnetic field structure from the tail to the ionosphere to be seen in a novel manner.


1. Introduction

[2] Plasmoids are a significant element in the picture of substorm reconnection [Baker et al., 1996]. They are magnetic and plasma structures that are ejected down the magnetotail from a substorm reconnection site. They were first proposed by Hones [1977] as closed magnetic field loops formed by magnetic reconnection at a near-Earth neutral line (NENL). In this essentially 2-D depiction of the magnetotail, reconnection occurs simultaneously along an X line spanning the width of the magnetotail. Further studies revealed the presence of strong core magnetic fields in plasmoids [Sibeck et al., 1984; Moldwin and Hughes, 1991] and that the orientation of the core field is predominantly determined by the direction of the interplanetary magnetic field (IMF) $B_y$ [Moldwin and Hughes, 1992].

[3] Hughes and Sibeck [1987] considered the 3-D structure of plasmoids that would occur in the presence of a nonzero IMF $B_y$. In this depiction, the magnetic field lines of a plasmoid form a helical structure, or flux rope, rather than a series of closed loops. As a three-dimensional structure the plasmoid would no longer be required to move tailward uniformly across its entire length. Observations of flux ropes in the magnetotail have confirmed the strong correlation between them and substorm activity at Earth [Moldwin and Hughes, 1993].

[4] Flux ropes have been modeled using simple 2 1/2 D magnetic field models by Birn et al. [1989] and Moldwin and Hughes [1991] and a 3-D MHD simulation of the magnetotail by Birn et al. [1996]. These models showed how the presence of nonzero IMF $B_y$ would change the structure of the plasmoid from closed loops to the helical structure. This results in a change to the topological evolution of the plasmoid. At the beginning of reconnection, the field lines comprising the flux rope remain topologically closed, but they can be distinguished from nonflux rope field lines because the flux rope field lines have a helical structure [Baker and McPherron, 1990]. These simulations also show that the presence of IMF $B_y$ leads to the creation of a flux rope structure during magnetic reconnection in the tail, which leads to a winding of field lines of different topologies as the structure moves tailward.

[5] Global-scale magnetohydrodynamic simulations have been used to study the evolution of substorms. The first simulation of an actual event was reported by Lyon et al. [1998] which showed the ability of this technique to capture the loading of energy into the magnetosphere during the growth phase and its subsequent release during the expansion phase. As part of the Geospace Environment Modeling substorm challenge event Raeder et al. [2001] showed a clear dependence of substorm modeling on the inclusion of auroral influences on the Pedersen and Hall conductances in the ionosphere. Using the GUMICS-4 simulation Tanskanen et al. [2005] showed that this technique can capture the temporal evolution of the energy...
input into the ionosphere during a substorm event. Wingee et al. [1998] showed a series of favorable comparisons between an MHD simulation with Hall physics extensions and satellite observations for flux ropes in the magnetotail during a variety of conditions.

[6] A global symmetric MHD simulation of the magnetosphere was performed by Walker and Ogino [1996]. This simulation was of the dawn half of the magnetosphere with symmetric boundary conditions describing the dusk half. The inner boundary of the simulation was at 5.5 $R_E$. Like the earlier studies it also showed that the introduction of IMF $B_y$ led the reconnection in the magnetotail to form helical flux ropes rather than closed loop plasmoids. They also showed that the initial tailward movement of the plasmoid flux rope started very slowly and then accelerated as the flux rope moved tailward. The transition of topologies from closed to open as well as extensive mixing between the different topologies was also seen. Kivelson et al. [1996] discussed the ionospheric signatures of the flux ropes seen in this simulation. Their key observation is that when the flux ropes first form on closed field lines, the end points of the field in the southern and northern ionospheres are no longer conjugate, but rather separated in local time. For a positive IMF $B_y$ this results in the dusk end of the flux rope being connected to the Northern Hemisphere and the dawn end to the Southern Hemisphere.

[7] In the study reported here, we use the Lyon-Fedder-Mobarry MHD code [Lyon et al., 2004] to simulate an actual substorm event by using solar wind data from the ACE spacecraft propagated to Earth as the input parameters. In section 2 we present an overview of the substorm interval from ground-based and satellite observations, presenting the timings of the event derived from the AL index. In section 3 we show the simulation results and compare them with data from both ground stations as well as satellites in the magnetotail (Cluster, Polar, and GOES) to illustrate how well the simulation is representing the event. In section 4 we show the evolution of the magnetic flux rope observed in the tail from its formation through its propagation and tailward ejection into the solar wind. The global 3-D nature of the LFM model allows for cross-tail asymmetries of the flux rope to be observed. We also use the global nature of the code to map the entropy of flux tubes to the ionosphere. This mapping allows the ionospheric signature of the flux rope to be easily followed. In section 5 we make particular comparisons of the simulated flux rope with observations of flux ropes performed by Slavin et al. [2003] to further validate the simulation results.

2. Event Overview

[8] The substorm event studied here occurred on 11 August 2002 and was chosen primarily because of a particularly favorable arrangement of observing spacecraft. The ACE spacecraft was upstream of Earth near the L1 point providing the solar wind data. GOES 10 was in geosynchronous orbit heading from postmidnight toward dawn. Polar was near its apogee at $-9 R_E$ in the postmidnight sector, traveling from south to north. The Cluster constellation was also near its apogee at $-19 R_E$ in the postmidnight sector traveling from north to south.

[9] Figure 1 shows the solar wind conditions for the event as measured by ACE and propagated to 15 $R_E$ upstream of Earth along with the Kyoto Quicklook AL index. Some features to note are the period of southward $B_Z$ from 1015 to 1200 UT and the extended period of southward $B_Z$ beginning at 1300 UT. Figure 2 shows the Quicklook AL index for the day. We use the AL index to define timings for the substorm phases (see Baker et al. [1996] for a review) with the beginning of the growth phase being the beginning of AL activity, the onset of the expansion phase being the point when the magnetometer disturbance steepens, and the start
of the recovery phase being the maximum magnetometer disturbance. There are two large substorm bays that occur with the following timings from the index: 1019 UT for the beginning of the growth phase, 1101 UT for substorm onset, and 1156 UT for the start of the recovery phase for the first substorm, and timings of 1310, 1343, and 1446 UT, respectively, for the same events during the second substorm. The times for the second substorm are depicted as vertical lines in Figure 1. This event has been previously studied by Taylor et al. [2006] who discussed an electron beam seen by one of the Cluster satellites during the expansion phase of the second substorm. The Cluster satellites were just outside the thinned plasma sheet when only Cluster 3 (the southernmost satellite) observed a strong electron beam at 1422 UT. Then all the satellites reentered the plasma sheet at 1445 UT because of the rapid expansion of the plasma sheet. The interpretation presented there is that the Cluster constellation observed a traveling compression region (TCR) while only Cluster 3 observed the streaming elections along the boundary of a plasmoid that formed Earthward and southward of the Cluster constellation.

3. LFM Simulation

[10] The LFM global-scale magnetospheric simulation uses the ideal magnetohydrodynamic equations to model the interaction between the solar wind and the coupled magnetosphere-ionosphere system. The simulation includes electrodynamic coupling with the ionosphere by using the field-aligned currents generated in the magnetosphere as drivers for an electrostatic potential with a conductivity model that includes both solar extreme ultraviolet (EUV) effects and auroral enhancements [Wilberger et al., 2003; Fedder et al., 1995]. In the past, this modeling technique has been quite successful at simulating the onset and development of substorms using observed solar wind conditions as input. Lopez et al. [1998] showed good agreement between the observations and the simulation for the onset, evolution, and second onset of a series of substorms which occurred on 9 March 1995. Wilberger et al. [2000] described the results from a substorm which occurred on 10 December 1996. They showed good agreement between geosynchronous magnetic field dipolarizations and the simulation results. The simulation results we present here have been run with a higher-resolution version of the code, which has cell sizes in the inner magnetosphere as small as 1/8 $R_E$. For input, the simulation uses the ACE parameters from Figure 1. The dashed line on the $B_x$ panel is the approximation to $B_x$ used for the LFM input. This approximation is a linear function of $B_y$ and $B_z$ and is used to maintain the solenoidal nature of the magnetic field at the front boundary. In the context of LFM substorm simulations it is important to note that while the code is solving the ideal MHD equation reconnection is still possible because of the numerical resistivity present in finite volume discretization. In particular, magnetic reconnection occurs when the plasma conditions force oppositely directed magnetic fields inside a single grid cell. Typically, this configuration happens near the dayside magnetopause and within the magnetotail when the magnetic field and flow conditions force it to occur.

[11] In Figure 2, we show ground magnetometer data and comparisons with the LFM results. Figure 2a shows the AL Quicklook data from the Kyoto World Data Center for Geomagnetism. Figure 2b shows the simulated AL index calculated from the simulation.

[12] We get the following times for the substorm phases for the simulated substorms. For the first substorm the growth phase began at 1017 UT, the expansion phase at 1045 UT, and the recovery phase 1136 UT. The corresponding times for the second substorm are 1306, 1333 and 1430 UT, respectively. The times for the second substorm are depicted as vertical lines in Figures 2 and 3. In comparing the various
times from the simulation with the data, we note that the starts of the growth phases are quite close, while the times for substorm onset and recovery occur approximately 15 min earlier in the simulation than in the data. This possibly indicates that the substorm process in the simulation is occurring slightly faster than it actually occurs in nature. This could be because we see low densities in the inner magnetosphere and the simulation does not have any ionospheric outflow to refill the plasma that is lost during the substorm, which results in an earlier and faster recovery than is seen in the data. Future versions of the simulation will contain the outflow and we will study what effect that has on the substorm process. Another reason for the separated timings could be differences in the propagation of the solar wind input from ACE; however, the physical features are reproduced quite well, and the relative timings are consistent for both substorms.

Figure 3 displays the magnetic field elevation angle from the Cluster, Polar and GOES spacecraft along with the result from the equivalent virtual spacecraft in the LFM. In all panels the red dashed line is from the LFM simulation, and the blue solid line is the satellite data. The vertical lines are the start of the growth, expansion, and recovery phases for the second substorm. The dashed lines indicate the times from the simulation, and the solid lines indicate the times from the AL index.

4. Flux Rope Formation and Evolution

In this section we show the evolution of the plasmoid flux rope that formed during the second substorm. Figures 4–7 show different images of the flux rope at seven time steps during its development. The complete animation is included as Animation 1. For each time step four images are displayed. In Figures 4a, 5a, 5e, 6a, 6e, 7a, and 7e, we show a time series plot of the AL as calculated from the simulation. The vertical line shows the location of the current time step.

In Figures 4b, 5b, 5f, 6b, 6f, 7b, and 7f, we show flux tube entropy values for the nightside northern ionosphere. The white lines indicate the geomagnetic latitude (70° and 80° are shown) and magnetic local time (2100, 0000, and 0300 are shown). This image is generated by taking a grid of points on the inner boundary of the simulation and then tracing the magnetic field line from each point to a termination point, which is either at the inner boundary in Southern Hemisphere or the outer boundary of the simulation. We then calculate the flux tube entropy, η, which is defined as

$$\eta = \rho V^{5/3} = \rho \left( \int \frac{ds}{B} \right)^{5/3}$$  (1)

Figure 3. (a) The LFM AL from Figure 2. The magnetic field elevation angle from the (b) Cluster, (c) Polar, and (d) GOES spacecraft along with the result from the equivalent virtual spacecraft in the LFM. In all panels the red dashed line is from the LFM simulation, and the blue solid line is the satellite data. The vertical lines are the start of the growth, expansion, and recovery phases for the second substorm. The dashed lines indicate the times from the simulation, and the solid lines indicate the times from the AL index.
where $\bar{p}$ is the average pressure along the flux tube and $V$ is the flux tube volume. The entropy image is displayed in units of $\text{nPa}^*(R_E/\text{nT})$. Since we cannot compute the full flux tube volume for open field lines they have been given a value of 0 and appear as dark blue in the image. This formulation clearly reveals the open/closed boundary of the polar cap as well as showing the foot points that correspond to flux tubes. The latter feature is particularly useful in the study of flux ropes since it distinguishes between flux rope field lines from non-flux rope field lines even when both are topologically closed. This is because flux rope field lines have a higher entropy because of both being longer (they have a substantial deflection in the $y$ direction), as well as having a higher internal pressure.

[16] In Figures 4c, 4d, 5c, 5d, 5g, 5h, 6c, 6d, 6g, 6h, 7c, 7d, 7g, and 7h, we show the flux rope field lines themselves in the GSM coordinate system. Figures 4c, 5c, 5g, 6c, 6g, 7c, and 7g show a YZ view (looking from downtail toward Earth) and Figures 4d, 5d, 5h, 6d, 6h, 7d, and 7h show an XY view (looking from the north toward Earth). In both images the tick marks are $5 R_E$ apart. As the flux rope becomes larger and retreats downtail the images zoom out gradually. To create these images, we used a manual procedure for each time step. First, we estimated the parameters for the flux rope axis: the location of the flux rope center, the longitudinal angle, and the latitudinal angle. The longitudinal angle is 0° for flux ropes parallel to the $x$ axis and 90° for those parallel to the $y$ axis. We then created a 2-D array of points with spacing of 1 $R_E$ oriented perpendicular to the flux rope axis. Tracing the magnetic field line from each of the points, we classified the field lines that made at least one complete loop around the flux rope as belonging to the flux rope. We then adjusted the flux rope axis parameters until the helical field lines were looping around the chosen axis. The coloring of the field lines is as "topologically" follows: blue and red field lines are both closed field lines, distinguished only to aid the visualization of the flux rope structure. Likewise, the orange and green lines are both open field lines, connected to the northern ionosphere at one end and the solar wind at the other. In Figures 6e–6h and 7a–7h, red and blue are also used to show IMF field lines which are no longer connected to Earth. The complete animation is included as Animation 1.
Figure 5. (a–d) From 1400 UT and (e–h) from 1405 UT, using the same format as Figure 4.
Figure 6. (a–d) From 1411 UT and (e–h) from 1418 UT, using the same format as Figure 4.
Figure 7. (a–d) From 1423 UT and (e–h) from 1428 UT, using the same format as Figure 4.
The flux rope field lines first became distinguishable at 1337 UT (Figure 4) as reconnection began on closed field lines. This is near the substorm onset time as seen from the simulated AL index. Initially, two flux ropes appear at about 35 $R_E$ down tail from Earth. In the ionosphere plot, the foot points for the flux rope are at about 75° latitude and 2230 MLT. This appears as a green region with a sharp transition to the lower entropy flux tubes just equatorward. The red area on the open/closed boundary represents field lines mapping to the distant neutral line. At this point they are much higher in entropy than the flux rope flux tubes. Not shown is the Southern Hemisphere in which the foot points of the flux rope are in the postmidnight sector. This asymmetry is in agreement with the results from the simulation by Walker and Ogino [1996] in which the northern and southern ends of the flux rope are separated in MLT. The YZ image shows the plasma sheet to be at about +4 $R_E$ along the Z direction.

Over the next 20 min, the two simulated flux ropes merge into a single structure and expand in size while remaining in roughly the same location in the magnetotail. The region of high entropy in the ionosphere expands and moves slightly westward, and a new region of foot points appears near midnight that maps to the flux rope as well. The second image at 1400 UT (Figures 5a–5d) shows these changes. In the ionosphere plot the flux rope foot points are now the dominant feature, being seen clearly equatorward of the open/closed boundary. Also seen is the sharp boundary (blue to green) at about 72° that is separating the inner tail field lines from more active field lines. In the field line images, we see that the flux rope now spans across the entire tail in the y direction with a slight twist in the longitudinal direction from the nominal 90° direction. The XY image shows the new set of field lines that is mapping from the midnight region and in the YZ image we see that there is minimal twisting in the latitudinal angle.

Five minutes later at 1405 UT (Figures 5e–5h) it is seen that the flux rope began reconnecting onto open field lines. In the ionosphere image one can easily see the mixing of open foot points (dark blue spots) with closed foot points at the flux rope foot point regions. The region near midnight is also beginning to join with the open/closed boundary. The field line images show that the open field lines are exiting the flux rope structure at two different locations. One is at the Earthward edge of the flux rope near midnight. This is at about −25 $R_E$ at this time. This location is consistent with the expected reconnection site in the near-Earth neutral line (NENL) substorm model as described by Baker et al. [1996]. The other location where open field lines are separating from closed field lines is at the dawn edge of the flux rope along the flank of the magnetotail. In the XY image we can see that field lines exiting the structure at both of those locations are also traversing another flux rope that is located along the dawn flank of the magnetotail. As the selection criteria for the field lines shown are determined by the main flux rope, there are probably other field lines traversing only the secondary flux rope and so are not displayed. This dawn/dusk asymmetry is also reflected in the overall orientation of the flux rope as it has now rotated longitudinally by a large amount to an angle of about 40°. The dawn end of the flux rope is now about 30 $R_E$ further tailward than the dusk end.

At 1411 UT (Figures 6a–6d) we see that the transition of the flux rope from closed to open field lines has continued with the flux rope now consisting of mostly open field lines. In the ionosphere we see the large “holes” in the image which are the open field lines mapping to the flux rope surrounded by foot points mapping to closed field lines. In the XY image the secondary flux rope has increased in size to about the size of the primary flux, being dawnward and earthward of it. The dusk end of this flux rope is also very close to Earth at −15 $R_E$. At about this time, the virtual Cluster spacecraft (not shown) sees a negative $B_z$ signature similar to that observed by the Cluster spacecraft from Taylor et al. [2006]. The main flux rope has maintained similar size and orientation as before, but it has now moved about 10 $R_E$ tailward from previous time step. In the field line images we also see the first IMF field line traversing the flux rope structure. In the XY image it is the red field line exiting the structure at the dusk flank at −60 $R_E$ downtail. IMF field lines are also shown in red and blue with the difference again only present to aid the visualizing of the structure.

In the fifth image at 1418 UT (Figures 6e–6h), it is seen that the flux rope is now roughly an even mixture of open and IMF field lines. The two flux ropes have merged together in a larger plasmoid structure. The inner dusk end of the structure is now at −40 $R_E$. The two groups of field lines entering the structure that were previously separate are now a large continuous group of field lines connecting the structure to the solar wind on the dawn side. In the ionosphere we see that the flux rope foot point region has diminished in size and moved slightly eastward.

At 1423 UT (Figures 7a–7d) the flux rope structure consists almost entirely of IMF field lines with only a few flux tubes still connected to the Earth. The structure is still maintaining roughly the same orientation angles while retreating tailward further with the center of the flux rope being at about −90 $R_E$. Another feature of the structure now present is the distortion from the basic cylindrical structure on the dusk end. The inner boundary in the premidnight region is forming a line at a 90° longitudinal angle that is somewhat separated from the main axis of the structure. This inner edge is at about −50 $R_E$. In the ionosphere the flux rope signature is now just a narrow band across the premidnight sector at about 70° latitude that is now separated from the open/closed boundary of the polar cap.

In the last image at 1428 UT (Figures 7e–7h) the structure consists solely of IMF field lines. The center is now at about −120 $R_E$ and the inner edge on the dusk end at about −80 $R_E$. The AL plot shows that the minimum has been reached and the system begins to recover. In the ionosphere the flux rope signature has disappeared as there are no more open fields in it. From this point the structure passes out of the tail end of the simulation with little further change in shape or orientation.

5. Discussion

It is useful to present a comparison of the flux rope described above with an study of flux ropes performed by Slavin et al. [2003]. They performed a superposed epoch analysis study of flux ropes using Geotail data. Their study encompassed both tailward moving (plasmoid-type) flux
ropes as well as earthward moving (BBF-type) flux ropes. Figure 8 shows the results for five different parameters from the superposed epoch study of satellite traversals of the plasmoid flux ropes compared with the same parameters from a cut through the flux rope simulated here. We used a spatial plot at a single time step rather than a time series plot at a fixed virtual spacecraft location because the high degree of longitudinal twisting makes it difficult for a single location to accurately capture the spatial extent of the flux rope. Also since the comparison is being made with a superposed epoch study, using a spatial cut will lessen the discrepancies that would be caused by the longitudinal twisting. The cut shown is taken at 1411 UT and is centered at the $B_z$ reversal. This time step was chosen as representative of the flux rope after it has begun its tailward retreat and the features displayed are consistent with other time steps. The flux features seen in these plots are the bipolar signature in $B_z$, a peak in $B_y$, an increase in density and pressure on the tailward edge of the flux rope, and strong tailward flows on the earthward side of the flux rope. The $B_y$ signature has a similar magnitude of 6 nT in the simulation and 7 nT in the data. This peak is lined up with the $B_z$ reversal in both plots. The change in $B_z$ is slightly higher in the simulation than in the data, 8 nT vs. 5 nT. In the simulation it is asymmetric going from $+3$ nT to $-5$ nT, while the data is symmetric about the reversal going from $+2.5$ nT to $-2.5$ nT. In the density plot, both show compression on the leading edge of the flux rope, while the magnitude of the density is stronger in the simulation. The velocity plot matches quite well with the velocity of the flux rope about 400 km/s tailward in both plots. In the simulation the strong tailward flow continues to increase further from the flux rope. Also in the plots the features have a larger spatial extent in the simulation than in the data. We believe the main reason for this is that the flux rope presented here is at the large end of the distribution of flux ropes that were analyzed by Slavin et al. [2003]. Another probable factor contributing to the differences is the resolution of the simulation. That could affect the size of the flux rope by preventing the boundary from being as sharp as it is in reality. Also, the asymmetry in the simulation plot may be due to the longitudinal twisting of the flux rope which may have been averaged out in the superposed epoch study.

[25] The statistical distribution of flux rope size, velocity, and orientation is also reported by Slavin et al. [2003]. For size, they observed an average radius of 2.2 $R_E$ with a significant tail at 6 $R_E$. Velocity had an average of $-451$ km/s. The latitudinal angle was strongly centered near horizontal while the longitudinal angle showed a wide spread in orientations. Again, the flux rope present in the simulation fits these results with the following parameters taken from the flux rope at the time of the cut in Figure 8: the diameter was about 10 $R_E$, velocity of about $-400$ km/s, a latitudinal angle of $4^\circ$, and a longitudinal angle of $35^\circ$. We can also use the measurements from the flux rope cut to estimate the magnetic
flux transported by the flux rope. Using 6 nT for the average B and estimating the volume of the flux rope as a cylinder with a radius of 5 R_E and length of 40 R_E, we get:

\[ E = \left( \frac{B^2}{\mu_0} \right) V = 2.4 \times 10^{13} J \]  

(2)

The results from the LFM simulation show that, as in Walker and Ogino [1996] simulation, the flux rope formed during southward B_Z. Also the ionospheric connection is consistent with those prior results as well. In this case, the positive IMF B_Z caused the flux rope to be connected to the Northern Hemisphere on the dusk side and the Southern Hemisphere on the dawn side; however, we also see that simple 2-D pictures of substorm reconnection and transport of the flux rope tailward are potentially missing a fair portion of the dynamics of the magnetospheric structures during substorms. The flux rope described in detail in section 4 has very high dawn-dusk asymmetry in its behavior during the substorm. When it reconnected to the solar wind, it only did so at specific locations and the flux rope became highly asymmetric in the y direction. This result is consistent with the speculation of Hughes and Sibeck [1987], that reconnection occurring at different times along the flux rope could result in the flux rope being skewed from the nominal cross-tail direction. The results presented here are also consistent with the Winglee et al. [1998] simulation which showed flux ropes beginning at a size of a few R_E at a distance of 20–30 R_E down the tail.

[26] The ionospheric results are also in agreement with Kivelson et al. [1996] study, with the north and south ends of the flux rope being separated in local time. The ionospheric results from the simulation also showed the complicated nature of mapping ionospheric signatures to tail signatures, as the location of the flux rope foot points does not change significantly with respect to the open/closed boundary, while in the tail the flux rope retreated, going from earthward of the distant neutral line to being tailward of the new distant neutral line. The use of flux tube entropy to study an evolution of the flux rope is a useful tool for discriminating between flux rope and nonflux rope field lines while the flux rope remains on closed field lines.

6. Conclusion

[27] In this study we have used the LFM MHD simulation to study the evolution of a plasmoid flux rope formed during a substorm. We used the capabilities of the global 3-D simulation to connect the structure in the magnetotail to signatures on the ionosphere using the mapping of the entropy of flux tubes to the ionosphere. This process allows the complexity of the mapping of the magnetic field structure from the tail to the ionosphere to be seen in a novel manner. Comparisons of the simulation with data from satellites and the ground-based data show that the LFM code does a very respectable job of reproducing the global nature and timings of the substorm event. During the expansion phase of the second substorm, a plasmoid flux rope was observed to form, grow, and then retreat tailward in good agreement with the NENL substorm model [Baker et al., 1996]. The flux rope seen in the simulation was consistent with both previous MHD simulations of the magnetotail as well as satellite observations of flux ropes. The fully global 3-D nature of the LFM simulation allows the asymmetries seen in observed flux ropes to be reproduced, implying that the dawn-dusk asymmetry is caused by the fact that reconnection was initially localized along the flux rope causing different parts of the structure to retreat tailward at different times.

[28] Acknowledgments. We would like to thank the Kyoto World Data Center for Geomagnetism for the AL Quicklook data and James Weygand at IGPP at UCLA for providing the propagated ACE data. We would also like to thank the Cluster, Polar, and GOES instrument teams for the magnetometer data. This material is based upon work supported by CISM which is funded by the STC Program of the National Science Foundation under agreement ATM-0120950. The National Center for Atmospheric Research is sponsored by the National Science Foundation. This work was also supported by grants from the NASA Cluster program.

[29] Wolfgang Baumjohann thanks Stefan Kiehas and two other reviewers for their assistance in evaluating this paper.

References


