Size and Shape of the Distant Magnetotail

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Key Points:

- An ecliptic IMF causes prolate bow shock but oblate magnetotail cross-sections
- The oblate lunar magnetotail cross-sections include broad slow mode fans
- Lunar magnetotail and bow shock cross-sections respond rapidly to IMF variations

Abstract

We employ a global magnetohydrodynamic model to study the effects of the interplanetary magnetic field (IMF) strength and direction upon the cross-section of the magnetotail at lunar distances. The anisotropic pressure of draped magnetosheath magnetic field lines and the inclusion of a reconnection-generated standing slow mode wave fan bounded by a rotational discontinuity within the definition of the magnetotail result in cross-sections elongated in the direction parallel to the component of the IMF in the plane perpendicular to the Sun-Earth line. Tilted cross-tail plasma sheets separate the northern and southern lobes within these cross-sections. Greater fast mode speeds perpendicular than parallel to the draped magnetosheath magnetic field lines result in greater distances to the bow shock in the direction perpendicular than parallel to the component of the IMF in the plane transverse to the Sun-Earth line. The magnetotail cross-section responds rapidly to variations in the IMF orientation. The rotational discontinuity associated with newly reconnected magnetic field lines requires no more than the magnetosheath convection time to appear at any distance downstream, and further adjustments of the cross-section in response to the anisotropic pressures of the draped magnetic field lines require no more than 10-20 minutes. Consequently for typical ecliptic IMF orientations and strengths, the magnetotail cross-section is oblate while the bow shock is prolate.

Index terms: 2744 (Magnetotail), 2724 (Magnetopause and Boundary Layers), 2748 (Magnetotail Boundary Layers), 2728 (Magnetosheath)

1. Introduction

Theory predicts that the strength and direction of the interplanetary magnetic field (IMF) determine the size, shape, and internal configuration of the Earth's distant magnetotail. During intervals of southward IMF orientation, the magnetic flux removed from the dayside magnetosphere and added to the magnetotail by reconnection on the dayside equatorial magnetopause causes the magnetotail magnetopause to flare outward and increases its dimensions [Coroniti and Kennel, 1972; Maezawa, 1975]. During periods of northward IMF orientation, reconnection appends magnetic field lines to the dayside magnetopause, removes flux from the magnetotail, and reduces magnetotail dimensions [Dungey, 1963; Song and Russell, 1992].

The cross-section of the distant magnetotail need not be circular. Michel and Dessler [1970] noted that magnetic tension or curvature forces associated with shocked IMF lines draped about the magnetotail in the magnetosheath apply an anisotropic pressure to the magnetotail. They argued that this anisotropic pressure should progressively flatten the nominally circular near-Earth cross-section into an elliptical distant magnetotail cross-section with a major axis parallel to the component of the IMF in the plane transverse to the Sun-Earth line.

The IMF orientation also determines the locations where plasma and magnetic field lines enter and exit the magnetotail as well as the tilt of the current sheet that separates the north lobe from the south lobe. Component reconnection occurs along a dayside reconnection line whose tilt itself depends upon the IMF orientation [Gonzalez and Mozer, 1974]. The solar wind flow carries one end of the newly reconnected magnetic field lines antisunward along the magnetopause, while the other end remains rooted in the Earth's ionosphere [Russell, 1972; 1973]. This antisunward motion causes magnetic field lines with one end connected to the northern ionosphere to gain north lobe orientations while those with one end connected to the southern ionosphere to gain south lobe orientations. For duskward IMF orientations, field lines gaining south lobe (antisunward) magnetic field orientations lie draped against the duskside magnetotail at latitudes both above and below the midplane of the magnetotail while those gaining north lobe (sunward) magnetic field orientations lie draped against the dawnside magnetotail at latitudes both above and below the midplane of the magnetotail [Kaymaz and Siscoe, 1998]. As a result, the cross-tail current layer separating north and south lobe magnetic field lines twists counterclockwise with downstream distance when viewed from Earth. For dawnward IMF orientations, the twist is clockwise.

Figure 1 presents the Y-Z plane projection of magnetosheath and magnetotail magnetic streamlines. While all the interplanetary magnetic field lines that enter and exit the magnetotail originate in relatively narrow windows [Stern, 1973], there is evidence that these same magnetic field lines then proceed to spread out and cross the entire surface of the magnetotail, including its flanks [Kaymaz and Siscoe, 1998]. The transition between magnetospheric and magnetosheath magnetic field orientations along interconnected magnetosheath and magnetospheric magnetic field lines requires two magnetohydrodynamic (MHD) discontinuities: a sharp rotational discontinuity and a broad slow mode expansion fan [Levy et al., 1964; Coroniti and Kennel, 1979; Siscoe and Sanchez, 1987]. The sharp rotational discontinuity bends draped magnetosheath magnetic field lines with arbitrary orientations towards the sunward or antisunward magnetotail magnetic field orientations found in the northern and southern lobes, respectively. The broad slow mode expansion fan enables a smooth transition from (generally) weaker and more variable magnetosheath magnetic field strengths to stronger values in the plasma mantle and magnetotail and from colder denser magnetosheath to warmer and more tenuous plasma mantle and magnetotail plasmas. Tangential discontinuities separate magnetic field lines within the fans from those deeper within the magnetosphere.

Global MHD models for the interaction of the solar wind with the Earth's magnetosphere provide an opportunity to quantify theoretical predictions concerning the effect of draped magnetosheath magnetic field lines upon the shape and configuration of the Earth's magnetotail cross-section. During southward IMF orientations, they predict that the magnetotail extends well beyond lunar distances with a large cross-section and greater north/south than east/west dimensions [Usadi et al., 1993]. During periods of northward IMF orientation, simultaneous reconnection poleward of both cusps removes magnetotail magnetic field lines and appends closed magnetic field lines to the dayside magnetopause. These closed magnetic field lines subsequently slide antisunward around the flanks of the magnetotail [Li et al., 2005], enabling the magnetotail to extend to lunar distances [Usadi et al., 1993; Gombosi et al., 1998] or perhaps much further [Fedder and Lyon, 1995; Raeder et al., 1995] even during strongly northward IMF intervals. East/west dimensions diminish steadily with increasing distance from Earth, ultimately resulting in a tadpole distant magnetotail configuration with greater north/south (~30 R_E) than east/west (~20 R_E) dimensions at lunar distances.

The IMF generally does not point due northward or southward, but rather has a strong dawnward or duskward (By) component. Consistent with theoretical expectations, simulations indicate that the cross-section of the magnetotail is elongated in the direction parallel to the component of the IMF in the plane perpendicular to the Sun-Earth line [Lu et al., 2013]. At locations near Earth, the effect should be particularly noticable during intervals of low solar wind Mach number [Lavraud et al., 2013]. The tilted current sheet expected during intervals of strong IMF B_Y is readily visible in simulations, particularly on the flanks [Kaymaz et al., 1995; Gombosi et al., 2000].

The effects of transient variations in the IMF orientation have also been simulated. Northward IMF turnings append newly closed magnetic field lines to both flanks of the distant magnetotail, briefly creating a transient bifurcated magnetotail that ultimately evolves into the tadpole configuration [Ogino et al., 1994]. At any downstream distance the time required to reconfigure the magnetotail cross-section from one associated with a southward IMF orientation to the tadpole-shape associated with a northward IMF orientation is the sum of the transit time for IMF discontinuities to sweep antisunward from the subsolar point to that distance and an intrinsic time scale associated with the reconfiguration itself [Raeder et al., 1995]. Berchem et al. [1998] presented results from a simulation of the magnetotail cross-section for time-varying solar wind conditions. The magnetotail cross-sections were greatly elongated in the direction parallel to the component of the IMF within the Y-Z plane at distances ~200 R_E from Earth. The axes of the elongations kept pace with slow rotations in the IMF orientation during an interval of northward IMF, resulting in a magnetotail whose cross-section was frequently twisted, with north lobes appearing below the ecliptic and south lobes above.

Observations confirm model predictions for the dependence of the dimensions of the near-Earth magnetotail upon the IMF orientation. The radius of the near-Earth magnetotail can shrink to as little as ~12 R_E at $X = -25\ R_E$ during prolonged intervals of northward IMF orientation [Milan et al., 2004], is 19 R_E on average for northward IMF, but grows to 24 R_E for southward IMF [Kaymaz et al., 1992]. There is a tendency for the cross-section of the near-Earth magnetotail to become elongated in the direction parallel to the component of the IMF in the Y-Z plane, particularly during intervals of low solar wind Mach number [Lavraud et al., 2013]. Observations also confirm predictions concerning the locations where rotational and tangential discontinuities are found in the near and distant magnetotail. Sibeck et al. [1985a; b] presented case and statistical studies indicating that the locations of the distant (~200 R_E) magnetotail transitions between magnetosheath and magnetotail parameters were consistent with expectations based on MHD models. Sanchez et al. [1990] reported that the same was true for open and closed boundaries on the high latitude magnetopause at distances some 25 R_E downstream from Earth. Hasegawa et al. [2002] showed that, as predicted, the open portion of the magnetotail magnetopause migrates to high latitudes during intervals of southward IMF orientation.

Observations also confirm predictions for magnetotail twisting. Sibeck et al. [1985a; 1986b] presented case and statistical studies of magnetotail cross-sections indicating the twisting expected in response to IMF B_Y variations. As seen from the Earth, the distant magnetotail cross-section twists anticlockwise for duskward IMF orientations, but clockwise for dawnward IMF orientation [Owen et al., 1995]. The degree of twisting for duskward and northward IMF orientations exceeds that for duskward and both northward and southward orientations [Maezawa et al., 1997]. It can sometimes exceed 90° [Macwan, 1992]. Berchem et al. [1998] presented a case study of Geotail observations consistent with the predictions of an MHD model for a magnetotail twisted in response to a varying IMF orientation in the y-z plane.

By contrast, there is less agreement about the size and shape of the distant magnetotail. In accord with model predictions, Sibeck et al. [1986a] and Fairfield [1992] reported that the distant (200 R_E) magnetotail cross-section typically exhibits greater dawn/dusk than north/south dimensions. Fairfield [1993] inferred a tadpole-shaped magnetotail cross-section with far greater north/south than east-west dimensions during intervals of strongly northward IMF orientation. And Nakamura et al. [1997] reported a distant magnetotail whose dawn/dusk extent exceeded its north/south extent during quiet intervals when IMF B_Y exceeded B_Z, but whose north/south extent exceeded its dawn/dusk extent during the main and recovery phases of geomagnetic storms when IMF B_Z exceeded B_Y. On the other hand, Tsurutani et al. [1984] reported that the distant magnetotail cross-section typically exhibits greater north/south than dawn/dusk dimensions, while Maezawa et al. [1997] reported a nearly circular cross-section.

Maezawa et al. [1997] suggested several possible reasons why the distant magnetotail might fail to flatten in response to the anisotropic pressure of draped IMF lines. First, the anisotropic pressure of the draped IMF lines might be too small to affect the shape of the distant magnetotail. Second, the cumulative effect of the anisotropic pressure resulting might simply be to transform a north/south elongated near-Earth magnetotail cross-section into a circular distant magnetotail cross-section. Third, the IMF might vary too rapidly for the magnetotail cross-section to complete its response. Fourth, there might be no preferred orientation for the IMF in the Y-Z plane. In this case, a statistical study might smear elongations in many directions, resulting in a blurry circular average magnetotail cross-section.

With the two ARTEMIS spacecraft in lunar orbit, a wealth of magnetotail observations are becoming available at lunar distances. This paper employs results from global MHD models to predict the size, shape, and structure of the magnetotail at cislunar distances as a function of typical solar wind parameters and steady-state or time-varying IMF orientations for comparison with these ARTEMIS observations. Our first task is to test the degree to which the anisotropic pressure of the draped magnetosheath magnetic field lines affects the shape of the lunar magnetotail. We demonstrate that the model predicts significant flattening of the magnetotail cross-sections at lunar distance for typical solar wind plasma and magnetic field parameters. Our second task is to test whether the cumulative effect of the anisotropic pressure applied by IMF lines draping over the magnetotail transforms a north/south elongated near-Earth magnetotail cross-section into a circular lunar magnetotail cross-section. We demonstrate that during periods of duskward IMF orientation the effect of the anisotropic pressure is instead to transform an already oblate near-Earth magnetotail cross-section into an even more oblate distant magnetotail cross-section. Our third task is to test the degree to which the size and shape of the magnetotail depend upon the identification criteria used. We demonstrate that the slow mode expansion fan has already grown to a substantial width by lunar distances, and that including or excluding this region has an important effect on any determination of the magnetotail dimensions. Our fourth task is to determine the time required by the model magnetotail to adjust to abrupt variations in the IMF orientation. We demonstrate that the IMF typically lies near the ecliptic plane on the relevant time scales and has sufficient strength to noticeably elongate the lunar magnetotail in the east/west direction. We show that the location of the magnetotail magnetopause responds rapidly to variations in the IMF orientation.

2. Magnetohydrodynamic Model

We use the facilities of the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Fight Center to run the Block-Adaptive-Tree-Solar wind-Roe-Upwind-Scheme (BATS-R-US). BATS-R-US is a global magnetohydrodynamic model that employs ideal single-fluid MHD equations to describe the solar wind-magnetosphere-ionosphere interaction [Powell et al., 1999; Tóth et al., 2012]. The equations are solved on a three-dimensional block-adaptive Cartesian grid. In the runs presented here, cell sizes increase from 0.25 x 0.25 x 0.25 R_E^3 in a small region near the inner boundary to a uniform 0.5 x 0.5 x 0.5 R_E^3 throughout the remainder of the simulation domain, including the distant magnetotail magnetopause. The near-Earth inner boundary of the code at 3 R_E from Earth is handled by incorporating a coupled model for the ionospheric electric field [Ridley et al., 2004]. Field-aligned currents are calculated and mapped along dipole field lines to the ionosphere where they are used as the source term for the height-integrated potential equation. The calculated potential is then mapped back out to the inner boundary where it is used to determine boundary conditions for the velocity and electric field. The ionosphere comprises a two-dimensional layer with prescribed finite Pederson and Hall conductivities [Gombosi et al., 2000].

3. The Steady-State Distant Magnetotail

This section addresses the steady-state structure of the distant magnetotail for typical solar wind parameters. We begin by examining the predictions of the global MHD simulations for magnetotail cross-sections at lunar distances for four different IMF strengths and three different IMF directions. Next we inspect the shape of the magnetotail as a function of distance downstream. Finally, we consider the transition from magnetosheath to magnetotail parameters. We find that for typical solar wind conditions, the orientation of the IMF in the Y-Z plane not only has an important influence on the shape of the magnetotail, the tilt of the current sheet in the midplane of the magnetotail, and the nature of the magnetopause transition, but also a significant impact on the shape of the bow shock.

3.1 Effect of the IMF strength on the dimensions of the magnetotail cross-section.

Figure 2 presents magnetotail cross-sections at X = -60 R_E predicted by the BATS-R-US model run at the CCMC for typical solar wind plasma parameters (n = 5 cm^{-3}, V = 400 km s^{-1}, T_i = $2x10^5$ K), IMF B_X = B_Z = 0 nT, and four values of IMF B_Y = 1, 3, 5, and 7 nT. Each panel shows the magnitude of the B_X (sunward/antisunward) component of the magnetic field in color, the component of the magnetic field in the Y-Z plane as arrows normalized to 15 nT, and the total electric current with 32 contours per 0.0008 $\mu A/m^2$. The cross-sections shown in the four panels exhibit numerous similarities. In each case a plasma sheet marked by weak magnetic field strengths separates northern lobe magnetic fields that point sunward (red) from southern lobe magnetic fields that point antisunward (blue). For the weak IMF B_Y case shown in Figure 2a, bifurcated current sheets bound a broad plasma sheet in the center of the magnetotail, separating it from both lobes. For the stronger IMF B_Y case shown in Figure 2d, a single asymmetric current sheet with low magnetic field strengths and high plasma pressures separates northern lobe and plasma sheet magnetic field lines from southern lobe and plasma sheet magnetic field lines. On the dusk side of the magnetotail, the half-width of the current sheet is narrower on its southern than northern side. Hot tenuous plasma sheet plasma flows rapidly antisunward through the weak magnetic field region on the northern side of the current layer (not shown). Consistent with observations reported by Gosling et al. [1985], densities in the southern lobe exceed those in the northern lobe, while temperatures in the southern lobe are less than those in the northern lobe. The situation reverses on the dawn side of the magnetotail, where the half-width of the current sheet is narrower on the northern side of the plasma sheet.

Strong currents, particularly over the northern and southern boundaries of the magnetotail, identify the magnetopause. Magnetosheath magnetic fields diverge outside the dawn magnetopause and converge outside the dusk magnetopause to pass around the magnetotail. Intense currents mark the location of the bow shock near the outer edge of the domain depicted in each panel.

The strength of the IMF B_Y component controls the tilt of the magnetotail current and plasma sheets, the cross-sections of the magnetopause and bow shock, the dimensions of the magnetosheath and the strength of the draped magnetosheath magnetic field. For IMF B_Y = 1 nT, a single current sheet that lies in the equatorial plane on both flanks of the magnetotail bifurcates to form a plasma sheet that tilts gently from southern dawn to northern dusk through the center of the magnetotail. The tilts of the plasma and current sheets coincide and are larger (~30°) for greater values of IMF B_Y but do not increase as IMF B_Y varies from 3 to 7 nT. The magnetotail cross-section is nearly circular for IMF B_Y = 1 nT, but becomes increasingly oblate as IMF B_Y increases. For IMF B_Y = 3 nT, the magnetotail cross-section is modestly oblate at 26 x 33 R_E, while for IMF B_Y = 7 nT it is more severely oblate at 21 x 37 R_E. By contrast, the bow shock cross-section is nearly circular for IMF B_Y = 1 nT, but become increasingly prolate as IMF B_Y increases. Figure 3 presents the polar and equatorial dimensions of the magnetotail and bow shock at X = -60 R_E as a function of IMF B_Y. The dimensions are taken as the radial distances from the magnetotail axis in the Y (duskward) and Z (northward) directions to the locations where current strengths peak. In the case of the equatorial magnetopause, the distance is to the current layer associated with the rotational discontinuity. The width of the magnetosheath at high latitudes exceeds that at low latitudes, and the imbalance increases as IMF B_Y increases. For IMF B_Y = 1 nT the component of the magnetic field along the Sun-Earth line is uniformly weak throughout the magnetosheath (Figure 2a). For stronger IMF B_Y values (Figures 2c, d), draping over the magnetosphere produces sunward magnetic field orientations in the dawn magnetosheath and antisunward magnetic field orientations in the dusk magnetosheath.

The simulation predicts a transition from magnetotail to magnetosheath magnetic field strengths and directions that is consistent with theoretical expectations for a standing slow mode fan and rotational discontinuity. Figure 4 presents a close-up view of the dusk magnetopause for the $B_Y = 7$ nT case. Letters N and S indicate the locations of the sunward-pointing magnetic fields in the northern and antisunward-pointing magnetic fields in the southern lobes. Letter M indicates the duskward-pointing magnetic fields in the magnetosheath proper. Field lines originating in the southern ionosphere drape against the lobe current layer (CL), then extend northward, antisunward, and duskward through the duskside slow mode expansion fan (F), before turning sharply towards the duskward and antisunward magnetosheath orientation at the rotational discontinuity (R). Antisunward and southward flows (not shown) cause the initially northward pointing magnetospheric magnetic field lines within the slow mode expansion fan near Earth to gradually gain the antisunward orientations expected for the south lobe as they move antisunward down the magnetotail.

Next let us consider the effect of the IMF orientation upon the cross-section of the magnetotail at lunar distances. The three panels in Figure 5 present magnetotail cross-sections at $X = -60\ R_E$ predicted by the BATS-R-US model run at the CCMC for typical solar wind plasma parameters ($n = 3.3$ cm^{-3}, $V = 560$ km s^{-1}, $T_i = 1.16\times10^5$ K) and three IMF orientations: (B_X, B_Y, B_Z)= (0, 0, -7.15), (0, 7.15, 0), and (0, 0, 7.15) nT. For southward IMF orientations (Figure 5a), the magnetotail cross-section is prolate with prominent northern ($B_X > 0$) and southern ($B_X < 0$) lobes separated by an equatorial current sheet. Gradual transitions from magnetosheath to magnetotail magnetic field orientations mark the polar boundaries of the magnetotail. We associate these transitions with the slow mode expansion fans and (in this case nearly indistinct) rotational discontinuities predicted by theory. At lower latitudes, the magnetotail magnetopause current layer is quite prominent. The cross-section of the bow shock is nearly circular, resulting in a magnetosheath with greater equatorial than polar widths.

For duskward IMF orientations (Figure 5b), a current layer tilted from southern dawn to northern dusk separates the northern and southern lobes. Detached current layers that we associate with rotational discontinuities stand upstream from the dawn and dusk magnetopause, just as in the case of the model results shown in Figure 4. The cross-section of the magnetotail is oblate and that of the bow shock is prolate, resulting in broader polar than equatorial magnetosheath dimensions.

The situation for northward IMF orientations differs strikingly (Figure 5c). Within the boundaries of a north/south elongated region much smaller than those shown in Figures 5a and b, a bundle of magnetic field lines that point antisunward lies northward of a bundle that points sunward. These are interplanetary magnetic field lines draping over the closed, tear-drop shaped, magnetotail predicted by Dungey [1963] for a strongly northward IMF orientation. As illustrated in Figure 6, and discussed by Gombosi et al. [1998] and Guzdar et al. [2001], open, northward pointing, IMF lines (blue, labeled A) drape against the magnetopause in the magnetosheath (B), and reconnect simultaneously at magnetopause sites poleward of both cusps (C). Reconnection appends the now closed (red) equatorial portions of the IMF lines to the dayside magnetosphere and they move slowly antisunward along the flanks of the magnetosphere [Song et al., 1992], eventually sinking into the magnetotail (not shown in this noon-midnight meridional cut). The same poleward of the cusp reconnection also detaches closed magnetotail magnetic field lines from the Earth's ionosphere. Magnetic curvature forces accelerate these newly opened magnetic field lines antisunward, particularly in the vicinity of the high-latitude magnetopause (D), where antisunward velocities (arrows) exceed those in both the adjacent magnetosheath and magnetosphere. The high velocities along the magnetopause pull the poleward portions of the formerly closed magnetic field lines antisunward far faster than the equatorial portions of these magnetic field lines, resulting in antisunward pointing magnetic fields north of the magnetotail midplane (E) and sunward pointing magnetic fields south of the midplane (F) in the distant magnetotail. Consequently, the model predicts a transition from a closed near-Earth magnetotail configuration with sunward-pointing magnetic fields northward of the equator and antisunward-pointing magnetic fields south of the equator at locations sunward of X = -50 R_E to an open distant magnetotail configuration with antisunward-pointing magnetic fields north of the equator and sunward-pointing magnetic fields south of the equator at locations beyond X = -50 R_E. Note that the magnetic field lines within this 'open distant magnetotail' are actually interplanetary with no connection to Earth.

The results presented in this section demonstrate that even a ~3 nT IMF component in the plane transverse to the Sun-Earth line can have an important effect on the structure of the magnetotail at lunar distances. The presence of a duskward-pointing IMF component with this magnitude results in an oblate magnetotail cross-section, a prolate bow shock cross-section, a tilted cross-tail current sheet, and an equatorial slow mode expansion fan and rotational discontinuity through which magnetotail and magnetosheath magnetic field lines interconnect.

3.2 Variation in magnetotail dimensions with downstream distance.

The steady application of anisotropic pressures associated with draped IMF lines transforms the near-Earth into the distant magnetotail cross-section. Figure 7 compares cuts in the (a) meridional and (b) equatorial planes for the n = 3.3 cm^{-3}, V = 560 km s^{-1}, $T_i = 1.16x10^5$ K and IMF (B_X, B_Y, B_Z)= (0, 7.15, 0) nT case shown in Figure 5b. The half-width of the magnetotail in the Z-direction (as identified from the peak in the current density at the magnetopause MP) decreases steadily from Z = 20.8 R_E at X = -30 R_E to Z = 17.5 R_E at -80 R_E. By contrast the east/west dimension (as identified by the standing rotational discontinuity) increases steadily from Y = 27.3 to 39.5 R_E over the same distance. Rather than flattening a prolate near-Earth magnetotail cross-section into a near-circular distant magnetotail cross-section, the anisotropic pressure applied by the IMF flattens an already oblate near-Earth magnetotail cross-section into an even more oblate distant magnetotail cross-section.

3.3 The magnetopause transition and magnetotail identification

It is relatively easy to determine the location of the magnetopause when this boundary is an abrupt transition in magnetic field strengths and directions from distinctly different magnetospheric to magnetosheath values. Examples include the high latitude magnetopause for duskward IMF orientations (Figure 5b) and the low-latitude magnetopause for southward IMF orientations (Figure 5a). When the magnetopause comprises a slow mode expansion fan and rotational discontinuity, determining its location can be much more difficult. This is particularly true when there is little or no rotation of the magnetic field at the rotational discontinuity, for example at the high-latitude magnetopause during intervals of southward IMF orientation (Figure 5a). Under these circumstances, some other scheme must be applied to identify magnetotail intervals and determine magnetotail dimensions. Sibeck et al. [1986] identified the magnetotail as a region in which more than 50% of observations exhibit magnetic fields nearly aligned with the Sun-Earth line ($|Bx|/B > (4/5)^{1/2}$) or temperatures greater than 5×10^5 K. By contrast, Maezawa et al. [1997] identified the magnetotail as a region in which more than 50% of observations exhibit velocities less than 80% those in the simultaneously measured solar wind or temperatures in excess of 3×10^6 K.

Consider the criterion applied by Sibeck et al. [1986]. The top two panels of Figure 8 present $|B_X|$, B_Y, and B values along cuts through the magnetotail at X = -60 R_E for the very strong IMF B_Y = 7.15 nT case shown in Figure 5b. The top panel shows values along the Z axis at Y = 0 R_E, while the second panel shows values along the Y axis at Z = -2 R_E. The latter cut is chosen to avoid intersections with the curved plasma sheet at the magnetotail flanks. By the criterion of Sibeck et al. [1986], regions where B_X is large compared to B lie within the magnetotail. By contrast, B_X and B_Y are comparable in the equatorial magnetosheath, and B_X vanishes in the northern magnetosheath. The third panel of Figure 8 compares profiles for the ratio of $|B_X|/B$ along the Y = 0 R_E and Z = -2 R_E axes with the $|Bx|/B > (4/5)^{1/2}$ magnetotail identification criterion of Sibeck et al. [1986]. According to this criterion, the 25 R_E half-width of the magnetotail in the east/west direction exceeds the 20 R_E half-width in the north/south dimension. Were the (arbitrary) criterion to be raised to $|Bx|/B = 0.96$, the magnetotail cross-section would be nearly circular with a radius of 19 R_E.

Now consider the criterion applied by Maezawa et al. [1997]. Figure 9 presents the magnetotail cross-section at X = -60 R_E for the very strong IMF By = 7.15 nT case shown in Figure 5b. The color coding indicates temperatures, the vectors indicate the component of the magnetic field in the plane perpendicular to the Sun-Earth line, and the contours indicate velocities along the Sun-Earth line. Greatly enhanced temperatures highlight the thin tilted cross-tail current sheet, as well as the locations of the high-latitude southern dawn and northern dusk magnetopause. As before, the magnetic field vectors in the magnetosheath diverge outside the dawnside magnetopause to pass around the magnetotail and converge outside the duskside magnetopause. The bow shock can be readily identified as the location where velocities drop from 560 km s^{-1} in the solar wind to lesser values in the magnetosheath. Although sharp gradients in the velocity can be used to identify the high latitude magnetopause as a distinct interface where velocities drop from enhanced (>600 km s^{-1}) magnetosheath values exceeding those in the solar wind [Lavraud et al., 2007] to much lower values in the magnetotail, identifying the dawn and dusk magnetopause on the basis of the velocities is far more difficult.

The bottom panel of Figure 8 compares profiles for the ratio of $|V_X|/V$ along the Y = 0 R_E and Z = 0 R_E axes with the $|Vx|/V < 0.8$ magnetotail identification criterion of Maezawa et al. [1997]. According to this criterion, the 23 R_E half-width of the magnetotail in the east/west direction exceeds the 18 R_E half-width in the north/south dimension. Were the criterion to be raised to $|Vx|/V < 0.5$, the magnetotail cross-section would be nearly circular with a radius of 16 R_E. Note that the standing rotational discontinuities in Figure 5b, themselves plausible locations for the equatorial magnetopause, lie as far as 35 R_E dawnward and duskward from the center of the Earth's magnetotail.

By choosing to examine magnetotail cross-sections for a 7.15 nT value of IMF B_Y, we have emphasized the role of IMF B_Y in creating a slow mode fan with a gradual transition in plasma and magnetic field parameters from magnetotail to magnetosheath values on the flanks of the lunar magnetotail. Had we chosen smaller values for IMF B_Y, the widths of the fans would have been much smaller. As can be seen in Figure 2, the current layers corresponding to the rotational discontinuities at the outer edges of the slow mode fans move away from the magnetotail axis as IMF B_Y varies from 1 to 7 nT. The discontinuities propagate away from the magnetotail axis at the local Alfvén velocity. For a magnetosheath Alfvén velocity of 20 km s^{-1}, corresponding to a magnetic field strength of 3 nT and a density of 10 cm^{-3}, the Alfvén waves propagated 10 R_E outward during the time it takes the 400 km s^{-1} solar wind to flow 200 R_E downstream. Consequently the thickness of the slow mode fan behind these discontinuities in the distant magnetotail is significant even for typical values of IMF B_Y.

In contrast to the orientations perpendicular to the Sun-Earth line assumed above, the IMF typically assumes a spiral orientation, pointing either antisunward and duskward or sunward and dawnward [Wilcox and Ness, 1965]. Simulation results for the antisunward and duskward case (not shown) are similar to those for the perpendicular IMF orientation except: (1) magnetic field strengths and rotational discontinuities outside the dawnside magnetopause are weaker than those outside the duskside magnetopause, (2) the dawnside magnetopause lies further from the Sun-Earth line than the duskside magnetopause, and (3) the dawnside bow shock lies nearer to the Sun-Earth line than the duskside bow shock. The weaker magnetic field strengths outside the dawn magnetopause result from draping. The lower pressure that they apply to the magnetopause allows it to move outward. The diminished magnetic field strengths reduce fast mode speeds and the standoff distance of the bow shock.

Returning to region identification, we conclude that in the presence of very gradual transitions between magnetosheath and magnetospheric plasma and magnetic field parameters, the magnetotail dimensions depend sensitively on the criteria used to identify this region of space.

4. The time-dependent magnetotail

This section addresses the time-dependent response of the magnetotail to varying IMF orientations. We seek to determine how the magnetotail responds to variations in the IMF orientation on time scales ranging from minutes to days, and to determine the typical shape of the magnetotail cross section at lunar distances.

4.1 Concerning the time required for the magnetotail to respond to varying IMF orientations

If the IMF strength and orientation change too rapidly, then the cross-section of the distant magnetotail will not have sufficient time to attain the steady-state configurations presented in Figures 2-9. To decide whether the magnetotail successfully responds to the individual IMF fluctuations imposed upon it, we must determine the time required for the magnetotail to adjust from one configuration to another. We allowed two hours for the simulation with IMF $B_Z = -7.15$ nT to reach the equilibrium shown in Figure 5a and then imposed an abrupt rotation of the IMF to $B_Y = 7.15$ nT. The upper and lower panels of Figure 10 present the cross-sections of the magnetotail magnetopause in the meridional and equatorial planes as a function of time following the IMF rotation. The high-latitude magnetopause is either a rotational discontinuity (RD, red/orange) or a tangential discontinuity (MP, blue). The low-latitude magnetopause is either a combination of the current layer at the inner edge of the slow mode expansion fan (CL, green) and the rotational discontinuity (RD, red/orange) or a tangential discontinuity (MP, blue).

Early in the simulation (0200-0220 UT), as a result of the initial southward IMF orientation, the high latitude magnetopause is a rotational discontinuity and flares outward. The radial distance from the magnetotail axis to this boundary increases steadily with distance downstream. The 0220

UT contour in the upper panel catches the IMF discontinuity propagating through the system: at this moment the discontinuity lies against the magnetopause at distances sunward of X = -25 R_E, where it has essentially become the new high latitude magnetopause. There is no identifiable high latitude magnetopause at distances beyond the discontinuity at this time. By 0230 UT, the discontinuity has exited tailward, the magnetosheath magnetic field points duskward, high-latitude magnetotail magnetopause flaring has ceased, and the distance to the closed high-latitude magnetopause from the magnetotail axis has diminished to a nearly constant value beyond X = -20 R_E. By 0240 UT, the distance to the closed high latitude magnetopause even diminishes with increasing distance beyond X = -45 R_E.

Early in the simulation, the distance to the tangential discontinuity equatorial magnetopause (MP) initially increases with increasing distance downstream but then remains nearly constant beyond X = -50 R_E. The passage of the discontinuity causes a discontinuous jump in the location of the equatorial magnetopause at 0220 UT. Sunward of this jump at X = -50 R_E, the magnetopause has been replaced by a rotational discontinuity (RD) lying far outside the preexisting magnetopause boundary (MP). Beyond the jump, the magnetopause remains in place (MP). Following the discontinuous jump attending the passage of the discontinuity, the location of the rotational discontinuity barely changes with time. The current layer (CL) at the inner edge of the slow mode expansion fan jumps outward from 0220 to 0230 UT and then moves outward only incrementally from 0230 to its final position at 0300 UT.

From the simulation results shown in Figure 10, we conclude that rotational discontinuities both appear and disappear almost instantaneously in their initial and final positions in conjunction with the passage of antisunward-moving IMF discontinuities and that the current layer at the inner edge of the slow mode rarefaction fan requires no more than 10 min to approach its final position and then moves only slightly further outward during the subsequent 30 min.

4.2 Strength and direction of the IMF

For comparison with the model predictions, we now wish to inspect IMF orientations and strengths averaged over relevant times scales. NASA GSFC's OMNIWeb service (omniweb.gsfc.nasa.gov) provides average values for the IMF strength and direction in GSE coordinates. The three panels in Figure 11 present distributions for the strength of the IMF component $(B_Y^2+B_Z^2)^{1/2}$ in the plane transverse to the Sun-Earth line versus the clock angle (or latitude) of the magnetic field within this plane ($\tan^{-1} B_Z/|B_Y|$). From top to bottom, the panels show the percentage of time the IMF lies within 2 nT bins in magnitude and 10° bins in clock angle for minute, hourly, and daily averages covering the full year of 2005. On minute time scales, the component of the IMF in the plane perpendicular to the Sun-Earth line occasionally attains magnitudes greater than 12 nT and both due northward and southward orientations. More typically its magnitude lies between 2 and 6 nT and its clock angle within 30° of the ecliptic, consistent with results obtained long ago by Ness and Wilcox [1964]. A magnetotail cross-section capable of responding instantaneously to IMF variations will generally be moderately oblate with occasional strong north/south elongations.

On the hourly time scales by which stable magnetopause locations must surely be established, IMF strengths are typically 2-4 nT and clock angles generally lie within 20° of the ecliptic plane. Based on our findings concerning the response of the magnetotail to IMF variations reported above, the corresponding magnetotail cross-section is generally modestly oblate, north/south elongations are very rare, and pronounced flattening very unusual. Were the magnetotail to require one day to attain its final shape, it would almost invariably be weakly east/west elongated.

5. Discussion and Conclusions

We presented the predictions of the BATS-R-US model for magnetotail and bow shock cross-sections at lunar distance as a function of IMF strength and orientation. The model predicts a transition from magnetotail to magnetosheath magnetic field lines through a standing slow mode rarefaction wave and a rotational discontinuity, a magnetotail cross-section elongated in the direction of the component of the IMF in the plane perpendicular to the Sun-Earth line, a cross-tail current sheet whose tilt depends upon the IMF orientation, and a bow shock whose cross-section is elongated in the direction perpendicular to the component of the IMF in the plane perpendicular to the Sun-Earth line.

There are two reasons why the magnetotail cross-section is elongated in the direction of the component of the IMF in the plane perpendicular to the Sun-Earth line. First, the anisotropic pressure of the magnetosheath magnetic field lines draped over the magnetotail deforms the magnetotail cross-section. Second, we take the slow mode rarefaction wave to lie within the magnetotail and the standing rotational discontinuity to be the magnetopause. Were we to exclude the standing slow mode rarefaction wave from the magnetotail, the magnetotail cross-section would be less elongated.

We attribute the elongation of the bow shock to greater fast mode speeds perpendicular than parallel to the draped magnetosheath magnetic field. Thanks to the differing responses for the cross-sections of the bow shock and magnetopause, the model predicts the thickness of the dawn and dusk magnetosheath to increase when the IMF rotates northward or southward out of the ecliptic plane. Although the degree of magnetotail elongation depends upon the strength of the IMF and the tilt of the plasma sheet increases as IMF B_Y increases from 1 to 3 nT, we find no further increase in the tilt of the current sheet as IMF B_Y increases beyond 3 nT. During periods of strongly northward IMF orientation, reconnection poleward of both cusps removes open lobe magnetic field lines, leaving behind a magnetotail that closes earthward of $X = -50\ R_E$.

The model predicts that the anisotropic pressures of shocked, duskward-pointing, IMF lines progressively flatten an already oblate near-Earth magnetotail cross-section into an even more oblate distant magnetotail cross-section. It can be difficult to identify the magnetopause at locations where magnetosheath and magnetospheric magnetic field lines are interconnected, such as the high-latitude magnetopause during periods of strongly southward IMF orientation. Here the magnetopause becomes a standing slow mode expansion wave bounded by a rotational discontinuity. In the absence of an abrupt rotation at the discontinuity, the magnetopause boundary is simply a gradual transition in densities, temperatures, velocities, and magnetic field strengths over several Earth radii. The dimension of the magnetotail in the vicinity of such a magnetopause depends strongly on the criteria used to identify the magnetosphere..

The transition from northward magnetic field lines in the slow mode expansion fan to duskward magnetic field lines in the magnetosheath shown in Figure 4 occurs north of the equator. This is consistent with the counterclockwise twist in magnetic field line draping around the magnetotail that Kaymaz et al. [1992] found in IMP-8 observations for a duskward IMF orientation. As predicted, the cross-tail current sheet within the magnetotail cross-section also rotates counterclockwise for the same IMF orientation [Kaymaz et al., 1994]. Finally, note the prediction of the model in Figure 9 for high temperatures on the southern dawn northern dusk magnetopause during intervals of duskward IMF orientation. Siscoe and Kaymaz [1999] identified precisely such a feature was identified in IMP-8 observations.

The cross-section of the distant magnetotail responds almost immediately to abrupt transitions in the IMF orientation. These transitions cause changes in the location of reconnection on the dayside magnetopause as well as the locations where the resulting newly reconnected magnetic field lines enter the magnetotail. Where magnetosheath and magnetotail magnetic field lines interconnect, a slow mode expansion fan and rotational discontinuity enable the transition from magnetospheric to magnetosheath plasma and magnetic field parameters. Elsewhere a tangential discontinuity suffices. The slow mode expansion fan is bounded by two current layers: one at the inner edge where the reconnected magnetic field lines drape against older magnetic field lines within the lobes and the other at the outer edge where the rotational discontinuity is located. Because the discontinuities bounding the slow mode fan are present on any newly reconnected magnetic field line, the time required for them to appear at any downstream distance is simply the time required for magnetosheath plasma to convect from the dayside magnetopause to that distance downstream.

Following the arrival of abrupt transitions in the IMF orientation, there is some evidence for incremental motion of the tangential discontinuities marking the closed portion of the magnetopause and the inner edge of the slow mode expansion fan. These variations can be attributed to the anisotropic pressure of magnetosheath magnetic field lines draped around the magnetotail. They cause a further flattening of the magnetotail cross-section over periods ranging from 10-20 minutes. Since the IMF typically lies near the ecliptic plane and has a strength on the order of ~3 nT, the magnetotail cross-section is generally modestly oblate (26 x 33 R_E for IMF B_Y = 3 nT), occasionally more severely oblate (21 x 37 R_E for IMF B_Y = 7 nT), and (very rarely) prolate.

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References

Berchem, J., J. Raeder, M. Ashour-Abdalla, L. A. Frank, W. R. Paterson, K. L. Ackerson, S. Kokubun, T. Yamamoto, and R. P. Lepping (1998), The distant tail at 200 R_E: Comparison between Geotail observations and the results from a global magnetohydrodynamic simulation, J. Geophys. Res., 103, 9121-9141, doi:10.1029/97JA02926.

Coroniti, F. V. and C. F. Kennel (1972), Changes in magnetospheric configuration during the substorm growth phase, J. Geophys. Res., 77, 3361-3370, doi:10.1029/JA077i019p03361.

Coroniti, F. V. and C. F. Kennel (1979), Magnetospheric reconnection, substorms, and energetic particle acceleration in Partile Acceleration in Planetary Magnetospheres, ed. J. Arons, C. Max, and C. McKee, American Institute of Physics, New York, pp. 169-178, doi:10.1063/1.32078.

Dungey, J. W. (1963), The structure of the exosphere or adventures in velocity space, in *Geophysics: The Earth's Environment*, Gordon and Breach, New York, ed. C. DeWitt, J. Hieblot, and A. Lebeau, p. 503.

Fairfield, D. H. (1992), On the structure of the distant magnetotail: ISEE 3, J. Geophys. Res., 97, 1403-1410, doi:10.1029/91JA02388.

Fairfield, D. H. (1993), Solar wind control of the distant magnetotail: ISEE 3, J. Geophys. Res., 98, 21265-21276, doi:10.1029/93JA01847.

Fedder, J. A. and J. G. Lyon (1995), The Earth's magnetosphere is 165 RE long: Self-consistent currents, convection, magnetospheric structure, and processes for northward interplanetary magnetic field, J. Geophys. Res., 100, 3623-3635, doi:10.1029/94JA02633.

Gombosi, T. I., D. L. DeZeeuw, C. P. T. Groth, K. G. Powell, and P. Song (1998), The length of the magnetotail for northward IMF: Results of global 3D MHD simulations, Phys. Space Plas., 15, 121-128.

Gombosi, T. I., D. L. DeZeeuw, C. P. T. Groth, and K. G. Powell (2000), Magnetospheric configuration for Parker-spiral IMF conditions: Results of a 3D AMR MHD simulation, Adv. Space Res., 26, 139-149, doi:10.1016/S0273-1177(99)01040-6.

Gonzalez, W. D. and F. S. Mozer (1974), A quantitative model for the potential resulting from reconnection with an arbitrary interplanetary magnetic field, J. Geophys. Res., 79, 4186-4194, doi:10.109/JA079i028p04186.

Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, and E. J. Smith (1985), North-south and dawn-dusk plasma asymmetries in the distant tail lobes- ISEE 3, J. Geophys. Res., 6354-6360.

Guzdar, P. N., X. Shao, C. C. Goodrich, K. Papadopoulos, M. J. Wiltberger, and J. G. Lyon (2001), Three-dimensional MHD simulations of the steady state magnetosphere with northward interplanetary magnetic field, J. Geophys. Res., 106, 275-287.

Hasegawa, H., K. Maezawa, T. Mukai, and Y. Saito (2002), Plasma entry across the distant magnetopause 1. Global Properties and IMF dependence, 107, 10.1029/2001JA900139.

Kaymaz, Z., G. L. Siscoe, and J. G. Luhmann, IMF draping around the geotail: IMP 8 observations, Geophys. Res. Lett., 19, 829-832, 1992, doi:10.1029/92GL00403.

Kaymaz, Z., G. L. Siscoe, J. G. Luhmann, R. P. Lepping, and C. T. Russell, Interplanetary magnetic field control of magnetotail magnetic field geomeetry: IMP 8 observations, J. Geophys. Res., 99, 11113-11126, 1994, doi:10.1029/94JA00300.

Kaymaz, Z. and G. Siscoe (1998), Open geometry of the magnetotail cross section, J. Geophys. Res., 103, 14829-14836, 1998, doi:10.1029/98JA00812.

Kaymaz, Z., G. Siscoe, J. G. Luhmann, J. A. Fedder, and J. G. Lyon (1995), Interplanetary magnetic field control of magnetotail field: IMP 8 and MHD model compared, J. Geophys. Res., 100, 17163-17172, doi:10.1029/95JA00593.

Lavraud, B., J. E. Borovsky, A. J. Ridley, E. W. Pogue, M. F. Thomsen, H. Reme, A. N. Fazakerley, and E. A. Lucek (2007), Strong bulk plasma acceleration in Earth's magnetosheath: A magnetic slingshot effect?, Geophys. Res. Lett., 34, 10.1029/2007GL030024.

Lavraud, B., E. Larroque, E. Budnik, V. Génot, J. E. Borovsky, M. W. Dunlop, C. Foullon, H. Hasegawa, C. Jacquey, K. Nykyri, A. Ruffenach, M. G. G. T. Taylor, I. Dandouras, and H. Reme, Asymmetry of magnetosheath flows and magnetopause shape during low Alfvén Mach number solar wind, J. Geophys. Res., 118, 1089-1100, doi:10.1002/JGR.50145.

Levy, R. H., H. E. Petschek, and G. L. Siscoe (1964), Aerodynamic aspects of magnetospheric flow, AIAA J., 2, 2065.

Li, W., J. Raeder, J. Dorelli, M. Øieroset, and T.-D. Phan (2005), Plasma sheet formation during long period of northward IMF, Geophys. Res. Lett., 32, doi:10.1029/2004GL021524.

Lu, J. Y., Z.-Q. Liu, K. Kabin, H. Jing, M. X. Zhao, and Y. Wang (2013), The IMF dependence of the magnetopause from global MHD simulations, J. Geophys. Res., 118, 3113-3125, doi:10.1002/jgra.50324.

Macwan, S. E. (1992), A determination of twisting of the Earth's magnetotail at distances 115-220 R_E – ISEE 3, J. Geophys. Res., 97, 19239-19249, doi:10.1029/91JA03145.

Maezawa, K. (1975), Magnetotail boundary motion associated with geomagnetic substorms, J. Geophys. Res., 80, 3543-3548, doi:10.1029/JA080i025p03543.

Maezawa, K., T. Hori, T. Mukai, Y. Saito, T. Yamamoto, S. Kokubun, and A. Nishida (1997), Structure of the distant magnetotail and its dependence on the IMF B_y component: Geotail observations, Adv. Space Res., 20, 945-959, doi:10.1016/S0273-1177(97)00503-6.

Michel, F. C. and A. J. Dessler (1970), Diffusive entry of solar-flare particles into geomagnetic tail, J. Geophys. Res., 75, 6061-6072, doi:10.1029/JA075i031p06061.

Milan, S. E., S. W. H. Cowley, M. Lester, D. M. Wright, J. A. Slavin, M. Fillingim, C. W. Carlson, and H. J. Singer (2004), Response of the magnetotail to changes in the open flux content of the magnetosphere, J. Geophys. Res., 109, doi:10.1029/2003JA010350.

Nakamura, R., S. Kokubun, T. Mukai, and T. Yamamoto (1997), Changes in the distant tail configuration during geomagnetic storms, J. Geophys. Res., 102, 9587-9601, doi:10.1029/97JA00095.

Ness, N. F. and J. M. Wilcox (1964), Solar origin of interplanetary magnetic field, Phys. Rev. Lett., 13, 1461-464, doi:10.1103/PhysRevLett.13.461.

Ogino, T., R. J. Walker, and M. Ashour-Abdalla (1994), A global magnetohydrodynamic simulation of the response of the magnetosphere to a northward turning of the interplanetary magnetic field, J. Geophys. Res., 99, 11027-11042, doi:10.1029/93JA03313.

Owen, C. J., J. A. Slavin, I. G. Richardson, N. Murphy, and R. J. Hynds (1995), Average motion, structure and orientation of the distant magnetotail determined from remote sensing of the edge of the plasma sheet boundary layer with E greater than 35 keV ions, J. Geophys. Res., 100, 185-204.

Powell, K. G., P. L. Roe, T. J. Linde, T. I. Gombosi, an dD. L. de Zeeuw (1999), A solution-adaptive upwind scheme for ideal magnetohydrodynamics, J. Comp. Phys., 154, 284-309, doi: 10.1006/jcph.1999.6299.

Raeder, J. R. J. Walker, and M. Ashour-Abdalla (1995), The structure of the distant geomagnetic tail during long periods of northward IMF, Geophys. Res. Lett., 22, 349-352, doi: 10.1029/94GL03380.

Ridley, A. J., T. I. Gombosi, and D. L. DeZeeuw (2004) Ionospheric control of the magnetosphere: Conductance, Ann. Geophys., 22, 567-584, doi:10.5194/angeo-22-567-2004.

Russell, C. T. (1972), The configuration of the magnetosphere, in Critical Problems of Magnetospheric Physics, ed. E. R. Dyer, pp. 1-16, IUCSTP Secretariat, National Academy of Sciences, Washington, D. C..

Russell, C. T. (1973), Comments on the paper ‘The internal structure of the geomagnetic neutral sheet’ by K. Schindler and N. F. Ness, J. Geophys. Res., 78, 7576-7579, doi:10.1029/JA078i031p07576.

Sanchez, E. R., G. L. Siscoe, J. T. Gosling, E. W. Hones, Jr., R. P. Lepping (1990), Observations of rotational discontinuity-slow expansion fan structure of the magnetotail boundary, J. Geophys. Res., 95, 61-73, doi:10.1029/JA095iA01p00061.

Sibeck, D. G., G. L. Siscoe, J. A. Slavin, E. J. Smith, B. T. Tsurutani, and R. P. Lepping (1985a), The distant magnetotail’s response to a strong IMF By: Twisting, flattening and field line bending, J. Geophys. Res., 90, 4011-4019, doi:10.1029/JA090iA05p04011.

Sibeck, D. G., G. L. Siscoe, J. A. Slavin, E. J. Smith, B. T. Tsurutani, S. J. Bame, and R. P. Lepping (1985b), Magnetic field properties of the distant magnetotail, magnetopause and boundary layer, J. Geophys. Res., 90, 9561-9575, doi:10.1029/JA090iA10p09561.

Sibeck, D. G., G. L. Siscoe, J. A. Slavin, R. P. Lepping (1986a), Major flattening of the distant geomagnetic tail, J. Geophys. Res., 91, 4223-4237, doi:10.1029/JA091iA04p04223.

Sibeck, D. G., J. A. Slavin, E. J. Smith, and B. T. Tsurutani (1986b), Twisting of the geomagnetic tail, in Solar Wind-Magnetosphere Coupling, ed. Y. Kamide and J. A. Slavin, Terra, Tokyo, 731-738.

Siscoe, G. L. and E. Sanchez (1987), An MHD model for the complete open magnetotail boundary, J. Geophys. Res., 92, 7405-7412, doi:10.1029/JA092iA07p07405.

Siscoe, G. L. and Z. Kaymaz (1999), Spatial relations of mantle and plasma sheet, J. Geophys. Res., 104, 14639-14646, doi:10.1029/1999JA900113.

Song, P. and C. T. Russell (1992), Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field, J. Geophys. Res., 97, 1411-1420, doi:10.1029/91JA02377.

Stern, D. P. (1973), A study of the electric field in an open magnetospheric model, J. Geophys. Res., 78, 7292-7305, doi:10.1029/JA078i031p07292.

Tóth, G., B. van der Holst, I. V. Sokolov, D. L. De Zeeuw, T. I. Gombosi, F. Fang, W. B. Manchester, X. Meng, D. Naji, K. G. Powell, O. F. Stout, A. Glocer, Y.-J. Ma, and M. Opher (2012), Adaptive numerical algorithms in space weather modeling, J. Computational Phys., 231, 870-903, doi:10.1016/j.jcp.2011.02.006.

Tsurutani, B. T., D. E. Jones, and D. G. Sibeck (1984), The two-lobe structure of the magnetotail, from x = -60 to -240 R_e, Geophys. Res. Lett., 11, 1066-1069, doi:10.1029/GL011i010p01066.

Usadi, A., A. Kageyama, K. Watanabe, and T. Sato (1993), A global simulation of the magnetosphere with a long tail: Southward and northward interplanetary magnetic field, J. Geophys. Res., 98, 7503-7517, doi:10.1029/92JA02078.

Wilcox, J. M. and N. F. Ness (1965), Radial and latitudinal variations of the magnetic field strength in the outer heliosphere, J. Geophys. Res., 70, 5793-5805.

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Figure Captions

Figure 1. A qualitative view of the magnetotail cross section from the Earth during an interval of due duskward IMF orientation, including a window through which draped magnetosheath magnetic field lines pass, a standing rotational discontinuity (red dashes, R), a slow mode expansion fan (F), and tangential discontinuities A-B and A'-B' outside the plasma sheet (adopted from Kaymaz and Siscoe, [1998]).

Figure 2. The magnetotail cross-section at $X = -60\ R_E$ for IMF B_Y = (a) 1, (b) 3, (c) 5, and (d) 7 nT and typical solar wind plasma parameters ($n = 5\ cm^{-3}$, $V = 400\ km\ s^{-1}$, $T_i = 2x10^5$ K). Black contours depict current strengths in 32 linearly spaced steps from 0.0 to 0.0008 $\mu A/m^2$. Colors indicate values for B_X over the range from -12 to 12 nT. Arrows normalized to 15 nT indicate the strength and direction of the component of the magnetic field in the y-z plane.

Figure 3. The dimensions of the polar and equatorial magnetopause and bow shock as a function of IMF B_Y. The width of the polar magnetosheath increases, while the width of the equatorial magnetosheath diminishes with downstream distance for an IMF that points purely in the Y-direction.

Figure 4. A close-up view of the dusk magnetopause for the IMF B_Y = 7 nT case of Figure 2d. Letters N, S, F, and M indicate the north lobe, south lobe, slow mode fan, and magnetosheath proper, respectively. Dashed lines marked CL and R indicate the current layer at the inner edge of the fan and the rotational discontinuity at the outer edge of the fan, respectively. The color bar shows values for the component of the magnetic field parallel to the magnetotail axis, contours

depict current strengths, and vectors show the components of the magnetic field in the plane perpendicular to the Sun-Earth line.

Figure 5. The magnetotail cross-section at x = -60 R_E for (a) southward, (b) duskward, and (c) northward IMF orientations. Black contours depict current strengths in 16 linearly spaced steps from 0.0 to 0.001 μA/m^2. Colors indicate values for B_X over the range from -12 to 12 nT. Arrows normalized to 10 nT indicate the strength and direction of the component of the magnetic field in the Y-Z plane. The IMF strength is 7.15 nT and the solar wind plasma densities, velocities, and temperatures are 3.3 cm^{-3}, 560 km s^{-1}, and 1.16x10^5 K, respectively.

Figure 6. A cross-section of the magnetosphere in the noon-midnight meridional plane for the due northward IMF orientation of Figure 5c. The color bar indicates current strengths, arrows indicate plasma velocities, red curves indicate closed magnetic field lines with both ends on Earth, and blue curves indicate open magnetic field lines with one or both ends in the solar wind.

Figure 7. A comparison of magnetotail cross-sections in the (a) X-Y and (b) X-Z planes for IMF By = 7.15 nT case shown in Figure 5b. Colors indicate the current strength, arrows the flow velocities. Labels indicate the locations of the bow shock, magnetopause, cross-tail current sheet, rotational discontinuity (RD) and slow mode expansion fan. The north/south dimensions of the magnetotail diminish with downstream distance whereas the east/west dimensions increase.

Figure 8. Cuts through the simulation results for the case with B_Y = 7.15 nT shown in Figure 5b along the (a) Z-axis at (X, Y) (60, 0) R_E and (b) along the Y-axis at (X, Z) = (60, -2) R_E. Panel c compares B_X/B along each of these cuts with one of the magnetotail identification criteria of Sibeck et al. [1986], namely |B_X|/B = 0.89. Panel d compares |Vx|/V along the Y and Z axes with one of the

magnetotail identification criteria of Maezawa et al. [1997], namely $|Vx|/V = 0.8$. Arrows in the latter two panels point to the distances from the magnetotail axis along the Sun-Earth line where the criteria are satisfied.

Figure 9. The magnetotail cross-section at $X = -60\ R_E$ for the IMF $B_Y = 7.15$ nT case of Figure 5b. The color bar shows the log scale for the temperature, contours show the component of the velocity along the Sun-Earth line (V_X), and arrows indicate the direction of the component of the magnetic field in the plane perpendicular to the Sun-Earth line. The 550 km s^{-1} contour maps out the location of the bow shock, enhanced temperatures indicate the location of the tilted cross-tail plasma and current sheets. The equatorial magnetopause is ill-defined.

Figure 10. Cross-sections of the magnetotail in (a) the meridional and (b) the equatorial plane as a function of time. MP: the tangential discontinuity magnetopause (in blue), RD: a rotational discontinuity (in red and orange), CL: a current layer at the inner edge of the slow mode expansion fan (in green).

Figure 11. One year of IMF observations averaged over (a) 1-minute time intervals, (b) 1-hour time intervals, and (c) 1-day intervals. Each panel shows the distribution of IMF strengths in the plane perpendicular to the Sun-Earth line versus the distribution of IMF clock angles in the same plane.