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Flux transfer events in global numerical simulations of the magnetosphere

J. A. Fedder,[1] S. P. Slinker,[2] J. G. Lyon,[3] and C. T. Russell[4]

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[1] A magnetohydrodynamic numerical simulation model is used to study nonsteady features of magnetic reconnection between southward interplanetary magnetic field (IMF) and the geomagnetic field. The magnetic field near the dayside magnetopause intermittently shows the bipolar normal magnetic field and field-aligned flow features that are similar to the observed flux transfer events. The results show that the magnetic signature extends outward into the magnetosheath and inward into the magnetosphere. The magnetic features are not steady, and they evolve as they propagate along the magnetopause. Magnetic field lines are traced from the magnetopause in order to show the connectivity of the field from the ionosphere to the solar wind. The results shown are consistent with *Russell and Elphic*'s [1978] interpretation of the magnetic signals as evidence of nonsteady reconnection between the IMF and the geomagnetic field. Finally, we suggest a merging mechanism along the dayside magnetic null-null line that naturally leads to the observed magnetic structure. *INDEX TERMS:* 7843 Space Plasma Physics: Numerical simulation studies; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 7835 Space Plasma Physics: Magnetic reconnection; *KEYWORDS:* MHD simulation, magnetopause, flux transfer event, magnetosphere, magnetic reconnection

1. Introduction

[2] Magnetic merging between the interplanetary magnetic field (IMF) and the geomagnetic field (GMF) has been a central research theme in space physics since the pioneering suggestions of *Dungey* [1961, 1963]. A recurring topic of the research has been to determine both experimentally and theoretically whether the reconnection process between the GMF and the IMF is a steady or a time-dependent process. Early observations of magnetic field and plasma features near the dayside magnetopause by *Russell and Elphic* [1978] and by *Haerendel et al.* [1978] were interpreted by Russell and Elphic to indicate that nonsteady merging was a frequent occurrence. The observations showed characteristic magnetic field and plasma signatures and were interpreted to be an indication of nonsteady magnetic reconnection between the IMF and the GMF. These observations were named flux transfer events (FTEs) by *Russell and Elphic* [1978]. The FTE events and their causative mechanism are a continuing research topic. In a recent thorough review, *Elphic* [1995] summarizes progress in the observational studies. Additional studies by *Kawano and Russell* [1996] show that FTEs are formed on the dayside magnetopause and travel around the magnetopause in the antisunward direction. The primary identifying observational features of FTEs are a bipolar signal in the magnetopause-normal magnetic field and an associated field-aligned plasma flow. The observations reviewed by Elphic and studied by *Kawano and Russell* [1997] are convincing evidence that FTEs are a signature of nonsteady magnetic reconnection. Moreover, this unsteadiness can occur despite the presence of a steady southward IMF [*Le et al.*, 1993].

[3] Theoretical studies of nonsteady magnetic reconnection in a magnetopause context have also been reviewed by *Scholer* [1995]. These studies have mostly involved numerical simulation. Localized studies have been performed that are able to address the reconnection dissipation processes but have generally been limited to two dimensions and therefore omit the global connectivity and the self-consistent Maxwell stress balance between the ionosphere and the solar wind. In a series of recent papers, *Ku and Sibeck* [1997, 1998a, 1998b, 2000] present a comprehensive series of results for two-dimensional simulations using realistic magnetosheath and magnetospheric plasma and magnetic field parameters. These recent papers by Ku and Sibeck extend and expand on the previous two-dimensional results.

[4] A few global studies have been performed, but they have not generally been shown to exhibit the observational characteristics of FTEs. The global simulation by *Ogino et al.* [1989] showed an interesting flux tube geometry on the dayside magnetopause, which they suggest is related to FTE formation. On the other hand, the production process for those flux tubes has been interpreted differently by *Otto* [1991], and their subsequent evolution and propagation along the magnetopause is still unclear.

[5] Most researchers have attributed FTEs to the magnetic reconnection process because of their dependence on the north-south component of the IMF [e.g., *Kuo et al.*, 1995]. However, some observations of FTE signatures have also been attributed to magnetopause crossings induced by pressure pulses in the magnetosheath plasma [e.g., *Sibeck*, 1990]. Arguments against this latter point of view include the observations of FTEs on both the morningside and the afternoonside [*Kawano and Russell*, 1997] and their localization to the immediate magnetopause region [*Kawano and Russell*, 1996]. Pressure pulse effects are clearly present in magnetospheric observations, but they generally last longer than FTE signatures, and they penetrate deeper into the

[1]Institute for Computational Sciences and Informatics, George Mason University, Fairfax, Virginia, USA.
[2]Beam Physics Branch, Plasma Physics Division, Naval Research Laboratory, Washington, D.C., USA.
[3]Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA.
[4]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

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magnetosphere [*Sanny et al.*, 1996]. Pressure pulse effects have also been reported in magnetospheric simulation results [*Slinker et al.*, 1999a], but they do not exhibit the typical FTE signatures. Most recently, there has been general accord in the identification of FTEs as magnetic merging signatures [*Sanny et al.*, 1998].

[6] This paper describes recent results obtained from the Lyon-Fedder-Mobarry (LFM) global magnetospheric simulation code. The results show magnetic and plasma flow signatures in the vicinity of the dayside magnetopause that are similar to the FTE observations. These signatures occur both inside and outside the magnetopause and propagate along the magnetopause as a coherent structure. The signatures result from the nonsteady character of the magnetopause magnetic field as it is modulated by the magnetic merging process. Examples of the magnetic and plasma signals that would be measured by a spacecraft are shown. Field line traces through the FTE are presented to show the magnetic connectivity between the IMF and the geomagnetic field. The field line traces show that a single twisted flux rope is formed across the dayside magnetopause between the magnetic null points. The flux rope is intermittently opened to the IMF and is released at one null point or the other. It is subsequently convected by the Maxwell stress poleward across the magnetopause. For IMF B_y positive, flux ropes that open to the IMF at the southern morning (northern evening) null convect across the dayside magnetopause in a northward and dawnward (southward and duskward) direction. For a steady solar wind and IMF the formation and release process is repeated intermittently.

2. Simulation Method

[7] The numerical MHD simulation model has been described by *Fedder and Lyon* [1995] and *Fedder et al.* [1995a, 1995b]. The code models the solar wind and magnetosphere using an ideal MHD formalism in the solar magnetic (SM) coordinate system. External boundary conditions are the supersonic super-Alfvenic solar wind, and internal boundary conditions are applied by a conducting ionosphere as described in the papers referenced. For this work the self-consistent ionospheric model [*Fedder et al.*, 1995b; *Slinker et al.*, 1999b] has been used. The ionospheric conductances are appropriate for moderate solar ultraviolet flux conditions. The simulation code uses a nonuniform mesh, described in the papers referenced above, and has a typical resolution of a fraction of an R_E near the dayside magnetopause.

[8] The simulation was implemented by introducing a southward IMF with $B_y = 1.9$ nT and $B_z = -4.6$ nT to a northward IMF magnetosphere. The introduction of the southward IMF results in an increase in the magnetic merging rate and tailward convection in the polar cap ionosphere. The magnetosphere enters a substorm growth phase, with growing tail lobe magnetic flux, which ultimately results in a substorm expansion about an hour later. The results shown occur during the substorm growth phase when the FTE-like signatures are most noticeable in the simulation results. Other solar wind parameters used in this simulation are typical conditions: the solar wind plasma density $\rho = 1.125\ 10^{-23}$ g cm^{-3}, the velocity $V_x = 400$ km s^{-1}, and the sound speed $c_s = 23.5$ km s^{-1}. These solar wind conditions lead to an Alfven Mach number of 8 and a relatively low plasma β in the magnetosheath that tends to enhance the Maxwell stresses relative to the flow stresses there.

[9] In this study we use an ideal MHD simulation to study magnetic merging. This should be explained since the merging occurs owing to numerical dissipation. The numerical integration of the fluid quantities uses a "finite volume" method that enforces strict conservation of plasma mass, momentum, and energy except allowing for electromechanical energy conversion. The magnetic field integration uses a "finite area" method that enforces strict conservation of magnetic flux by satisfying Gauss's law for $\nabla \cdot B$ on each cell surface. For this method, plasma quantities are known as cell-centered volume averages, while the magnetic field is known as face-centered area average normal flux (see *DeVore* [1991] for an example of a similar formulation). The use of a face-centered average magnetic flux necessarily loses information about the fine-scale structure of the field. A zero net flux through a face could indicate either no field or equal amounts of oppositely directed field. Numerically, a zero average acts as if there were no field. This "averaging error" leads to dissipation. However, if the velocity field is divergent ($\nabla \cdot v \geq 0$), the averaging error generally leads to little global consequence. If the velocity field is convergent, it continually attempts to bring new sheared field into the averaging region, and a large dissipation (field slippage and merging) can occur. In practice, the dissipation regions are spatially very localized, ($\approx 0.5\ R_E$) being confined primarily to the bow shock and the magnetopause. For simulations of the solar wind interaction with the Earth's magnetosphere, the solutions feature large volumes of space where the plasma and field vary smoothly interspersed by thin current sheets (typically one or two cells wide) with large changes in the plasma and field parameters across the sheets. It is important to recognize that the magnetic merging rate is not being controlled by the magnitude of the numerical diffusion rate, which is not easily quantified, since it changes from one cell to another and from one time step to another. In the simulations of the Earth's magnetosphere the magnetic merging rate between the IMF and the geomagnetic field is controlled by the solar wind parameters and by the ionospheric conductance (the consequent field-aligned current strength) as has been previously reported [*Fedder and Lyon*, 1987; *Fedder et al.*, 1995a].

[10] For the present results we do not use a specified resistivity parameter, and none is needed. We suggest that magnetic reconnection is similar to the well-known shock formation in the MHD code. It is not necessary to resolve the dissipation-scale physics in order to numerically solve the conservation equations for the correct Hugoniot jump conditions. In addition to mass, momentum, and energy, the numerical solutions conserve magnetic flux in the merging process, which enforces a continuous tangential electric field at the merging line. Importantly in our experience, the global-scale magnetic merging process is virtually independent of the grid cell size and of the dissipation model and only depends on the solar wind parameters and the ionospheric load.

[11] The numerical simulation mesh is described by *Slinker et al.* [1999b]. It is highly nonuniform and was designed to achieve a reasonably high resolution in regions of concentrated magnetospheric current systems. For the present study the mesh cells in the dayside magnetopause region are $\sim 1/3\ R_E$ in the radial coordinate and somewhat larger in the angular coordinates.

3. Results

[12] The appearence of FTE-like magnetic signatures was discovered in the simulation results that were obtained in a study using strong southward IMF with a small IMF B_y component. The magnetic fluctuations were noticed in equatorial and noon-midnight plane animations, where they are seen as enhancements in B_y that form and grow on the subsolar magnetopause and subsequently propagate to one side of the magnetosphere or the other. The magnetic enhancements propagate northward and dawnward (northward and duskward) or southward and duskward (southward and dawnward) for IMF B_y positive (negative). Figure 1 shows a temporal series for the magnetic field and plasma properties near the magnetopause at $(x, y, z) = (8.5, -5., 2.5)\ R_E$ in SM coordinates. The vector components are in (l, m, n) coordinates, where l is the dipole axis direction, n is the outward normal, and m is along the magnetopause. In Figure 1, three FTE-like signals are seen on the dawn magnetopause. Two of these occur at 35 and at 50 min and are very clear at this location. Another occurs at 59 min and does not show up as clearly. (For this run, $t = 0.$ min was set when the southward IMF was input to the mesh.) Particularly noticeable are the bipolar signals in B_n, a core field enhancement in

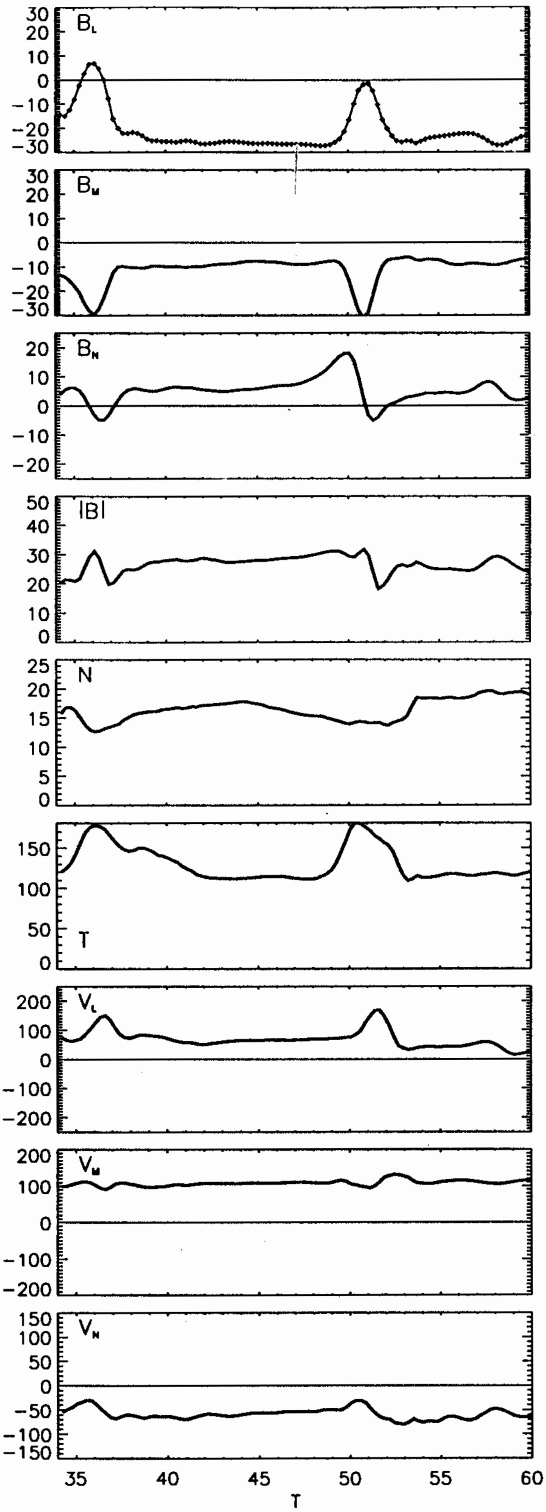

Figure 1. Time series of magnetic field and plasma parameters from the simulation on the morning magnetopause at $(x, y, z) = (8.5, -5., 2.5)$ R_E in the solar magnetic (SM) coordinates. The vector components are plotted in the (l, m, n) coordinates, where l is the dipole field direction and n is the outward normal to the magnetopause. The units for the magnetic field, plasma density, velocity, and temperature are nanoteslas, cm^{-3}, km s^{-1}, and degrees kelvin, respectively. The horizontal axis is in minutes.

B_m, and the strong nearly field-aligned flows seen in V_l, which are the classic signatures of the FTE observations [*Elphic*, 1995]. The bipolar signal at 50 min has nearly symmetric peaks to either side of the mean B_n. Although the bipolar magnetic structure and the core B_m field are closely confined to the magnetopause, their effects are observable both inside the magnetosphere as well as outside in the magnetosheath.

[13] Figure 2 shows time series at four different x coordinates but at the same y and z coordinates as those in Figure 1. The solid line, dotted line, dashed line, and dash-dotted line are at x = 7., 8., 9., and 10. R_E, respectively. The x = 8. R_E curve is situated right at the magnetopause, with the magnetopause moving inward of 8. R_E between 38 and 50 min. Bipolar signals are seen in B_n at all locations with positions closer to the magnetopause showing a stronger variation. The B_m core field enhancement is strong only adjacent to the magnetopause and is much weaker at the other locations. Similarly, the V_l enhancement is only seen at the magnetopause location. Away from the FTE signals, locations inside the magnetopause exhibit the positive B_l of the geomagnetic field, while outside the magnetopause it is negative because the IMF is draped over the magnetopause. Locations outside the magnetopause exhibit a negative V_n and a positive V_l, because they are in the magnetosheath flow, which is only weakly altered by the passage of the magnetic structures. Again, the B_n trace (dotted line) closest to the magnetopause position shows a nearly symmetric signal. While the FTE magnetic signature is seen clearly at the locations shown in Figures 1 and 2, it may or may not be so clear at other nearby locations.

[14] Figure 3 shows similar time series of the magnetic field and plasma parameters at $(y, z) = (-5., 0.5)$ and x = 7.5, 8.5, 9.5 R_E, which are shown by the solid, dotted, and dashed line, respectively. At this position, which is close to the geomagnetic equatorial plane, the clear B_n bipolar signature shows only at 34 min and is not clearly seen at the later times. At the later times the inward directed normal field component grows and then decays with the passage of the magnetic structure. The B_m core field also has a different character. It features a linear growth period followed by a dropout just as the normal component gets stronger. Nevertheless, the field-aligned flow merging signature is preserved at the x = 8.5 R_E location immediately adjacent to the magnetopause.

[15] Farther toward the magnetospheric flank and slightly higher above the equatorial plane at $(y, z) = (-8., 3.)$ and x = 6., 7., 8. R_E, the characteristic FTE magnetic signatures are clearly preserved as shown in Figure 4. The signals are delayed by ~2 min relative to their passage in Figures 1 and 2, owing to their propagation along the magnetopause. At this position, two of the traces show nearly symmetric bipolar signatures in B_n. The field-aligned velocity also shows the characteristic acceleration at the location nearest the magnetopause, x = 6. R_E. Close to the magnetopause the field-aligned flow is more continuous in time, but there is also a pulse in the field-aligned flow speed as the FTE-like structure passes by. From the results shown in Figures 1, 2, and 4 it is apparent that the FTE-like magnetic structure contains a decrease in density and an increase in temperature outside the magnetopause. It also shows a possible increase in density inside the magnetopause. These density and temperature changes are characteristic for a flux tube that interconnects the geomagnetic field and the IMF.

[16] In their discussion of the magnetic signatures, *Russell and Elphic* [1978] suggest that the FTE structure is composed of a twisted open geomagnetic flux tube with a central core and over draped field lines. Figure 5 shows four perspective views of the FTE-like structure that is responsible for the magnetic field and flow signatures seen in Figure 1 at 50 min. Figures 5a and 5c are viewed from above the North Pole and from dusk, respectively, with the solar direction to the left. Figure 5d is a view from the Sun-Earth line with dawn to the left. Figure 5b was selected to view along the FTE structure as it extends across the dayside

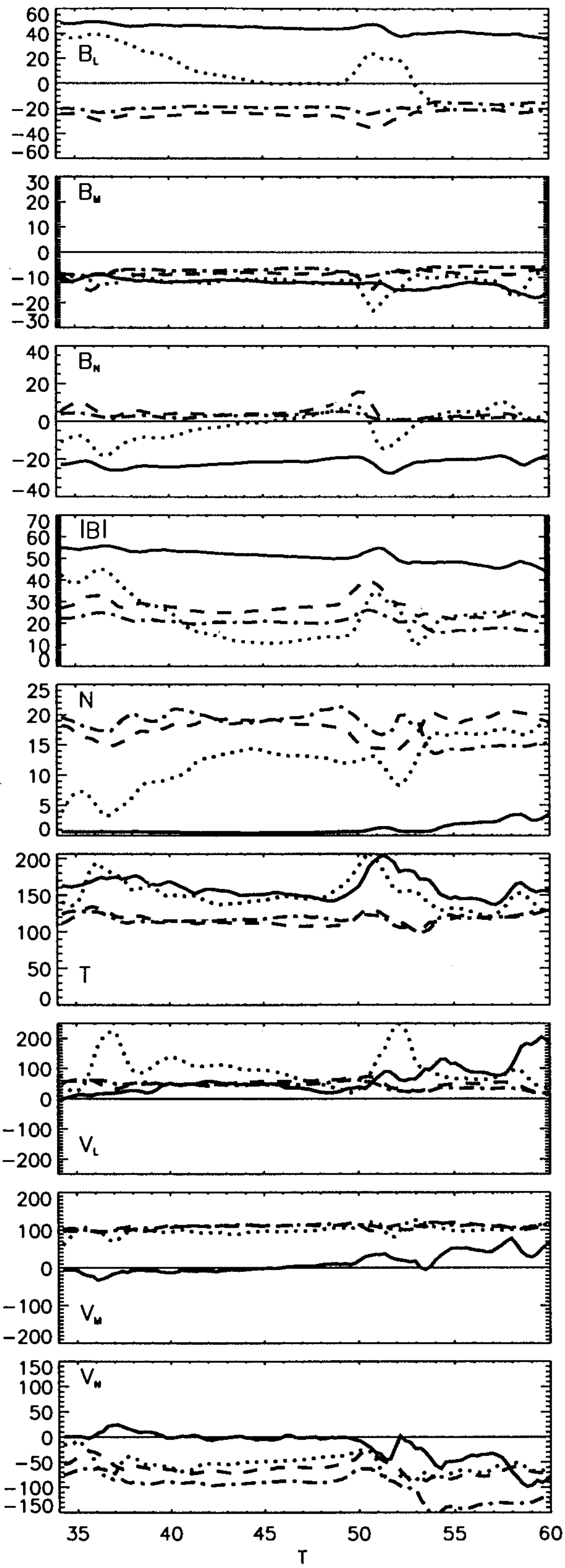

Figure 2. Same as Figure 1, except at four locations inside and outside of Figure 1. The solid, dotted, dashed, and dash-dotted lines are at (7., −5., 2.5), (8., −5., 2.5), (9., −5., 2.5), and (10., −5., 2.5) R_E in SM coordinates, respectively.

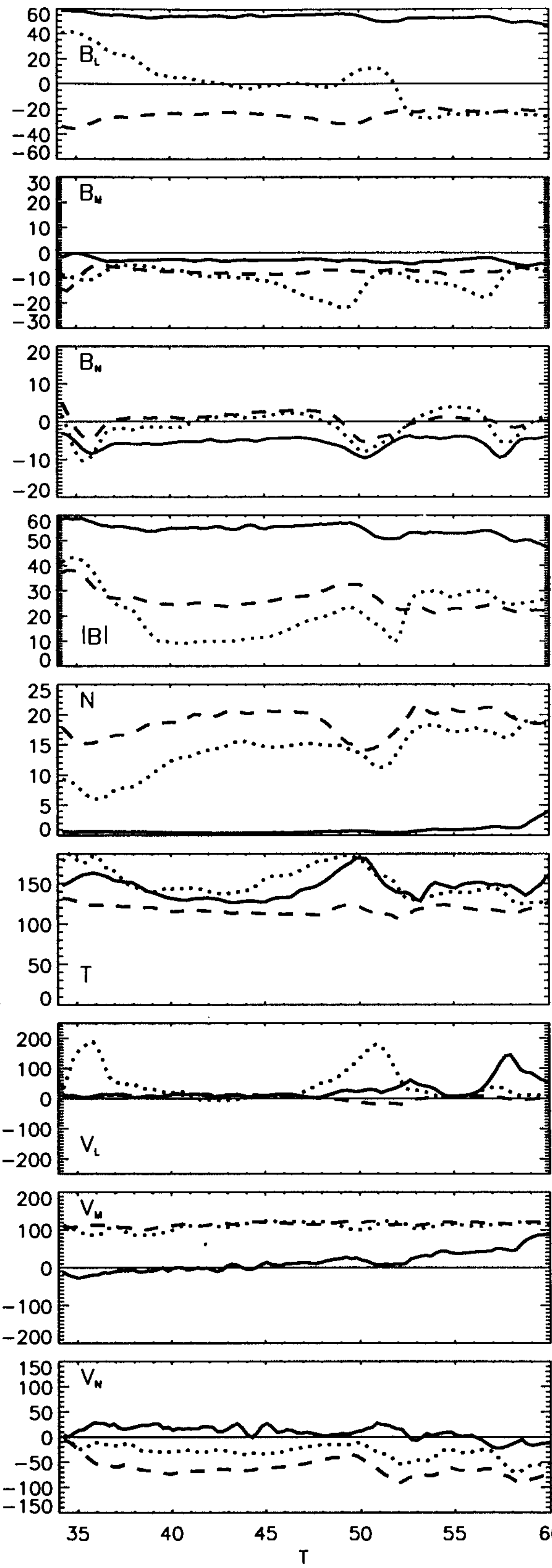

Figure 3. Same as Figure 1, except at three locations closer to the equatorial plane. The solid, dotted, and dashed lines are at (7.5, −5., 0.5), (8.5, −5., 0.5), and (9.5, −5., 0.5) R_E in SM coordinates, respectively.

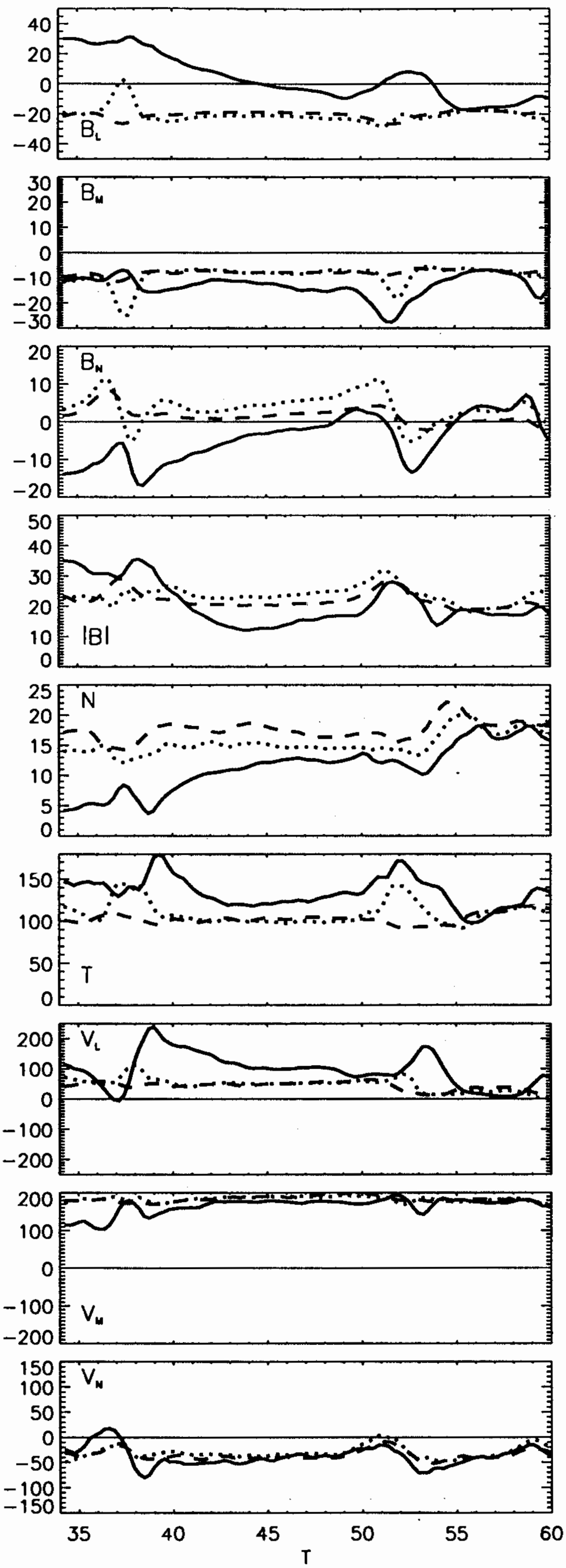

Figure 4. Same as Figure 1, except at three locations closer to dawn. The solid, dotted, and dashed lines are at (6., −8., 3.), (7., −8., 3.), and (8., −8., 3.)R_E in SM coordinates, respectively.

magnetopause. In Figure 5 the field lines are shown in two colors to make the field line wrapping clearly visible. One magenta overlying IMF field line and one magenta underlying geomagnetic field line are shown. The axes are the solar magnetospheric coordinates and are 8 R_E long. The gray sphere is the inner boundary of the MHD simulation mesh at 3.2 R_E geocentric radius.

[17] The field lines in Figure 5 clearly have the *Russell and Elphic* [1978] suggested structure. The field lines comprise a twisted magnetic flux tube that interconnects the IMF with the geomagnetic field. However, the images are also different from Russell and Elphic's sketch of the geometry. Figure 5 shows the flux tube extending across the dayside magnetopause from high latitudes on the afternoonside to low latitudes on the morningside. This extension across most of the dayside magnetopause is noteworthy. It shows that the magnetic merging process occurs along an extended line and provides a clue as to the formation geometry, which we will address below. While the core field lines make many wraps (at least five in Figure 5) around the flux tube, the outer field lines drape the core once. Magnetic field lines immediately earthward of the structure are closed; field lines immediately outside are IMF. In a plane section of the core the structure is very much like that suggested from the two-dimensional simulation studies of *Scholer* [1989] for time-dependent reconnection. The third dimension allows many wraps of the core without the formation of a second merging line. The third dimension of this study also allows us to follow the field line connection to the ionosphere. In this example and in all other examples studied to date, the extended, twisted magnetic structure maps to a region of the ionosphere which is broad (3–4 hours) in magnetic local time. Because of the broad latitudinal extent to which the magnetic structure maps, the perturbation to ionospheric convection caused by the FTE evolution is small.

[18] Figure 5 also shows the size of the twisted magnetic flux tube. The structure is ~1 R_E thick in its dimension normal to the magnetopause. It is ~2–3 R_E in its other cross section along the magnetopause. This size is reasonably consistent with that inferred from ISEE I and two measurements by *Walthour et al.* [1994]. The size of the structure is about as small as it could be and still be resolved on the numerical mesh.

[19] Studying the field lines more carefully, we notice that the twisted flux is confined to the magnetopause. The twist does not extend outward along the field into the magnetosheath. Neither does it extend inward into the magnetosphere and the ionosphere. The twisted FTE-like magnetic structure is localized to the magnetopause. Clearly, there is no substantial localized enhancement to field-aligned currents into the magnetosheath or into the magnetosphere and ionosphere. The lack of a localized convection response in the ionosphere therefore is not surprising. We have carefully searched for a local ionospheric convection response by plotting convection potential differences from a temporal average at a 1-kV level, and we have found none. Apparently, the twisted magnetic flux tube structure is simply a localized enhancement in the magnetopause current system with no ionospheric signature. On the other hand, the global-scale cross-polar voltage does regularly fluctuate at a few percent level, which may be linked to the temporally dependent merging.

[20] Finally, we point out that the magnetic structure shown in Figure 5 occurs only in the Northern Hemisphere and primarily on the dawn magnetopause. Similar magnetic structures also appear in the Southern Hemisphere and primarily on the dusk magnetopause. The structures are created sporadically and intermittently and propagate into one hemisphere or the other but do not necessarily alternate between hemispheres. Figure 6 shows the magnetic field B_y component on the magnetospheric equatorial plane. Individual frames are at ≈ 3 min intervals. The FTE-like magnetic structures appear in Figure 6 as enhancements in the B_y magnetic field component. The structures are seen to form on the magnetopause crossing the equatorial plane near noon. Subsequently, they drift

Figure 5. (a–d) Field lines through the flux transfer event (FTE)-like magnetic structure. The field lines are chosen in the vicinity of the Figure 1 plot at 50 min. The colors are used to clearly show the field line twist in the core of the structure. Perspective views are shown from four viewpoints; upstream on the Earth-Sun axis, from the duskside y axis, from the North Polar axis, and along the core of the FTE-like structure. The solar magnetic coordinate axes are shown outside the spherical 3.2 R_E radius simulation inner grid boundary. See color version of this figure at back of this issue.

either toward dawn or toward dusk. The structures that drift toward dawn (dusk) in Figure 6 also move toward the north (south) when seen in a noon-midnight section of the dayside magnetopause region. This northward and dawnward (southward and duskward) motion is organized by the sign of the IMF B_y component. If the IMF B_y were negative, the twisted flux tubes would drift northward and duskward (southward and dawnward). During a 1-hour simulation period that includes the sequence shown in Figure 6, seven distinct traveling magnetic structures are seen leading to a recurrence time of ~8.5 min.

4. Discussion

[21] The space measurements of the magnetic field and plasma parameters show a consistent set of features for the FTE phe-

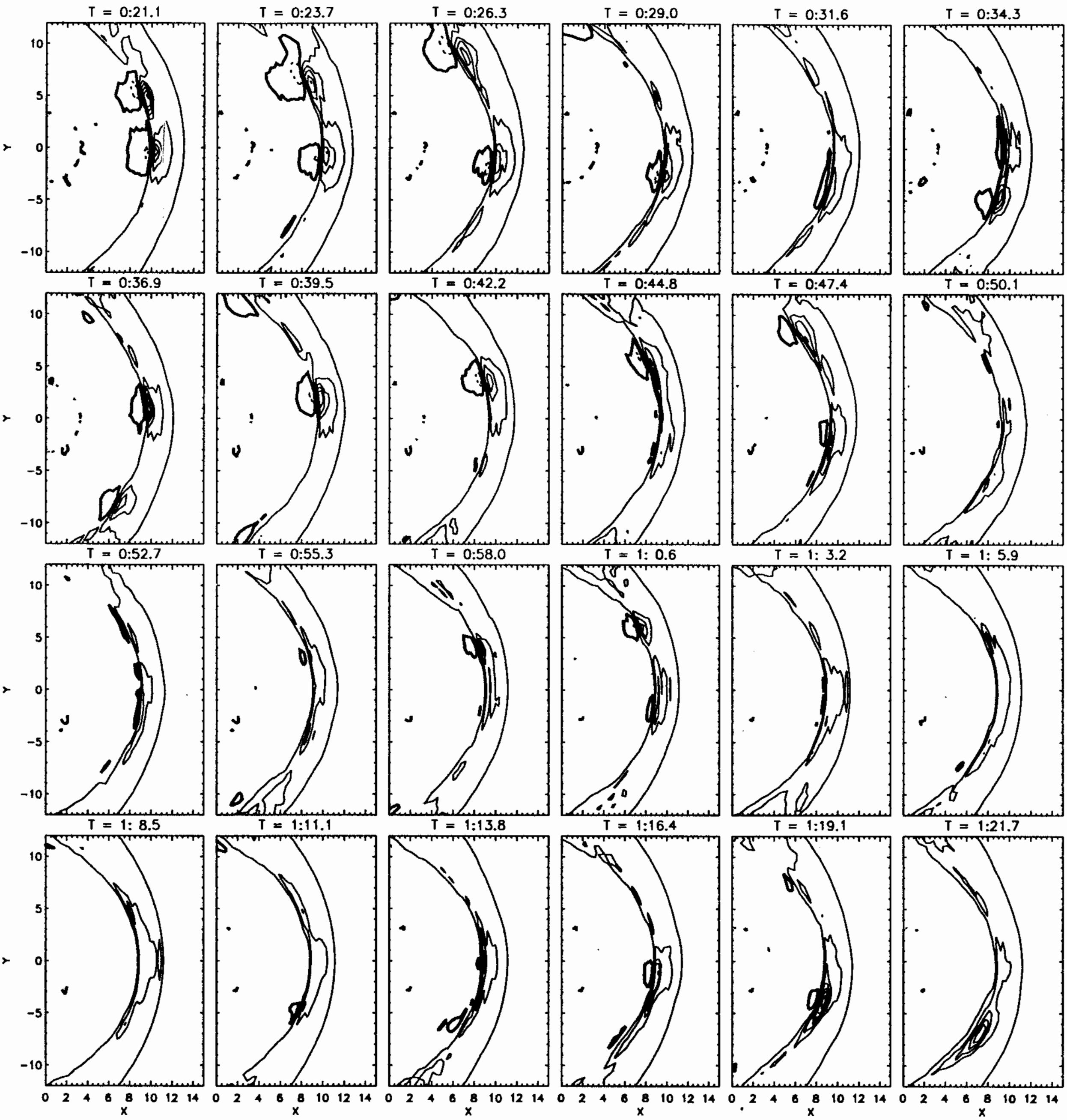

Figure 6. Plots of B_y on dayside magnetospheric equatorial plane for a 1-hour period during simulation run. The plots show B_y on the SM plane $0. \leq x \leq 15., -12. \leq y \leq 12., z = 0.$ R_E. Concentrations of B_y are seen to form on the magnetopause near the noon meridian and to drift toward dawn or dusk in the magnetosheath flow.

nomenon. A list of these commonly observed features is presented in the review by *Elphic* [1995, p. 226]. The identifying signatures in the magnetic field include "a characteristic bipolar signature in the B_n magnetic field component, which is normal to the nominal plane of the magnetopause" "the large B_m extrema and the field maxima at the center of the event," and "the southward then northward turning of the B_l component" (this final signature is typical of magnetosheath FTEs and not necessarily of magnetospheric FTEs, as shown in the examples shown in Elphic's review). As seen in Figures 1, 2, and 4, the simulations reproduce these observational signatures in the magnetic field structure. The simulation results also reproduce accelerated flows that were identified in magnetosheath FTEs by *Paschmann et al.* [1982]. In Figures 1, 2, and 4 the accelerated flows occur primarily in the l velocity component if the observation point is sufficiently close to the magnetopause. We also note that the accelerated flows in V_l are associated temporally with the northward turning in B_l as observed by *Paschmann et al.* [1982].

[22] Differences in the field and flow features in the observational data were organized in a proposed taxonomy of FTEs by *Elphic* [1995]. In the figures shown above, similar features are noticed in the FTE field and flow results, which are sensitive to the distance of the observation point from the magnetopause. We would point out that there is an increase in B_l near the magneto-

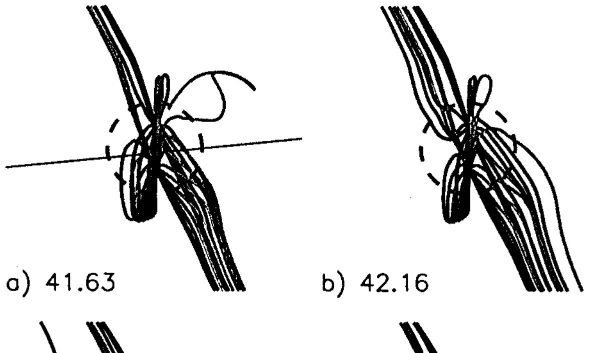

Figure 7. (a–f) Plots of the growth of the FTE-like magnetic structure in the vicinity of the Sun-Earth axis on the dayside magnetopause. The images show the initial growth of the magnetic structure over a 2.5-min time period. The dashed circle indicates the position of the 3.2 R_E inner boundary of the simulation. The solid straight line shows the orientation of the magnetic null-null line between the IMF and the geomagnetic field on the magnetopause.

pause and inside the magnetosphere as opposed to a decrease farther out in the magnetosheath. The IMF B_y component and the B_m signature of the core field are large near the magnetopause. This IMF B_y and the resulting large core field are important for the structure of the FTE as it is seen in Figure 5, since it allows for a substantial number of twists in the field lines in the outer part of the core. The bipolar signature in B_l is largest at the magnetopause and is reasonably symmetric there. Its magnitude decreases, and it becomes asymmetric farther inside and outside the magnetopause. There is an appearance of greater symmetry further from the merging line as seen in Figure 4, which has been suggested from data analysis by *Sanny et al.* [1998]. The accelerated flow in V_l is large only adjacent to the magnetopause. The density tends to decrease outside the magnetopause and increase inside, while the temperature increases outside. These features of the simulation results fit *Elphic*'s [1995] taxonomy reasonably well. The temperature decrease inside the magnetopause that is seen in the data is not reproduced in the simulation results, because the simulation does not have a low-density, high-temperature plasma component inside the dayside magnetopause.

[23] The present simulations are in certain respects similar to previous theory and modeling efforts. In particular, the results shown here bear a strong resemblance to the results of two-dimensional simulations by *Scholer* [1988, 1989] and by *Ku and Sibeck* [1997, 1998a, 1998b, 2000]. These previous two-dimensional results for time-dependent merging [e.g., *Scholer*, 1995, Figure 6] show the growth of a bulge in the field that moves poleward with accelerated field-aligned flow jets along the field immediately adjacent to the magnetopause. Scholer's field line plots are similar to the view along the FTE shown in Figure 5. In all the simulations the bulge leads to the bipolar signature as it propagates past the observing location. In the two-dimensional simulations this bipolar field is generally quite asymmetric with the inward (outward) field substantially stronger north (south) of the merging region. In contrast, the present simulations do show relatively symmetric bipolar signatures in many examples, which will be addressed below.

[24] The feature that leads to differences between the present results and the previous results is the added dimensionality along the merging line (seen in Figure 5) and the inclusion of the B_y IMF in the global simulation. The B_y field is concentrated in the bulge and forms a strong core field along the FTE as it drapes across the magnetopause as was suggested by *Scholer* [1988]. Because the strong core field is twisted a number of times along the extended field structure, it allows the nearly symmetric bipolar normal magnetic field to develop and grow in strength. This twisting is not produced in any of Scholer's or Ku and Sibeck's two-dimensional results. The twisted structure with multiple turns is clearly seen in Figure 5, where some field lines wrap six times around the core. The twisting will be seen again in Figure 7. It is also noteworthy that the two-dimensional simulation results were induced either by a suddenly enhanced southward IMF component or an increase in resistivity to excite a burst of merging. In contrast, the present results occur spontaneously and repeatedly under steady solar wind driving and without a prescribed temporal or spatial resistivity.

[25] On the other hand, the results presented here are very different from the multiple X line of *Lee and Fu* [1985] or the patchy reconnection of *Galeev et al.* [1986] or *LaBelle-Hammer et al.* [1988], all of which arise from a more local theory of magnetic merging as opposed to the global three-dimensional modeling used here. In those studies the resistivity was adjusted to localize the merging process. In the present study the merging process occurs over an extended region between the magnetic null points that form on the magnetopause between the magnetosheath field and the geomagnetic field. The merging in the present study is spontaneously time dependent, with the magnetic structures repeatedly forming and convecting downstream along the magnetopause with no imposed time dependence. The multiple X line models were thought to be necessary to reproduce the observed nearly symmetric bipolar normal field. The results shown here demonstrate that B_y and three dimensionality apparently alleviate that difficulty. Moreover, the present results are consistent with the recent work of *Boudouridis et al.* [2001], who infer on the basis of low-altitude, high-latitude plasma data that the multiple X line models must be revised. They propose a model similar to the results presented herein. However, Boudouridis et al.'s model suggested simultaneous northward moving and southward moving ropes and not the independent northward or southward moving structures that we find in the simulation results.

[26] In previous global magnetospheric simulations of *Ogino et al.* [1989], dayside magnetic reconnection was shown to lead to twisted magnetic flux tubes on the dayside magnetopause. In that work the authors show that twisted magnetic flux tubes develop on closed field lines just inside the dayside magnetopause. These structures subsequently break, and the north and south portions of the flux tubes convect over their respective poles. The formation and evolution of Ogino et al.'s structures are different from that in

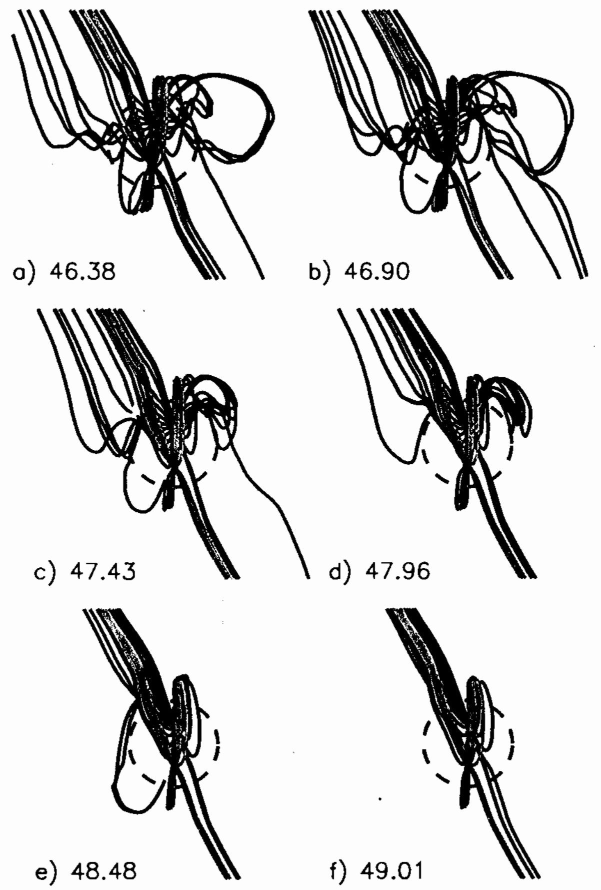

Figure 8. (a–f) Plots of the decay of the FTE-like magnetic structure in the vicinity of the Sun-Earth axis as the twisted flux tube propagates away. The images show field lines in the same location as Figure 7 over a 2.5-min period as the structure propagates poleward and dawnward at the end of the growth period.

the present study. We suspect that the different behavior may be the result of Ogino et al.'s symmetry assumption at the geomagnetic equatorial plane. The present results show an asymmetric development and propagation as described more completely below.

[27] The question arises, what is the physical mechanism for the magnetic structures? Figures 7 and 8 present snapshots of the field structure at 30-s intervals on the dayside magnetopause. The field lines are chosen on the noon-midnight meridian 2 R_E above (black) and below (gray) the equatorial plane and are spaced 0.1 R_E apart in x. The Figure 7 images are shown during the formation period of the magnetic structure. In the first few images the magnetic structure forms on the magnetopause, encompassing magnetosheath IMF, reconnected open field, and closed geomagnetic field lines. The presence of all three topological field classes shows that the formation takes place in the magnetic diffusion region. As is clearly seen, there is only one structure that forms slightly above the equatorial plane, in this example. Initially, the structure is small and encompasses only a few field lines. It subsequently grows in place, increasing the magnetic flux in the core and showing a continually increasing number of wrapped field lines. It is noteworthy that the initial appearance of the wrapped field structure is nearly aligned with the topological magnetic nulls. The orientation of the nulls is shown by the straight line in Figure 7a. The magnetic null-null line is a field line that connects the diverging and converging magnetic nulls that are formed between the IMF and the geomagnetic field on the dayside magnetopause [*Stern*, 1973]. This is a likely location for magnetic reconnection to take place [*Cowley*, 1973; *Greene*, 1988; *Lau and Finn*, 1990]. The Figure 8 images are shown at the end of the growth as the magnetic structure propagates away. At this time the evening end of the core field region has become open to the IMF in the dawn null region but remains attached to the geomagnetic field at dusk. Subsequently, it begins to propagate northward and toward morning across the dayside magnetopause. After the null-null line disconnects from the null point only open field lines can be identified in the magnetic structure, as seen in Figure 5, as it propagates across the dayside magnetopause. Because the structure is formed in the magnetopause diffusion region, it is not possible to follow a single or multiple flux tubes throughout the growth and propagation periods.

[28] The outlines of a physical picture are reasonably straightforward. The magnetic null-null line formed between the magnetosheath field and the geomagnetic field on the dayside magnetopause is the location for magnetic merging [*Cowley*, 1973; *Greene*, 1988; *Lau and Finn*, 1990]. In the simulation, magnetic merging occurs over an area of the magnetopause that extends across the dayside magnetosphere in the vicinity of the null-null line. The magnetic reconnection process transports the normal components of the magnetic field across the topological separatrices but accumulates the component parallel to the null-null line. The magnetopause current that connects the topological null points becomes increasingly concentrated along the merging line with a resultant twisting of the core magnetic field. At some point in this process one end of the twisted flux tube disconnects from one of the two nulls. The null drifts tailward and is annihilated, and a new null forms up stream. Merging begins at an adjacent latitude along the new null-null line, and the fossil null-null line with the characteristic FTE magnetic structure is convected poleward and around the magnetopause. For a positive IMF B_y component, connection to the IMF at the morning (afternoon) null point leads to northward (southward) and dawnward (duskward) transport of the FTE structure. For a negative IMF B_y component, connection to the IMF at the morning (evening) null point leads to southward (northward) and dawnward (duskward) motion. This morphology is consistent with the observational studies of *Kawano and Russell* [1996, 1997]. At present the physical details of precisely how this discarding of an old null-null line merging region in favor of a new null-null line merging region occurs are not known. Whether it results from structural instability of the null points in the sheared magnetopause flow, or from a self-pinch instability of the magnetopause current sheet, or from some other mechanism is not known. This question is undergoing additional study.

5. Conclusions

[29] Global magnetospheric simulation results show a magnetic structure that forms spontaneously on the dayside magnetopause during periods when the IMF has both southward and dawn-dusk components. The structure exhibits the observed characteristic bipolar normal component and core field enhancement features of the FTE magnetic measurements. They also show the nearly field-aligned accelerated plasma flow often associated with the magnetic reconnection process. The results show that the magnetic signatures are observable at considerable distance from the magnetopause both inside the magnetosphere and outward into the magnetosheath. These FTE features appear recurrently during the simulation and demonstrate that the magnetic reconnection process is unsteady in the global simulation results.

[30] The field traces (seen in Figure 5 and in Figures 7 and 8) clearly show the [*Russell and Elphic*, 1978] suggested twisted core and overdraped open field structure of an FTE. The results show that the structure is formed by the nonsteady magnetic reconnection process that takes place along the magnetic null-null line that

is formed between the geomagnetic field and the IMF on the dayside magnetopause. Noticing in Figure 5 and Figures 7 and 8 that the twisted flux tubes only extend along the magnetopause, it is clear that the current concentration associated with the field structure is confined to the magnetopause and does not enter the magnetosheath or the magnetosphere to any significant extent. The confinement of the field structure and the resultant current to the magnetopause greatly reduces any possible ionospheric signature of the FTE formation and propagation process to very small values.

[31] Interestingly, there is only a single magnetic structure, instead of a pair, formed at a time, and it propagates across one half of the dayside magnetopause. It has a large core field and is twisted many times. This result is different from all previous theoretical and modeling studies. The single merging line appears to be consistent with the data analysis and modeling of reconnection plasmas presented by *Boudouridis et al.* [2001].

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J. A. Fedder and S. P. Slinker, Code 6794, Naval Research Laboratory, 4555 Overlook Ave., S. W., Washington, DC 20375, USA. (fedder@ppd.nrl.navy.mil; slinker@ppd.nrl.navy.mil)

J. G. Lyon, Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA. (lyon@tinman.dartmouth.edu)

C. T. Russell, Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90024-1567, USA. (ctrussel@igpp.ucla.edu)