The response of ionospheric convection to changes in the IMF: 1. Lessons from a MHD simulation

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Abstract

Characteristics of magnetospheric and high-latitude ionospheric convection-pattern responses to abrupt changes in the interplanetary magnetic field (IMF) orientation have been investigated using an MHD model with a step-function reversal of IMF polarity (positive to negative B_Y) in otherwise steady solar-wind conditions. By examining model outputs at one-minute intervals, we have tracked the evolution of the IMF polarity reversal through the magnetosphere, with particular attention to changes in the ionosphere and at the magnetopause. For discussion, times are referenced relative to the time of first contact (t = 0) of the IMF reversal with the subsolar nose of the magnetopause at $\sim 10.5 R_E$. The linear change in large-scale ionospheric convection pattern begins at t = 8 minutes, reproducing the difference-pattern results of *Ridley et al.* [1997; 1998]. Field-aligned current-difference patterns, similarly derived, show an initial two-cell pattern earlier, at t = 4 minutes. The current-difference two-cell pattern grows slowly at first, then faster as the potential pattern begins to change. The first magnetic response to the impact of the abrupt IMF transition at the magnetopause nose is to reverse the tilt of the last-closed field lines and of the first-open field lines. This change in tilt occurs within the boundary layer before merging of IMF with closed magnetospheric field lines starts. In the case of steady-state IMF B_Y, IMF field lines undergo merging or "changing partners" with other IMF field lines, as they approach the nose and tilt in response to currents. When the B_Y reversal approaches the magnetopause nose, IMF field lines from behind the reversal overtake and merge with those in front of the reversal, thus puncturing the reversal front and uncoupling the layer of solar-wind plasma in the reversal zone from the magnetosphere. The uncoupled layer propagates tailward entirely within the magnetosheath. Merging of closed magnetospheric field lines with the new-polarity IMF begins at $t = 3$ minutes and starts to affect local currents near the cusp one minute later. While merging starts early and controls the addition of open flux to the polar cap, large-scale convection-pattern changes are tied to the currents, which are controlled in the boundary layers. The resulting convection pattern is an amalgamation of these diverse responses. These results support the conclusion of *Maynard et al.* [2000b], that the small convection cell is driven from the opposite hemisphere in B_Y dominated situations.

1. Introduction

That ionospheric convection is statistically dependent on the strength and orientation of the interplanetary magnetic field is well known [e.g., *Heppner*, 1972; *Heppner and Maynard*, 1987; *Weimer*, 1995, 2001]. *Cowley and Lockwood* [1992] have provided a simple conceptual picture of how flow may be driven by dayside reconnection or merging. Yet there is significant time variability in the shape and strength of convective electric-field patterns, indicating that the configuration of the merging site is complex. This is shown by the general variability of *in* *situ* measurements and by patterns derived from magnetometer and other data using the "assimilative mapping of ionospheric electrodynamics" (AMIE) technique [e.g., *Knipp et al.*, 1993; *Richmond and Kamide*, 1988].

Cowley and Lockwood [1992] postulate that flow is produced by the merging process connected to the cusp region and continues as new open magnetic flux is dragged tailward a few tens of R_E. The addition of new open magnetic flux to the polar caps expands the adiaroic portion of the open-closed boundaries, thereby communicating the flow to the whole polar-cap pattern [e.g., *Siscoe and Huang*, 1985] (adiaroic refers to a boundary across which there is no flux transfer). After that the "new" open flux becomes "old" open flux and has little further influence as a driver of the flow. With an IMF B_Y component, flow at the northern cusp is pulled initially in the direction opposite to that B_Y component before it turns back toward the tail. This is part of the source of the asymmetric convection pattern associated with these conditions [e.g., *Heppner and Maynard*, 1987]. Similarly, reconnection in the tail has an analogous effect on the nightside region. It too depends on IMF orientation, but with as much as a 70 minute additional delay caused by the time it takes for the connected solar-wind feature to move deep down tail [*Blanchard et al.*, 1996]. Interaction from a burst of merging on the dayside in the Cowley-Lockwood picture is complete over time scales of 15 minutes. Alternatively, *Toffoletto and Hill* [1988] have derived a model of ionospheric convection in which a portion of the interplanetary electric field is projected directly down to the ionosphere along open field lines. This model has problems matching ionospheric convection patterns with IMF orientations that have a significant northward component, as the patterns evolve through distorted two-cell configurations to a four-cell pattern for pure B_Z north [e. g., *Maynard et al.*, 1998].

The merging process was originally assumed to occur near the nose of the magnetopause between components of the IMF and Earth's dipole field that were antiparallel, i.e., component merging. *Crooker* [1979] introduced the concept of antiparallel merging, where merging would primarily take place where the vectors were antiparallel. For IMF conditions with a B_Y component, this criterion placed the merging sites at high latitudes near the cusp. The question of whether antiparallel or component merging dominates is not yet resolved. Preferential merging at high latitudes implies that the magnetic vectors are nearly antiparallel, or at least the rate of merging have a steep dependence on the angle between the vectors. Recent results of *Maynard et al.* [2000a, 2000b] support preferential merging at high latitudes.

Many researchers have attempted, with very mixed results, to pin down the timing and evolution of the ionospheric-convection response to changes in solar wind. *Wygant et al.* [1983], using S3-3 data, suggested that it takes several hours for the convection pattern to respond to a northward turning with the cross-polar-cap potential declining to progressively lower values and with the convection pattern responding to a weighted sum of the IMF over the previous 4 hours. *Hairston and Heelis* [1995] found in DMSP satellite passes that it takes 17 to 25 minutes for the new convection pattern to establish itself after a southward turning and 28 to 44 minutes after a northward turning. More recently, in statistical models driven by the IMF *Weimer* [2001] used an average over 30 minutes and found that the optimal integration time depends on the length of time that it takes the satellite to traverse the polar cap. A number of studies have placed the initial response time in the range of 3 to 5 minutes. For instance, *Clauer and Friis-Christensen* [1988] found the response near the cusp to be rapid and immediate, with the onset of reconfiguration of high-latitude currents occurring about 3 minutes after an abrupt northward turning of the IMF from -22 to $+22$ nT. Using ground-based radar observations, *Greenwald et al.* [1990] found responses to B_Y reversals to start between 3 to 5 minutes after incidence on the magnetopause, with the new pattern establishing itself within the field of view of the radar within 6 minutes after the start. Using ground magnetic-field perturbations recorded by the CANOPUS magnetometer network, *Saunders et al.* [1992] found a minimum delay in magnetic response of 5 minutes at the cusp and flow perturbations propagating toward dawn and dusk, initially at 5 km/s, but slowing to 2 km/s 2 hours away from the near-noon initiation point in magnetic local time. The question of how fast and by what mechanism the induced change reaches back across the whole convection pattern is still open.

Two recent sets of observations bear on these problems. First, *Ridley et al.* [1997, 1998] looked at AMIE pattern differences relative to a base pattern to investigate responses to changes in the IMF. They found that the difference pattern had a particular shape based on the IMF change, that it appeared over most of the polar cap region at once, maintaining its position and shape, and that the difference-pattern magnitude increased linearly with time. The communication time from when the change in IMF first contacted the magnetopause to when the difference pattern became established in the ionosphere was 8.4 ± 8.2 minutes. This large uncertainty indicates that the interaction process is not well defined. The average reconfiguration time was 12 minutes once the pattern started to change. The second measure of response times utilizes SuperDARN radar measurements. *Ruohoniemi and Greenwald* [1998] and *Shepherd et al.* [1999] found that some changes in convection patterns, resulting from abrupt switches in IMF direction, appear nearly simultaneously at all local times. *Shepherd et al.* invoke draping of the IMF around the magnetopause to delay the interaction until it can happen simultaneously along the entire merging line. They state that their results are inconsistent with models of single-point reconnection that spread antisunward at a few km/s.

Possible reasons for some of the differences between various timing studies rests with the perspective of each measurement set and the definition of when and where incidence starts that each employs. It is important to remember that timing can not be faster than either the cadence of the data set or on how long it takes to accumulate a pass of data. The satellite measurements, which are based on passes across the polar cap, take at least 10's of minutes to complete a measurement and focus on the large scale pattern changes and the time it takes to evolve from one state to another [e. g. *Hairston and Heelis*, 1995]. The early ground-based magnetometer and radar results focussed on more local effects around the cusp [e. g., *Clauer and Friis-Christensen*, 1988; *Greenwald et al.*, 1990]. The more recent results of *Ridley et al.* [1998] and *Shepherd et al.* [1999] provide a global perspective at high time resulution using AMIE and SuperDARN.

Ionospheric convection can be ascribed to the $\vec{J}\times\vec{B}$ force that is associated with the Pedersen current and caused by transverse momentum transmitted by field-aligned currents (FAC) [e.g., *Iijima*, 2000]. Thus, understanding field-aligned current structure is an important part of understanding convection response. The original Region 1 – Region 2 layered FAC structure found by *Iijima and Potemra* [1976] has a third (Region 0) layer located poleward in the dayside cusp region and of opposite polarity to the adjacent Region 1 FAC. While this came to be known as the cusp current, *Bythrow et al.* [1988] suggested that it would be better named a mantle current, and that it closed with a current of Region-1 sense generated near the open-closed boundary. This connection was confirmed by *Maynard et al.* [1991] who identified cusp-mantle currents as a separate system. *Erlandson et al.* [1988] and *Taguchi et al.* [1993] further defined the morphology of these currents with IMF, including effects of polarity reversal with IMF B_Y. If an IMF B_Y is reversed, the polarity of the cusp-mantle currents must also reverse.

MHD modeling has given us the ability to follow current systems in the magnetosphere and trace their circuits, as discussed by *Siscoe et al.* [2000a]. These authors traced the cusp-mantle current system using the Integrated Space Weather Prediction Model (ISM). In their model run for positive B_Y, the downward Southern-Hemisphere mantle currents close through the cusp to currents with Region-1 sense, pass across the frontside magnetopause to the opposite hemisphere's cusp, and close to the upward Northern-Hemisphere mantle current. The mantle currents close in the tail lobes, wrapping around the magnetotail. For cases dominated by B_Y, ionospheric current closure of the cusp-mantle currents is meridional, providing the driving force for dawnward flow in the Northern-Hemisphere ionosphere [*Siscoe et al.*, 2000b]. The generator comes from a dawnward tangential $\vec{J}\times\vec{B}$ force along the high-latitude magnetopause which is coupled to the ionosphere via field-aligned currents.

ISM provides a unique opportunity to investigate the evolution of the magnetosphere with changing IMF conditions. For this purpose we performed an ISM run in which the purely B_Y IMF was reversed from +5 to -5 nT, and the response was monitored at one-minute intervals. Results are described below and discussed in the context of previous observational results.

2. The Integrated Space Weather Model

The Integrated Space Weather Prediction Model operates within a cylindrical computational domain with its origin at the center of the Earth and extending 40 R_E sunward, 300 R_E anti-sunward, and 60 R_E radially from the Earth-Sun line. The domain has an interior spherical boundary at the approximate bottom of the E-layer (100 km in simulations described here). ISM is based on standard MHD equations augmented with hydrodynamic equations for a collisionally coupled neutral thermosphere. As one conceptually moves inward from the solar wind toward the Earth, these equations transition continuously from pure MHD for plasma in the solar wind and magnetosphere to proper ionospheric/thermospheric equations at low altitudes. For purposes of the simulations discussed here, specific selections of parameters and simplifying approximations have been made. Finite-difference grid resolution varies from a few hundred kilometers in the ionosphere to several R_E at the outer boundary of the computational domain. For the dayside magnetopause, resolution ranges between 0.3 to 1.0 R_E. Explicit viscosity in the plasma momentum equation has been set to zero. To approximate non-linear aspects of magnetic reconnection within the context of a finite-difference grid, the coefficient for explicit resistivity η_R in the ISM Ohm's Law equation is zero when current density perpendicular to $\vec{B}$ is less than $3.16 \times 10^{-3}\, A/m^2$; η_R is $2 \times 10^{10}\, m^2/s$ in regions with perpendicular current density above this threshold. In practice, this choice of η_R leads to non-zero explicit resistivity primarily in the subsolar region of the dayside magnetopause. Dissipation for numerical stability is based on a form of the partial donor-cell method (PDM) [*Hain*, 1987].

For these simulations, thermospheric hydrodynamics and explicit chemistry between ionospheric and thermospheric species have been disabled in the ISM code, but collision terms between ions, electrons, and neutral species have been retained for purposes of ion-neutral drag and electrical conductivity. Ionospheric Pedersen conductance was derived from a coarsely resolved vertical electron-density profile uniform in latitude and longitude. Pedersen conductance varies inversely with B^2 and at high latitudes is nearly uniform at 6 *Siemens*. No Hall conductance was used. Analysis of boundary layer transport properties in ISM simulations indicates the effective kinematic viscosity due to artificial numerical dissipation in ISM's finite-difference approximations to be on the order of $4 \times 10^8\ m^2/s$. This level of dissipation is consistent with estimates of kinematic viscosity and mass-diffusion coefficient in the magnetospheric low-latitude boundary layer derived from spacecraft observations of boundary-layer width and mass flow [*Sonnerup*, 1980; *Sckopke et al.*, 1981].

In the discussion to follow, specific simulation results are presented. Solar-wind inflow boundary conditions were based on typical values: speed = 350 km/s, density = 5 $protons/cc$; ion and electron temperature = 20 eV; initial IMF strength = 5 nT in the $+Y$ direction. After 2:00 h of simulation time, the IMF at the inflow boundary was reversed in one time step (0.2 s) to 5 nT in the $-Y$ direction. The IMF reversal reached the magnetopause at 2:12 h of simulation time. Figure 1a displays the magnitude of B_Z to help identify the position of the magnetopause. Figures 1b, 1c, and 1d respectively show the magnitude of B_Y along the X axis at three times: when the reversal was totally in the solar wind, when the reversal had moved inside the bow shock, and when the reversal was approaching the magnetopause. Limited grid resolution in X at the model inflow boundary at $X = 40\ R_E$ causes the MHD solution to spread the IMF reversal over an X distance of about 4 R_E. However, due to substantially higher grid resolution in the vicinity of the bow shock, magnetospheath, and magnetopause, and to flow properties of the bow shock and magnetosheath, the reversal in B_Y steepens in the magnetosheath to be about 1 R_E thick as it impacts the magnetopause. Grid resolution in the X direction at the subsolar magnetopause is $\sim 0.3\ R_E$, so the thickness of the reversal is limited by grid resolution.

Figure

Figure

3. Chronology of observations from ISM

During time intervals of interest, ISM model results were obtained every minute (the numerical time step was much shorter at fractions of a second). The IMF reversal reached the nose of the magnetopause at 2:12 h of simulation time, having been slowed by the bow shock and by convection through the magnetosheath. We take 2:12 h of simulation time to mark the reference time t = 0 used in the remainder of the paper. Some draping had already occurred at t = 0, since outside of the shock in undisturbed solar wind the IMF reversal had already propagated 9 R_E past the magnetopause nose.

In the following sections we describe a large number of observed changes in diverse regions as the reversal of B_Y impacts the magnetosphere. To maintain continuity and perspective for the following descriptions, the events are listed below in chronological order. This list may be used initially as a roadmap and then as a means to consolidate the information presented. At the end of each event-list entry, we provide the X coordinate of the IMF reversal at $Y = 50\ R_E$ (i.e., near the edge of the simulation box). References to sections and figures (plates) indicate where each event is introduced.

- -4 min.: Reversal reaches bow shock (Section 2: Figure 1)[13.2 R_E].
- 0 min.: Reversal impacts nose of the magnetopause (Section 5: Figure 4) [$-0.2\ R_E$].
- 1 min.: Field-aligned currents begin to reverse at nose as a result of the currents generated at the B_Y reversal (Section 5: Figure 4). Tilt of closed field lines begins to change [$-3.5\ R_E$].

- 2 min.: Current reversal at nose is nearly completed and begins to spread tailward in the equatorial plane (Section 5: Figure 4). Open field lines no longer drape over the nose (Section 5: Plate 10b). New tilt of closed field lines is obvious (Plate 10b) [$-6.9\ R_E$].
- 3 min.: First sign of merging is seen in the Northern Hemisphere (Section 5: Plate 9c) [$-10.2\ R_E$].
- 4 min.: First sign of difference pattern is seen in ionospheric currents (Section 4.3: Plate 7b). Boundary-layer cells in both the ionospheric current and potential-difference patterns begin to change slowly (Section 4.4: Figure 4). The new tilt of the last closed field lines is now complete across the dayside (Section 5: Plate 10c). The nose is still void of open field lines draped across it. Newly merged field lines can be traced from the dusk solar wind into the Northern Hemisphere cusp indicating merging and the beginning of new coupling (Section 4.2: Plate 4b) [$-13.6\ R_E$].
- 5 min.: Region of current reversal expands on magnetopause (Section 5: Compare progression in Plate 11a; Compare also Plates 9d and 9e) [$-17.0\ R_E$].
- 6 min.: The B_Y reversal reaches the high-latitude mantle above the cusp on the noon-midnight meridian, and the mantle current begins to reverse (Section 5: Plate 11b) [$-20.3\ R_E$].
- 8 min.: The mantle current reversal in the main current layer is complete (Section 5: Plate 11b), and the first indication of a potential-difference cell appears in the open-field-line region (Section 4.1: Plate 2c). This difference cell remains fixed in position (Plate 2) and grows in magnitude (Section 4.4: Figures 2 and 3). The current-difference pattern is also well established (Section 4.3: Plate 7 and Figures 2 and 3) [$-27.0\ R_E$].
- 12 min.: The potential difference pattern is clearly established, but still growing in magnitude, and effects are seen over the whole polar cap region. The current difference pattern is more concentrated toward the front side (Section 4.1: Plate 2d; Section 4.3: Plate 7d)[$-40.4\ R_E$].
- 27 min.: Maximum difference current reached (Section 4.4: Figure 2) [$-90.6\ R_E$].
- 32 min.: Maximum difference potential reached (Section 4.4: Figure 2) [$-107.4\ R_E$]. Note that details of the nightside patterns continue to evolve with time, but the maximum difference potential does not increase.

To describe these events, we concentrate in Section 4 on the ionospheric response and its correspondence to observations. In Section 5 we then explore phenomena near the magnetopause and in the magnetosheath to further develop our understanding of the reversal process. In Section 6 we comment on the causes for the ionospheric responses.

4. Simulation results – ionospheric response

4.1. Potentials

The first sign of Northern-Hemisphere merging with negative B_Y occurred at $t = 3$ minutes (this will be explored further in Sections 4.2 and 5). The Northern-Hemisphere potential patterns are presented in Plate 1 every 4 minutes between $t = 0$ and 20 minutes. The maximum (minimum) potential of the dawn (dusk) cells are given in the lower right (left) of each panel. For comparison, *Weimer* [2001] derived average potential values for the two ionospheric convection cells of -31 and $+16$ kV for IMF magnetic fields of 5.0 nT oriented in the B_Y direction and solar wind velocity of 350 kms^{-1}. ISM potential values before and at IMF switch initiation ($t = 0$) are slightly smaller in each cell. The red irregularly-shaped contour in the center is the intersection of the manifold of last-closed field lines with a spherical surface at 600 km altitude. The potential pattern starts as a normal 2-cell pattern for positive B_Y with the larger cell being the dusk negative cell (Plate 1a). The dusk cell pattern has some contours completely within the open-closed boundary indicating the presence of a small lobe cell. The pattern does not change significantly until at $t = 12$ minutes (Plate 1d), where the dusk cell is significantly weakened. By $t = 20$ minutes (Plate 1f) the dawn cell is strengthening as the pattern evolves toward the normal negative B_Y pattern.

Plate

We used the same technique as *Ridley et al.* [1998] to find a difference-potential pattern for each time. The reference-potential pattern was taken at $t = -2$ minutes, i.e., before the IMF reversal had reached the magnetopause. Plate 2 shows difference patterns at times corresponding to Plate 1. While there is a hint of the pattern to come at $t = 8$ minutes (Plate 2c), the difference pattern is not clearly established until $t = 12$ minutes (Plate 2d), when a 10 kV difference pattern is observed, centered just poleward of the open-closed field line boundary. The center of the pattern remains constant and grows in magnitude over the next 20 minutes (and longer), similar to the results obtained by *Ridley et al.* The negative pattern equatorward of the open-closed boundary also grows but is significantly weaker and smaller. In fact there is a hint of change in that area at $t = 4$ minutes, but at levels within the general variability of the patterns, which is well before the major change in ionospheric convection on open field lines. The positive difference cell on open field lines is in the same sense as the lobe cell expected for negative B_Y [*Reiff and Burch*, 1985].

Plate

4.2. Magnetic Field Line Traces

Shepherd et al. [1999] also found a sudden change in the convection pattern occurring in response to a sudden change in IMF. With IMP-8 located in the magnetosheath well behind the terminator, timing of the interaction was such that they determined that significant draping must occur before the pattern can change. To check this, in Plate 3 we plot eight groups of magnetic-field tracings at t = 12 minutes. These field lines were started at $Y_{GSE} = 50$ R_E and $Z_{GSE} = -2, -1, 0, 1$ and 2 R_E. In Plate 3a the X_{GSE} starting points are $-7.8, -11.1, -14.5$, and -17.9 R_E, while in Plate 3b they are $-21.2, -24.6, -27.9$, and -31.3 R_E. The starting points of each group are separated in X_{GSE} by approximately one minute of travel time in the unshocked solar wind. The field lines are green if they remain solar wind field lines and do not merge; they are red if they have merged and are connected to the Northern Hemisphere, becoming open field lines of the magnetosphere. The XY simulation plane is colored to indicate the magnitude of B_Y. The change in color from blue to tan clearly shows that, at the time of the significant change in the potential pattern (Plate 1d), the IMF-transition front has propagated to $X = -40$ R_E in the solar wind. In other words, significant draping has occurred before the potential change. The bow shock is delineated by the darker-blue region in front of the magnetopause. Some of the mapped field lines in group H (see plate) turn in the magnetosheath and return to the dusk boundary via the positive B_Y region further down tail. Note that in these figures the field lines were traced in three dimensions and projected onto the XY plane. The large amount of red in Plate 3b indicates that connectivity of the ionosphere to a wide region in the solar wind has been established at this time, $t = 12$ minutes, when significant changes in the convection pattern have appeared (see Plate 2d).

Plate

To explore further the evolution of this connectivity, we show in Plates 4 and 5 three-dimensional perspectives of these same eight groupings of traced field lines, viewed from the Sun, for each of the six times in Plates 1 and 2. Note that Plate 4 (5) plots the traced field lines for the first (last) three times in Plate 1. Field lines in Plates 4a, 4b, 4c, 5a, 5b, and 5c (4d, 4e, 4f, 5d, 5e, and 5f) are traced from the same points as in the Plate 3a (3b). Each field line is colored according to the polarity of $\vec{J} \cdot \vec{E}$, with red being positive (load) and blue being negative (generator). At $t = 0$ (Plate 4) all connectivity between the unshocked solar wind at the dusk edge of the simulation box is to the Southern Hemisphere. Under steady-state positive B_Y conditions, newly merged field lines in the Northern Hemisphere would be connected to the solar wind at the dawn edge of the simulation box. The first merging of negative B_Y with the Northern Hemisphere, connecting to the dusk side, is found in the simulation at $t = 3$ minutes, and we see that there are several connecting field line traces at t = 4 minutes (Plate 4b). Connectivity to the Northern Hemisphere grows until at $t = 12$ minutes (Plates 5a and 5d), all the merged field lines shown trace to the Northern Hemisphere as expected from Plate 3, which shows that the reversal front has passed beyond the starting points for the traces. The field lines above the cusp are blue (e.g., Plates 5d, 5e, and 5f) indicating that they are in a generator region as they are being dragged back away from their merging site. Note that field lines that are draped across the magnetopause nose are tilted and change their orientation between $t = 0$ minutes (Plate 4a), when they are still under control of $+B_Y$, and $t = 20$ minutes (Plate 5c), well after the reversal. The first sign of this change is in Plate 4b. We will return to this point in Section 5. Note also that some field lines turn in the magnetosheath (see, e.g., Plates 4b and 4e) as they connect to field lines behind the IMF reversal (see Plate 3b). Thus, there is a region around the layer of IMF reversal on the dusk side that has no connectivity to the magnetosphere, nor to the dawn flank once the layer has passed the magnetopause nose. This point will be

Plates

discussed further in Section 6.2.

4.3. Field-Aligned Currents

MHD modeling allows us to check other parameters. Field-aligned currents into and out of the ionosphere provide a different perspective. Plate 6 displays the field-aligned current patterns for the same times as in Plate 1. Upward (downward) currents are blue (tan). Maximum upward and downward currents are noted in each panel. As in Plate 1, the red line marks the intersection of the manifold of last-closed field lines with a spherical surface at 600 km altitude. The conditions at $t = 0$ minutes (Plate 6a) show dusk Region-1 currents [*Iijima and Potemra*, 1976] extending into the mantle (to Region 0) and overlapping the dawn Region-1 currents to form the cusp-mantle current system. The cusp-mantle currents connect the cusps on the dayside and close in the magnetotail [see *Siscoe et al.*, 2000a]. The downward cusp current straddles the open-closed field line boundary. Note that the patterns are similar for the first three times and then begin to change noticeably at 12 minutes (Plate 6d) with the maximum currents weakening and obvious shifts in pattern. The pattern continues to evolve, resulting in the opposite polarity cusp-mantle current system from that seen in Plate 6a at $t = 20$ minutes (Plate 6f). Here the morning side Region-1 current pattern overlaps the afternoon Region-1 pattern to form the cusp-mantle system for negative B_Y.

Just as we constructed difference patterns for potentials, we now do the same for field-aligned currents. Plate 7 shows the current differences for the same times, all referenced to the current pattern at $t = -2$ minutes. In this case, a pair of difference currents develops with polarity of the negative B_Y cusp-mantle current system and centered about the open-closed boundary. This behavior is very clear at $t = 8$ minutes (Plate 7c), and there is even a hint of the pattern to come at $t = 4$ minutes (Plate 7b). From the difference-current maximums displayed in each panel we see that the maximum positive difference at $t = 12$ minutes (Plate 7e) of $0.20\,\mu A/m^2$ is equivalent to the negative current at that location in Plate 6a at $t = 0$ minutes (on innermost dashed contour). Thus, $t = 12$ minutes is the time when the difference-current system, which has been growing since the beginning of the Northern-Hemisphere merging related to negative B_Y, first overcomes the original cusp-mantle system and changes its polarity. By $t = 20$ minutes the difference currents in Plate 7 are nearly twice the actual currents in Plate 6a, indicating that the system has nearly completed the necessary flip in its polarity. Note that the open-closed boundary divides the two difference-current patterns.

The pattern is basically fixed in location, similar to the potential difference patterns in Plate 2. In contrast to the potential-difference patterns, the magnitudes of the two current-difference-pattern cells remain much closer in magnitude as the pattern grows. A close comparison of Plate 7d with Plate 2d shows that the downward mantle part of the difference current is just equatorward of the positive potential-difference-pattern maximum.

4.4. Difference pattern growth

Figure 2 shows plots of the minute by minute increase in magnitude of the positive difference currents (a) and difference potentials (b) against minutes of simulation time after $t = 0$ minutes. The rapid onset of the potential difference begins at $t = 8$ minutes, climbing nearly linearly until $t = 27$ minutes and maximizing at $t = 32$ minutes. The difference currents start to increase already at $t = 4$ minutes, changing their rate of increase at $t = 8$ minutes when the potential starts to change. The difference currents reach their maximum value at $t = 27$ minutes, increasing slightly until $t = 32$ minutes, and then falling back to the value at $t = 27$ minutes. Figure 3 shows expanded views of the beginnings of both positive and negative current and potential differences. On the expanded scale it is clear that negative current and potential differences both begin to change at $t = 4$ minutes. These changes begin at the open-closed boundary with the cells remaining on closed field lines as they grow. The positive current-difference cell also grows immediately in the open field-line region, remaining outside the boundary. The lag from the first contact at $t = 0$ to the onset of merging is 3 minutes. There are additional lags of the order of 5 minutes from the first sign of merging to the start of a change in the potential patterns on open field lines and 8 to 9 minutes before the difference pattern exceeds 10 kV.

5. Magnetopause/magnetosheath dynamics

The ISM code can be used to investigate magnetopause boundary dynamics during the IMF switch. The last-closed field line boundary shown in the polar plots was determined by starting in the equatorial plane and tracing along magnetic field lines in both directions. The start points are incremented outward until the traced field line no longer connects to the ionosphere in both hemispheres. The “first” open set of field lines was then found by starting in each ionosphere and moving generally in the poleward direction a distance of about 50 km perpendicular to the boundary and initiating a trace from that point. Some of these field lines thread into open boundary layers. Plate 8 shows three-dimensional plots at six times of the “first” open field lines, as viewed looking down from the northern pole. Blue (red) lines connect to the northern (southern) ionosphere. The equatorial plane is colored with the intensity of B_Y and obscures the traces below that plane. The more sharply hooked field lines are products of local merging, e.g., as noted by the arrow in Plate 8b. At $t = 0$ minutes (Plate 8a) the change in B_Y is just reaching the magnetopause. All of the blue lines connect to the dawn boundary from having merged with the original $+B_Y$. The sash [*White et al.*, 1998] is a region of low magnetic field strength, extending from the cusp tailward toward dusk (dawn) along the high latitude magnetopause and is a locus of possible merging sites for positive (negative) B_Y. The red lines on the right, equatorward of the sash, connect to the Southern Hemisphere and form a thick extended open boundary layer on the equatorial plane on the dusk flank as found by *Maynard et al.* [2000c]. They defined the boundary layer as the region of open field lines between the last closed field line and magnetosheath field lines having no connection to the magnetosphere. At $t = 48$ minutes (Plate 8f) the picture is reversed, i.e., the shift to $-B_Y$ has been completed. Note that that switch begins in Plate 8b (4 minutes) with sharply-hooked blue field lines that extend to the dusk boundary. As previously stated, these are field lines that have been merged with the newly arriving $-B_Y$. Note also the lack of open field lines at noon at this time. In each subsequent panel, the number of blue lines that are hooked left and extend toward dawn diminish, and the number that extend toward dusk increases. In Plates 8d and 8e there are sharply-hooked blue field lines which have recently merged in the Northern Hemisphere, and those that head toward the equatorial plane at a lesser angle (denoted by the arrow). These latter field lines were opened by merging in the Southern Hemisphere. They are originally opened at the dawnside of the cusp and are being dragged more slowly toward dusk because of the additional length of the field line at the time of merging. If we looked at a Southern Hemisphere plot instead, these field lines would develop into a dusk-side open-boundary layer analogous to the red lines in Plate 8a.

Plate 8

To check our definition of the “first” open field line, we narrowed the search step away from the closed field-line boundary in the ionosphere to 25 km. Plate 9 presents the start pattern at $t = 0$ minutes (Plate 9a) and then the minute-by minute evolution from $t = 2$ to $t = 5$ minutes (Plates 9b, 9c, 9d, and 9f). We have also included the last-closed field lines in black. There is no longer a gap between the red and blue lines at $t = 0$ minutes (Plate 9a). At $t = 2$ and $t = 3$ minutes (Plates 9b and 9c), the magnetopause nose is covered only by black closed field lines, and the tilt of those field lines is changing. As noted in Plate 1, the first Northern-Hemisphere merged line extending toward dusk is seen at $t = 3$ minutes (Plate 9c). At $t = 4$ minutes (Plate 9d) and $t = 5$ minutes (Plate 9f) the changing from field lines hooked to the left for $+B_Y$ to those hooked to the right for $-B_Y$ is very evident. In some cases field lines are merged on the dusk side hooking left toward dawn and then are merged again with the newly arrived $-B_Y$ which pulls them to dusk. The magenta field lines in Plate 9e are examples of these. For clarity, only the closed black field lines are shown along with the magenta open field lines in this plate.

Plate 9

Plates 10a, 10b, 10c, and 10d show the open and closed field lines looking from the Sun at $t = 0$, 2, 4, and 6 minutes, respectively. Those newly opened field lines from dayside merging that are dragged over the high-latitude magnetopause are clearly seen. For clarity each field line trace was terminated whenever it reached $X \leq -15\ R_E$. Those merging products that connect to the opposite ionosphere are seen draped through the boundary layers. This point is illustrated in Plate 10a by the red (blue) lines that pass through the boundary layer post- (pre-) noon from merging sites in the Northern (Southern) Hemisphere. Between $t = 0$ minutes (Plate 10a) and $t = 4$ minutes (Plate 10c), the black closed field lines at the nose are seen to reverse their tilt. This is happening before the first sign of newly merged field lines and well before the change in convection patterns seen in Plate 2. By $t = 6$ minutes (Plate 10d) most of the high latitude field lines are missing as the old IMF polarity has passed and the new polarity is just getting established.

Plates

The field lines draped through the low latitude boundary layer conform to the new tilt of the closed field lines. The new tilt takes place as the field-aligned current at the nose is being reversed. We can see this in Figure 4. Here we have plotted B_Z (to show the position of the magnetopause), $J_\parallel$, and B_Y along the X axis for $t = 0$, 1, and 2 minutes. Note that as the reversal front approaches and drapes around the magnetopause, $\nabla \times \vec{B}$ will produce perpendicular currents in the Z and Y directions. These currents extend into the magnetosheath and

Figure

are part of the boundary-layer currents. As the magnetic-field reversal approaches the magnetopause, a negative field-aligned current associated with the reversal grows. We have chosen to display $J_{\parallel}$ here and in Plate 11 because it highlights the reversal and its interaction at the boundary, while maintaining the configuration of the cusp-mantle current system exiting the ionosphere. The current is initially separate from the upward cusp-mantle current at the magnetopause, but it quickly merges with it, and by $t = 2$ minutes has fully reversed it. This happens before the start of the current difference patterns (Plate 7 and Figures 2 and 3) and before there are any open field lines at the magnetopause nose or at high latitude created by the new IMF polarity. Thus, we have identified the means for reversing the current in the boundary layer. It is an adjustment of the boundary-layer currents and is not due to creation of open field lines by dayside merging. Plate 1

To further illustrate this, Plates 11a and 11b display, from $t = 0$ to 16 minutes, the evolution of the field aligned currents in the XY plane at $Z = 4$ and 12 R_E (below and above the cusp). Time increases to the left, in the direction of propagation of the reversal front. The asterisk in each frame denotes the position of the front at that time. In Plate 11a, traces of the open/closed boundary are in red. By $t = 4$ minutes the parallel current at the magnetopause nose is clearly reversed; however, there is no change in the downward (brown) cusp currents. Their closure across the nose must be retreating toward the flanks as evidenced by the gap in the brown region on closed field lines at the nose. This is more evident at $t = 8$ and 12 min.

The high-latitude mantle current must reverse as well. Above the cusp (Plate 11b), the reversal front contacts the mantle between $t = 4$ and 8 minutes. By ($t = 12$ minutes, significant downward current, evident in the figure, is needed to reverse the cusp-mantle current system. Remember that in the vicinity of the reversal in the magnetosheath, field lines behind the IMF reversal front close with those in front of the reversal (Plate 4) There is no connection to the ionosphere, which accounts for the paucity of mantle open field lines in Plate 10c. Here the reversal in B_Y reaches the high latitude magnetopause at $t = 6$ minutes and the mantle current reversal begins. The current polarity is fully reversed at $t = 8$ minutes and the reversed current has increased in magnitude at $t = 12$ minutes. While the current peak is larger than before the reversal, the layer is narrower and the current has not yet reversed behind the main layer as indicated by the blue color. The latter reversal must wait until the pattern has evolved further. We note that $t = 8$ minutes was the time when the first sign of the difference-potential pattern on open field lines connecting to the mantle was seen in Plate 2c and began to grow (see also Figures 2 and 3).

6. Discussion

MHD modeling provides results that replicate many of the new observational results from SuperDARN and AMIE. Being able to test the response to an IMF polarity reversal at all points in the solar-wind/magnetosphere/ionosphere system allows us to comment on causes and effects.

6.1. Causes of the Ionospheric Response to an IMF reversal

We have shown that potential-difference patterns predicted from ISM simulations for a step function change in IMF qualitatively evolve in the same manner as the difference patterns found by *Ridley et al.* [1997] using AMIE potential patterns from an actual, more gradual reversal of the IMF B_Y component. They found a single vortex structure developing over the central polar cap and spreading more toward midnight than toward noon. The largest potential change (or the center of the vortex), which remained in the same place as the pattern grew, was near the pole. It grew linearly and was positive for a negative change in B_Y. Plates 2c-2f also show a change over the whole polar cap, centered poleward of the open-closed boundary, that grows with time until the whole pattern is reversed. The same plates show that the change begins 8 minutes after first contact with the magnetopause and increases linearly (see Figure 2). Note that the open-closed boundary limits the extent of the pattern on the dayside. On the nightside there is an initial change when the pattern first appears. The potential at 22 h MLT at the open-closed boundary has changed by 4 kV between $t = 8$ and $t = 12$ minutes, compared with a maximum change over the same interval of 11 kV, consistent with the results of *Ruohoniemi and Greenwald* [1998]. The potential difference at the night side boundary grows linearly with the pattern until it reaches 8 kV where the penetration of the difference pattern seems to stop. A change that is propagating from a dayside initiation point in the cusp at a speed of 2 to 3 km/s, as suggested by *Cowley and Lockwood* [1992], would have taken over 15 minutes to reach that point. Information altering the flow must be communicated more rapidly across the polar cap for the initial change. *Ruohoniemi and Greenwald* [1998] found this communication time to be between 2 and 4 minutes and suggested that information was communicated by fast Alfvén mode waves. *Shepherd et al* [1999] suggested that draping of field lines allowed merging to begin "nearly simultaneously" over the magnetopause. We have shown that there is significant draping (Plates 4 and 5) as suggested by *Shepherd et al.* However merging started 5 minutes before the beginning of the changes in the vortex potential difference pattern on open field lines. It is the large-scale pattern change on which the conclusions of *Shepherd et al.*, *Ruohoniemi and Greenwald*, and *Ridley et al.* are based. Thus, we must look for other causes of the delay.

Siscoe et al. [2000a] found that the cusp-mantle current system is a tail-current system which closes between hemispheres over the magnetopause nose. They also found that the Chapman-Ferrero magnetopause currents for $+B_Y$ generate a set of nested spirals, offset from the particle entry cusp in both the Y and Z directions. *Siscoe et al.* [2000c] showed that the last closed field line is tilted at the nose and a field line can be found that runs from the null on the dusk side of the Northern-Hemisphere cusp to the null at the dawn side of the Southern-Hemisphere cusp (a field line along which a parallel potential equivalent to the cross-polar-cap potential is found). The transition from the northward-directed Earth's dipole field to the B_Y direction of the IMF must be accomplished by magnetopause currents creating the tilt. Figure 4 and Plate 10b clearly show that the initial response to the polarity switch is to reconfigure the currents at the nose to tilt the last closed field lines to the new direction. The nose becomes devoid of open field lines (Plate 10b), and the first new open field lines are seen after $t = 3$ minutes (Plates 9c and 9d) at high latitudes. We conclude that the reconfiguration of open field lines in the simulation must emphasize high latitude processes. The change in field-line tilt at the nose in the simulation must reflect the necessary change in the magnetopause currents from the changing $\nabla \times \vec{B}$. We will come back to this point in Section 6.2.

The first response detectable in ionospheric patterns is associated with the changing current patterns at $t = 4$ minutes (Figure 3 and Plate 7b). Note that this change begins with the first indication of open field lines at high latitudes connecting to the new polarity IMF. One could expect to see a local effect in the ionosphere from the merging, but not a general pattern shift. This is evidenced by the small change in both the potential and currents on closed field lines beginning at that time in Figure 3. However Plate 11a shows no appreciable change in the cusp currents at this time even though the boundary current at the nose has been reversed. Plate 11b shows that the major changes in the ionosphere start when the boundary currents above the mantle are impacted by the passage of the reversal front. During the change of configuration, cusp currents must be diverted away from the magnetopause nose in the closed boundary layer. Thus, the magnetopause currents must be significantly reconfigured both at the nose and above the cusp in order to allow the reversal of the cusp mantle system before the large-scale pattern change occurs (Plate 2d), comparable to that seen by *Ridley et al.* [1997] and *Ruohoniemi and Greenwald* [1998]. The chronology of events in Section 3 details the systematic events leading to the convection pattern change. Before this pattern changes, open flux is being added locally at the cusp, providing local evidence for the *Cowley and Lockwood* [1992] generation of convection. However, initial pattern changes are subtle, and the method of spreading to other locations is not strictly from propagation of the effects across the polar cap at a constant speed.

Thus, the interpretation which one might deduce with a limited data set could be a function of the location and scale size of the observations. The cusp is responding with open flux being added by merging [e.g., *Cowley and Lockwood* 1992] well before the large-scale convection pattern change, thus implying a propagation delay. The nightside of the polar cap does respond without significant delay when the large-scale pattern changes [*Ruohoniemi and Greenwald*, 1998; *Ridley et al.*, 1998]. However, this large scale pattern change occurs significantly after the beginning of merging, and the complete change in the large-scale pattern takes 20 minutes or more to complete, implying at least in part a propagation effect [*Lockwood and Cowley*, 1999]. The nightside open-closed boundary was still evolving for a significant time after the cross-polar-cap potential stopped changing. Draping around the magnetopause is involved [*Shepherd et al.*, 1999]; however, merging is not delayed until it can happen over the whole magnetopause. All of the empirically deduced interpretations above have elements of truth. None completely describes the process.

The ISM simulation has given us additional insight, according to which the delay in the large-scale response is attributed to the temporal adjustment of boundary layer currents, enabling the reversal of the cusp-mantle current system. While merging starts early and controls the addition of open flux to the polar cap, large-scale pattern changes are tied to currents, which are constrained in the boundary layers. Thus, the merging process could respond to small short-term variations in the IMF, changing its rate and location without large-scale changes in the pattern. This provides insight into the small-scale changes seen by *Maynard et al.* [2000b], who used the optical and local convection response to small-scale variations and B_Z polarity reversals in the IMF to deduce that coupling from merging regions in both hemispheres can be observed in locally proximate areas of the cusp region. We will further explore boundary layer phenomena in the next section.

6.2. Cusp and Boundary Layer Characteristics

MHD modeling allows one to relate these results to other issues. *Siscoe et al.* [2000c] have shown that there is a tilted field line that connects the null points in each hemisphere. This same tilt is seen in the open and closed field lines of Plate 10a. The reversal of the vertical components of the boundary-layer currents appears to provide the change in IMF tilt and magnetospheric field lines so that a smooth, continuous transition can occur as the IMF approaches the magnetopause. By tracing magnetic field lines from unshocked solar wind we were able to find only magnetospheric open field lines that appeared to have undergone merging at high latitudes. The question remained whether the tilt of the field lines at the nose was indicative of component merging there. To test this hypothesis, we traced field lines from both the dawn and dusk boundaries of the simulation at $t = 0$ minutes. The traces originated at $X_{GSM} = -8.6, -9.4, -10.2$, and -11.1 R_E. The traces are displayed in Plate 12. Plates 12 a-d are views in the XY plane of the traced field lines from above. Plates 12e-h are views in the YZ plane from the Sun. For $Y_{GSM} = -50.0$ R_E with $Z_{GSM} = 1.0$ R_E and -1.0 R_E, the traces are found in Plates 12a and 12e, and 12c and 12g, respectively. For $Y_{GSM} = 50.0$ R_E with $Z_{GSM} = 1.0$ R_E and -1.0 R_E, the traces are found in Plates 12b and 12f, and in 12d and 12h, respectively. Blue and red field lines connect to the Northern and Southern Hemispheres, respectively. Green traces are connected to the solar wind on each end. We could generate similar pictures for times after $t = 8$ minutes with the tilted field lines in the opposite direction because of the negative B_Y.

Plate

The solar wind upstream of the bow shock should have no knowledge of processes behind the shock. If magnetic field lines were simply deflected in the magnetosheath around the magnetopause, they should have end points at $|Y| = 50$ R_E that have the same Z and X coordinates. This is true just inside the shock. However, it is obvious from Plate 12 that this is not the case near the magnetopause. As the magnetopause is approached and the tilt grows, the end points are at significantly different Z and X values. If we paint the field lines with the parallel electric field, we find that there are small values in the magnetosheath around the entire nose of the magnetopause, a necessary condition of general reconnection [*Schindler et al.*, 1988]. The change in position of the end points and the parallel electric field indicate that the tilting process must involve "merging" between solar wind magnetic field lines as they are pulled and pressed against the nose. There is no observable connection at this point to the magnetosphere. As the Earth's field is approached, the tilt grows and the deflection in Z (and X) grows until connection with the magnetosphere field line occurs. The fourth line in Plates 12b (12f) and 12c (12g) have completed the merging process as evidenced by the red and blue traces. The same process leads to two merged field lines in Plates 12a (12e) and 12d (12h). Note that the simulation has flip symmetry for this B_Y-driven case, as can be seen from comparison of Plates 12b and 12c. Comparing to Plate 10a, we see that the tilt of the field lines in Plates 12f and 12g is similar to the tilt of the last closed field line. Thus, we infer that, at least in the simulation, general reconnection of IMF field lines with other IMF field lines is part of the process that generates boundary-layer currents that tilt the field lines across the magnetopause nose. In examining results from other numerical simulation codes, *Crooker et al.* [1998] have referred to analogous processes on the flank as "changing partners". They also drew a conceptual picture of offsetting connections to the solar wind at dawn and dusk, with the offset being a function of the potential of a lobe cell. The lobe cell potential at $t = 0$ is between 4 and 5 kV in Plate 1a. The several-R_E offset observed here in a solar-wind electric field of 11 kV per R_E is more indicative of the cross-polar-cap potential.

As the reversal front approaches the magnetopause, it is locally compressed, and the field-aligned current in the region between opposite polarities intensifies (Figures 1 and 5). As the front impacts the magnetopause, it is split by merging of field lines from both sides of the front. To illustrate this we have traced 41 field lines starting between $X = -14$ and -9 R_E with $Y = 50$ R_E and $Z = 0$ R_E. These field lines have been colored to identify energy conversion regions, with brown (blue) corresponding to positive (negative) values of $\vec{E} \cdot \vec{J}$. Plate 13 displays the progression starting one minute before the reversal front impacts the magnetopause ($t = -1$ minute) and continuing

Plate

at two-minute intervals. The nose of the magnetopause is generally a load (brown). However, at $t = 1$ minute $\vec{E} \cdot \vec{J}$ becomes negative as field lines are merged with those exiting the boundary near $X = -2\ R_E$. At $t = 3$ minutes we see the field line traces curling around the reversal front with the extension to the front being the load as the system is dragged downtail. By $t = 9$ minutes energy conversion at the magnetopause nose has returned to a load condition. The nose of the magnetopause serves to compress the IMF in the sheath until it merges. Merging at the nose that combines IMF field lines on both sides of the reversal boundary effectively eliminates contact of the unshocked IMF with the magnetopause for a region extending several R_E in X. This disconnection propagates downtail with time as can be seen in Plates 3b, 4b, and 4e. It also provides the reason for the absence of open field lines draping up over the lobe in Plate 10d, and over the magnetopause nose in Plate 10b.

This interuption of merging of the IMF with magnetospheric field lines is also reflected in the position of the open-closed boundary. While not easily discernible in Plate 1, expanding the scale shows that there is a small poleward movement of that boundary at the nose between $t = 0$ and $t = 4$ minutes while the interuption in merging with magnetospheric field lines is occurring. The boundary moves back equatorward between $t = 4$ and $t = 8$ minutes as merging increases with the new negative B_Y. Thus, some of the early changes in merging are absorbed in the *Cowley and Lockwood* [1992] and *Siscoe and Huang* [1986] picture of expanding and contracting adiaroic boundaries as the merging rates change. New open flux is added by the merging process. The major pattern change occurs with new directions of $\vec{J} \times \vec{B}$ forces from the changing currents and is not a result of direct imposition of the interplanetary electric field [e.g., *Toffoletto and Hill*, 1988].

Draping of field lines over the magnetopause nose from opposite-hemisphere merging is clearly seen in Plate 10a and illustrated also by the red lines in Plate 8a. Draping forms an open boundary layer across the nose and back along the flank. A similar conclusion was reached empirically by *Maynard et al.* [2000b], who suggested that the small convection cell is driven by opposite hemisphere merging. This ISM simulation is fully supportive of that conclusion for B_Y dominated conditions.

Siscoe et al. [2000c] located the separator line connecting the null points on the magnetopause in each hemisphere. From the existence of a parallel electric field distributed along that field line, they concluded that merging must be active to some degree all along the separator. The integrated potential along the field line was nearly the same as the cross-polar-cap potential, as was expected, although the distribution could be varied depending on whether explicit resistivity was used in the simulation. Tilting of field lines, field lines "changing partners," and merging between adjacent IMF field lines, discussed above, provides additional insight as to the processes operative at the nose.

7. Summary and Conclusions

The Integrated Space Weather Prediction Model (ISM), an MHD simulation model operating within a cylindrical computational domain with its origin at the center of the Earth (its inner boundary at 100 km altitude) and extending 40 R_E sunward, 300 R_E anti-sunward, and 60 R_E radially from the Earth-Sun line, has predicted effects in the magnetosphere-ionosphere system of a polarity reversal of IMF B_Y. By investigating model output each minute, we have tracked the evolution of the reversal disturbance and associated changes in the ionosphere and at the magnetopause. Results duplicate several empirically derived ionospheric effects and provide insight as to the causes. We list the following observations and conclusions from the simulation. All times are relative to $t = 0$, the time when the IMF reversal first contacts the nose of the magnetopause.

1. Merging with the new polarity begins at $t = 3$ minutes, affecting the local currents near the cusp starting one minute later. The occurrence of merging with $-B_Y$ is evident from the new directions open field lines take at high latitudes in each hemisphere.

2. The large-scale convection-pattern change begins at $t = 8$ minutes, confirming the difference pattern results of *Ridley et al.* [1997; 1998]. Within 2 to 4 minutes the difference-cell change is seen over the entire polar cap [*Ruohoniemi and Greenwald*, 1998]. The pattern center remains in place behind the cusp and the amplitude of the difference-pattern maximum increases linearly [*Ridley et al*, 1998] over approximately the next 20 minutes. However, the change is slower near the nightside open-closed boundary, with some change continuing long after the maximum change in the difference cell is reached.

3. IMF field lines are significantly draped around the nose with their roots back to $X = -27\ R_E$ in the solar wind when the large scale pattern change starts at $t = 8$ minutes, confirming the observations of *Shepherd et al.* [1999]. However their conclusion that merging is impeded until it can happen over a large region is not valid as the first signs of merging were at $t = 3$ minutes.

4. Field-aligned current difference patterns, derived similarly to the potential difference patterns, start to show a two-cell pattern earlier, at $t = 4$ minutes. They grow slowly at first, and then faster as the potential patterns change. The difference currents reach twice the magnitude of the original field-aligned currents, indicating that the cusp-mantle current system is being completely reversed.

5. Last-closed field lines and first-open field lines at the magnetopause nose are tilted toward dusk (dawn) for positive (negative) B_Y. The first response to the B_Y reversal impacting the magnetopause nose is to reverse the tilt of these field lines at the nose. This is done within the boundary layer before merging of the negative IMF B_Y with magnetospheric field lines starts.

6. The large scale pattern change does not happen until the boundary layer currents are reversed above the cusp by passage of the B_Y change over that boundary. This allows the cusp-mantle current system to reverse.

7. While merging starts early and controls the addition of open flux to the polar cap, large-scale pattern changes are tied to the currents, which in turn are controlled in the boundary layers. The change in the convection pattern is an amalgamation of these diverse responses.

8. In the steady state B_Y case IMF field lines undergo component merging or "changing partners" with other IMF field lines at the magnetopause nose, creating tilt in field lines as they approach the nose.

9. When the B_Y reversal approaches the magnetopause nose, IMF field lines from behind the reversal merge with those in front, splitting the reversal front, interupting merging with magnetospheric field lines, and effectively uncoupling a region of the unshocked IMF from the magnetosphere. This region propagates tailward in the magnetosheath. The open-closed boundary in the ionosphere at the cusp is seen to contract during the uncoupling and then expand as merging resumes with the new polarity.

10. Open field lines from merging in the Southern (Northern) Hemisphere are draped over the post-noon (pre-noon) nose region for positive B_Y. They form an open boundary layer along the flank [*Maynard et al.* 2000c] as they are pulled tailward by the advancing solar wind. ISM supports the conclusion of *Maynard et al.* [2000b] that the small convection cell is driven from the opposite hemisphere in B_Y dominated situations.

It is important to keep in mind that results depend in part on how well ISM replicates nature, i.e., on completeness of the physics, and on properties of numerical methods used to solve the physical equations. The distribution of merging on the magnetopause in the simulation may vary from physical reality where boundary layers are considerably thinner. However, the time-dependent and steady-state agreements with data pointed out above give credence that the large-scale processes are correctly simulated. We note that the prediction by ISM of the existence of the sash [*White et al.*, 1998] has been confirmed by experimental observation [*Maynard et al.*, 2000c]. In the same way our simulation results of merging or "changing partners" between IMF field lines near the nose is a prediction that needs to be confirmed experimentally and the theoretical implications assessed.

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References

Blanchard, G. T., L. R. Lyons, O. de la Beaujardière, R. A. Doe, and M. Mendillo, Measurements of the magnetotail reconnection rate, *J. Geophys. Res., 101*, 15,265, 1996.

Bythrow, P. F., T. A. Potemra, R. E. Erlandson, L. J. Zanetti, and D. M. Klumpar, Birkeland currents and charged particles in the high-latitude prenoon region, A new interpretation, *J. Geophys. Res., 93*, 9791, 1988.

Clauer, C. R., and E. Friis-Christensen, High-latitude dayside electric fields and currents during strongly northward interplanetary magnetic field: Observations and simulation, *J. Geophys. Res., 93*, 2749, 1988.

Cowley, S. W. H., and M. Lockwood, Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system, *Ann. Geophysicae, 10*, 103, 1992.

Crooker, N. U., Dayside merging and cusp geometry, *J. Geophys. Res., 84*, 951, 1979.

Crooker, N. U., J. G. Lyon, and J. A. Fedder, MHD model merging with IMF B_Y; Lobe cells, sunward polar cap convection and overdraped lobes, *J. Geophys. Res., 103*, 9143, 1998.

Erlandson, R. E., L. J. Zanetti, T. A. Potemra, P. H. Bythrow, and R. Lundin, IMF B_Y-dependence of Region 1 Birkeland currents near noon, *J. Geophys. Res., 93*, 9804, 1988.

Greenwald, R. A., K. B. Baker, J. M. Ruohoniemi, J. R. Dudeney, M. Pinnock, N. Mattin, J. M. Leonard, and R. P. Lepping, Simultaneous conjugate observations of dynamic variations in high latitude dayside convection due to changes in IMF B_Y, *J. Geophys. Res., 95*, 8057, 1990.

Hain, K., The partial donor cell method, *J. Comp. Physics, 73*, 131, 1987.

Hairston, M. R., and R. A. Heelis, Response time of the polar ionospheric convection pattern to changes in the north-south direction of the IMF, *Geophys. Res. Lett., 22*, 631, 1995.

Heppner, J. P., and N. C. Maynard, Empirical high latitude ionospheric electric field models, *J. Geophys. Res., 92*, 4467, 1987.

Hesse, M., and K. Schindler, A theoretical foundation of general magnetic reconnection, *J. Geophys. Res., 93*, 5559, 1988.

Iijima, T., Field-aligned currents in geospace: Substance and significance, in *Magnetospheric Current Systems, Geophysical Monograph 118*, edited by S. Ohtani, R. Fujii, M. Hesse, and R. L. Lysak, pp. 107-129, American Geophys. Union, Washington, D. C., 2000.

Iijima, T., and T. A. Potemra, The amplitude distribution of field-aligned currents at northern high-latitudes observed by Triad, *J. Geophys. Res., 81*, 5971, 1976.

Knipp, D. J., et al., Ionospheric convection response to slow strong variations in a northward interplanetary magnetic field: A case study for January 14, 1988, *J. Geophys. Res., 98*, 19,273, 1993.

Lookwood, M. J., and S. W. H. Cowley, Comment on "A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique" by A. J. Ridley st al., *J. Geophys. Res., 104*, 4387, 1999.

Maynard, N. C., T. L. Aggson, E. M. Basinska, W. J. Burke, P. Craven, W. K. Peterson, M. Sugiura, and D. R. Weimer, Magnetospheric boundary dynamics: DE-1 and DE-2 observations near the magnetopause and cusp, *J. Geophys. Res., 96*, 3505, 1991.

Maynard, N. C., W. J. Burke, D. R. Weimer, F. S. Mozer, J. D. Scudder, C. T. Russell, W. K. Peterson, and R. P. Lepping, Polar observations of convection with northward IMF at dayside high latitudes, *J. Geophys. Res., 103*, 29, 1998.

Maynard, N. C., et al., Driving dayside convection with northward IMF: Observations by a sounding rocket launched from Svalbard, *J. Geophys. Res., 105*, 5245, 2000a.

Maynard, N. C., W. J. Burke, P. E. Sandholt, J. Moen, D. M. Ober, D. R. Weimer, A. Egeland, and M. Lester, Observations of simultaneous effects of merging in both hemispheres, submitted to *J. Geophys. Res.,* 2000b.

Maynard, N. C., et al., Observation of the magnetospheric "sash" and its implications relative to solar-wind/magnetospheric coupling: A multisatellite event analysis, in press, *J. Geophys. Res.,* 2000c

Reiff, P. H., and J. L. Burch, B_Y-dependent dayside plasma flow and Birkeland currents in the dayside magnetosphere, 2, A global model for northward and southward IMF, *J. Geophys Res., 90*, 1595, 1985.

Richmond, A. D., and Y. Kamide, mapping electrodynamic features of the high latitude ionosphere from localized observations: Technique, *J. Geophys. Res., 93*, 5741, 1988.

Ridley, A. J., G. Lu, C. R. Clauer, and V. O. Papitashvili, Ionospheric convection during nonsteady interplanetary magnetic field conditions, *J. Geophys. Res., 102*, 14,563, 1997.

Ridley, A. J., G. Lu, C. R. Clauer, and V. O. Papitashvili, A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique, *J. Geophys. Res., 103*, 4023, 1998.

Ruohoniemi, J. M., and R. A. Greenwald, The response of high-latitude convection to a sudden southward IMF turning, *Geophys. Res. Lett., 25*, 2913, 1998.

Saunders, M. A., M. P. Freeman, D. J. Southwood, S. W. H. Cowley, M. Lockwood, J. C. Samson, C. J. Farrugia, and

T. J. Hughes, Dayside ionospheric convection changes in response to long period interplanetary magnetic oscillations: determination of the ionospheric phase velocity, *J. Geophys. Res., 97*, 19,373, 1992.

Schindler, K., M. Hesse, and J. Birn, General magnetic reconnection, parallel electric fields, and helicity, *J. Geophys. Res., 93*, 5547, 1988.

Sckopke, N., G. Paschmann, G. Haerendel, B. U. Ö. Sonnerup, S. J. Bame, T. G. Forbes, E. W. Hones, Jr., and C. T. Russell, Structure of the low latitude boundary layer, *J. Geophys. Res., 86*, 2099, 1981.

Shepherd, S. G., R. A. Greenwald, and J. M. Ruohoniemi, A possible explanation for rapid, large-scale ionospheric responses to southward turnings of the IMF, *Geophys. Res. Lett., 26*, 3197, 1999.

Siscoe, G. L., and T. S. Huang, Polar cap inflation and deflation, *J. Geophys. Res., 90*, 543, 1985.

Siscoe, G. L., N. U. Crooker, G. M. Erickson, B. U. Ö. Sonnerup, K. D. Siebert, D. R. Weimer, W. W. White, and N. C. Maynard, Global geometry of magnetospheric currents inferred from MHD simulations, in *Magnetospheric Current Systems, Geophysical Monograph 118*, edited by S. Ohtani, R. Fujii, M. Hesse, and R. L. Lysak, pp. 41-52, American Geophys. Union, Washington, D. C., 2000a.

Siscoe, G. L., G. M. Erickson, B. U. Ö. Sonnerup, N. C. Maynard, K. D. Siebert, D. R. Weimer, and W. W. White, Deflected magnetosheath flow at the high-latitude magnetopause, *J. Geophys. Res., 105*, 12,851, 2000b.

Siscoe, G. L., G. M. Erickson, B. U. Ö. Sonnerup, N. C. Maynard, K. D. Siebert, D. R. Weimer, and W. W. White, Global role of $E_\parallel$ in magnetopause reconnection: An explicit demonstration, in press *J. Geophys. Res.*, 2000c.

Sonnerup, B. U. Ö., Theory of the low-latitude boundary layer, *J. Geophys. Res., 85*, 2017, 1980.

Taguchi, S., M. Sugiura, J. D. Winningham, and J. A. Slavin, Characterization of the IMF B_Y-dependent field-aligned currents in the cleft region based on DE 2 observations, *J. Geophys. Res., 98*, 1393, 1993.

Weimer, D. R., Models of high-latitude electric potential derived with least error fit of spherical harmonic coefficients, *J. Geophys. Res., 100*, 19,595, 1995.

Weimer, D. R., An improved model of ionospheric electric potentials including substorm perturbations and application to the GEM November 24, 1996 event, *J. Geophys. Res., 106*, 407, 2001.

White, W. W., G. L. Siscoe, G. M. Erickson, Z. Kaymaz, N. C. Maynard, K. D. Siebert, B. U. Ö. Sonnerup, and D. R. Weimer, The magnetospheric sash and the cross-tail S, *Geophys. Res. Lett., 25*, 1605-1608, 1998.

Wygant, J. R., R. B. Torbert, and F. S. Mozer, Comparison of S3-3 polar cap potential drops with the interplanetary magnetic field and models of magnetopause reconnection, *J. Geophys. Res., 88*, 5727, 1983.

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Figure 1. (a) A plot of B_Z versus distance from the Earth at 2:06 minutes simulation time to show the position of the magnetopause. (b-d) Plots of B_Y at 2:06, 2:09, and 2:11 minutes illustrating the width of the reversal in B_Y in the solar wind, just inside the bow shock, and as it approaches the magnetopause.

Figure 2. The (a) positive difference current maximum and the (b) positive difference potential maximum versus time after first contact of the reversal front with the nose. Both are for the difference cells in the polar cap in Plates 7 and 2, respectively. The first sign of merging was found at t = 3 min.

Figure 3. Initial portions of the maximums in both negative and positive difference cells for (a and c) currents and (b and d) potentials versus time after the first contact.

Figure 4. (a) B_Z plotted against distance from the Earth, showing the location of the magnetopause. (b, d, and f) The magnitude of the parallel current on the X axis at t = 0, 1, and 2 min, respectively. Note the reversal of the current as the change to negative B_Y impacts the magnetopause. (c, e, and g) B_Y along the X axis for the same times.

Plate 1. Potential patterns for the Northern Hemisphere every 4 minutes starting at t = 0, i.e., when the reversal front impacts the magnetopause.

Plate 2. Potential difference patterns using the pattern at t = -2 minutes as the reference. The patterns are shown every 4 min, at the same times as for the potential patterns in Plate 1.

Plate 3. Field lines traced from near the dusk simulation boundary at 8 different X locations and 5 different Z locations at 12 min. The spatial differences in X correspond to approximately 1 minute of travel time in the unshocked solar wind (specific coordinates of the starting points are given in Plates 4 and 5). The plane is colored with the magnitude of B_Y which shows the progression of the reversal front, draping around the nose and extending back along the flanks. The bow shock is located by the intensification of B_Y.

Plate 4. Three-dimensional views looking from the Sun of the field lines traced in Plate 3 at the first three times used for the potential patterns in Plate 1.

Plate 5. Three-dimensional views looking from the Sun of the field lines traced in Plate 3 at the last three times used for the potential patterns in Plate 1.

Plate 6. Field-aligned current patterns for the Northern Hemisphere every 4 minutes starting as the reversal front impacts the magnetopause at t = 0 min.

Plate 7. Field-aligned current difference patterns for the same times as those shown in Plate 6. The reference pattern for the current differences is that for t = -2 min.

Plate 8. Plots of the "first" open field lines with footprints in the ionosphere within 50 km of the last closed field line boundary for selected times. The equatorial plane is shaded with the magnitude of B_Y and obscures all traced field lines below the plane. (a) The initial pattern is controlled by positive B_Y. (f) The pattern at t = 48 min, after the change has been completed is a mirror image of (a). (b-e) Pattern changes every 2 minutes starting at t = 4 min.

Plate 9. Plots of the "first" open field lines with footprints in the ionosphere within 25 km of the last closed field line boundary. In addition the last closed field lines are plotted in black. (a) Pattern for t = 0 minutes for comparison with Plate 8a. (b, c, d, and f) Evolution of the pattern covering the time of beginning of Northern Hemisphere merging with the negative B_Y. Note the double-hooked field lines in (d), which indicate that they were first merged with positive B_Y and then merged again with the new negative B_Y. Two of these are singled out in (e), along with the last closed field lines.

Plate 10. 3-dimensional views looking from the Sun of the last closed field lines and the "first" open field lines with the 25 km criterion (see Plate 9). The plots are separated by 2 min, and cover the initial interaction at the nose. All lines have been terminated beyond X = -15 R_E.

Plate 11. Field-aligned currents in (a) the $Z = 4$ R_E plane, i.e., below the cusp and (b) the $Z = 12$ R_E plane, i.e., above the cusp. In (a) the intersection of the last closed field line boundary with the plane at $Z = 4$ R_E is shown in red. It highlights both the magnetopause and the open/closed boundary defining the polar cap. In each plane the progression of the reversal front is marked by the asterisks at the top of the panels. Since the reversal front would in nature be moving to the left, we have displayed the patterns with time also moving to the left, as indicated by the arrow.

Plate 12. A progression of 4 field lines traced from near the simulation boundary on the flanks. The simulation time is t = 0 minutes while the pattern is under control of positive B_Y. (a)-(d) show views of the XY plane from above. (e)-(h) show views in the YZ plane from the Sun. The start points in each case were from X = -8.6, -9.4, -10.2, and -11.1 R_E. The Y, Z coordinates of the start points are (a)and (e) -50, +1, (b) and (f) +50, +1, (c) and (g) -50, -1, and (d) and (h) +50, -1 R_E. The asterisks denote the starting location within each plot of the field line traces. Green lines remain interplanetary field lines, while blue (red) field lines trace to the northern (southern) ionosphere. Note the increasing tilt of the field lines as one moves from field line to field line toward the magnetopause.

Plate 13. Field lines traced from near the dusk boundary of the simulation box and colored with $E \cdot J$. A total of 41 traces were started at equal intervals between X = -14 and -9 R_E at Y = 50 and Z = 0 R_E. The double asterisk indicates the start of the trace while the symbol **E** indicates the end. As shown by the arrow, time runs to the left, i.e., in the direction of the propagation of the reversal front. Note that the energy conversion at the nose turns negative at t = 1 minute and then returns to being positive after the IMF reversal front has fully passed. The newly merged IMF lines are dragged back through the magnetosheath on both sides, following the progression of the reversal front.