Direct Effects of the IMF on the Inner Magnetosphere

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Several direct and well-established inner-magnetospheric effects following changes in Interplanetary Magnetic Field direction find natural explanations in terms of the Rice Convection Model. A southward turning of the IMF normally causes an increase in both cross-polar-cap potential drop and in polar-cap size. In RCM simulations, these two factors combine to produce a condition termed “undershielding,” characterized by increased penetration of the dawn-dusk convection electric field into the inner magnetosphere, erosion of the nightside plasmapause, and drainage of plasmaspheric plasma via plumes that stretch to the dayside magnetopause. A northward turning of the IMF causes a condition known as “overshielding,” characterized by dusk-to-dawn directed electric fields across the inner magnetosphere. A recent run with the coupled BATSRSU/RCM computer code suggests that the overshielding electric field peaks 12-25 minutes after the IMF direction at the dayside magnetopause turns northward, and that this time delay is about the same on both the day- and night-sides of the Earth. Changes in solar wind and IMF conditions may also influence the inner magnetosphere in more subtle ways, through their influence on the plasma-sheet plasma distribution represented by the specific entropy. Results of combining a Tsyganenko magnetic field model and Tsyganenko-Mukai representation of plasma-sheet plasma suggest that a northward turning of the IMF may reduce the specific entropy in the plasma sheet and cause interchange instability in the plasma sheet and auroral ionosphere.

1. INTRODUCTION

Penetration to the low- and mid-latitude ionosphere and inner magnetosphere of electric fields associated with the interaction of the flowing solar wind plasma with Earth’s magnetosphere is known to have important practical effects on the near-Earth plasma environment and on manmade systems. This paper attempts a brief summary of the effects that changes in the solar wind and Interplanetary Magnetic Field (IMF) have on the inner magnetosphere and underlying ionosphere. Of particular interest is the response of the inner magnetosphere to changes in the direction and strength of the IMF. In the inner magnetosphere, electric field (E×B) and gradient/curvature drifts determine the dynamics of the inner edge of the plasma sheet and the buildup and evolution of the ring current. At subauroral latitudes magnetospherically generated electric fields control the dynamics of the plasmapause and the formation and dynamics of the main ionospheric trough. Under steady solar wind and IMF conditions, the inner magnetosphere
becomes shielded from the effects of the cross-tail magnetospheric convection electric field by magnetic field-aligned currents (the so-called Region 2 current system) that couple the inner plasma sheet to the underlying ionosphere. Disruption of this current system in response to changes in solar-wind/magnetosphere coupling causes inward penetration of convection electric fields that can have profound ionospheric implications, changing ionospheric layer heights and leading to the generation and evolution of a number of different plasma instability processes.

Our discussion proceeds mainly from the viewpoint of the Rice Convection Model (RCM), a computer model specifically formulated to model the physics of the inner magnetosphere and its coupling to the ionosphere. In Section 2 we describe how empirical models of solar-wind/magnetosphere coupling are used to estimate the RCM's principal electromagnetic inputs, the cross-polar-cap electric potential drop and the structure of the magnetospheric magnetic field. In Sections 3 and 4 we summarize well-established ways in which the inner magnetosphere reacts to southward and northward turnings of the IMF. In addition, Section 4 also includes new results from a coupled MHD/RCM code that address the time delay of the inner magnetospheric response to a northward turning of the IMF. Section 5 discusses possible effects of IMF-associated changes in the specific-entropy function $PV^{5/3}$ at the RCM's tailward boundary, and the inner-magnetospheric implications of these changes.

2. RCM—ASSUMPTIONS AND INPUT PARAMETERS

The RCM was specifically designed for accurate treatment of the closed-field-line, slow-flow part of the magnetosphere. In the model, inertial currents are assumed negligible, precluding the inclusion of MHD waves and limiting the model to regions where the flows are highly subsonic. Magnetic flux tubes are assumed to contain plasma in bounce equilibrium. Cross-field motions of charged particles are assumed to consist of $E \times B$, gradient, and curvature drift. The model assumes elastic pitch-angle scattering, resulting in isotropic pitch-angle distributions. For a detailed discussion of the formulation of the RCM, see Toffoletto et al. [2003] and references therein.

The ionospheric conductance distribution due to sunlight and other non-auroral processes is calculated by field-line-integrating an IRI-90 ionospheric model [Bilitza et al., 1993] combined with the MSIS-90 empirical neutral atmosphere [Hedin, 1991]. Conductance enhancements associated with auroral electron precipitation are computed assuming that electrons scatter in pitch angle at a fixed fraction of the strong-pitch-angle-scattering rate and using
the empirical formulas of Robinson et al. [1987]. The effects of neutral winds are currently neglected.

In the RCM runs discussed here, the magnetosphere is assumed to be initially empty, and the upward flow of ionospheric ions directly into the RCM-modeled inner magnetosphere is neglected. Magnetospheric plasma is assumed to enter the RCM modeling region through its tailward boundary, where the distribution is assumed to have the form of either a Maxwellian or kappa distribution. For standard RCM runs, the values of $PV^{5/3}$ and $nV$ at the tailward boundary are estimated empirically, a subtle issue that will be discussed further in Section 5.

The cross-polar-cap potential drop, which is a crucial input for the RCM because it measures the total strength of convection, is estimated from solar-wind data using an empirical formula developed by Boyle et al. [1997], but set to linearly saturate at 200 kV, in accordance with the observations of Hairston et al. [2003]. That formula implies that the polar-cap potential drop depends strongly on the southward component of the IMF. Magnetospheric magnetic fields within the RCM modeling region have been estimated in various ways. The semi-empirical Hilmer-Voigt [1995] magnetic field model was used for the older RCM runs discussed in Sections 3 and 4, while a T96 model [Tsyganenko and Stern, 1996] was used to obtain the results shown in Section 5. For the coupled MHD-RCM run discussed in Section 4, the MHD code [De Zeeuw et al., 2004] supplies theoretically computed magnetic fields.

3. ELECTROMAGNETIC EFFECTS OF A SOUTHWARD TURNING OF THE IMF

As predicted by Schield et al. [1969], Vasyliunas [1970], and Wolf [1974], magnetic-field aligned currents (the so-called “region-2 Birkeland currents”) flow between the inner plasma sheet and ionosphere and act to shield the inner magnetosphere from the main effects of the dawn-dusk convection electric field. However, the shielding is clearly ineffective in times when convection is changing with time. For example, suppose that solar wind and IMF conditions are steady for a long period of time, resulting in a long period of steady convection such that the inner edge of the plasma sheet is able to adjust itself to shield the inner magnetosphere effectively. Then the IMF turns southward, causing a sudden increase in convection and leaving the region-2 currents inadequate to shield the inner magnetosphere under the changed conditions. Much of the dawn-dusk convection field will now penetrate into the near-Earth inner magnetosphere. The westward electric field across the night side will cause the plasma-sheet inner edge to move sunward, resulting in a gradual increase of the region-2 currents and more effective inner-magnetosphere shielding, but that takes time. The
temporary penetration of the dawn-dusk field into the inner magnetosphere after an increase in convection is termed “undershielding.” Figure 1 shows two electric equipotential patterns, as computed by the RCM for a time of good shielding just before a sudden increase in cross-polar-cap potential drop, and just after the potential drop increase. The potential patterns are shown in the magnetospheric equatorial plane. The electric field that penetrates into the inner magnetosphere after the increase departs significantly from a simple dawn-dusk orientation, mainly because of the effects of the sharp conductance jumps associated with the dawn and dusk terminators; note the computed westward electric field near Earth in the midnight-to-dawn sector and eastward electric field in the dawn-to-noon sector. Figure 2 shows very good agreement between RCM-computed downward $E\times B$ drift near the ionospheric equator and corresponding average velocities derived by Fejer and Scherliess [1997] from Jicamarca radar data, using statistical analysis of many convection-increase events. Detailed theoretical discussions of shielding can be found in Wolf [1983] and Spiro et al. [1988].

Recent years have produced one major change in the 1970s picture of the physics of undershielding. It is now clear that the undershielding that occurs after a southward IMF turning is not due entirely to the potential drop increase, but also to a change in the magnetic configuration. Wolf et al. [1982] presented theoretical arguments showing that effective shielding requires that dayside magnetic flux tube volume values exceed nightside values, while Fejer et al. [1990] applied these arguments to the effect of magnetic configuration changes on low-latitude perturbation electric fields. Figure 3 displays magnetic field lines in the noon-midnight plane computed for steady-state conditions using the RCM coupled to an equilibrium magnetic field solver that maintains approximate force balance between the RCM-computed plasma distribution and the inner-magnetosphere magnetic field [Toffoletto et al., 2000]. The effect of a southward IMF turning is twofold: (1) an increase in the dawn to dusk convection electric field; and (2) an increase in the tail-lobe magnetic field and stretching of inner-plasma-sheet flux tubes. Because of this stretching, the equatorial mapping point of a given point arising from the nightside auroral ionosphere moves tailward; this stretching corresponds to $E\times B$ drift in an eastward induction electric field that exists in the tail but does not map to the ionosphere. This eastward induction electric field tries to move the inner edge of the plasma sheet tailward, increasing the flux tube volume and reducing or eliminating the shielding and thus contributing to the undershielding. The eastward induction field and westward potential field (undershielding) oppose each other near the equatorial plane; however, an ionospheric observer sees only the westward potential field,
because the induction field does not map to the ionosphere. Thus, both the increase in polar-cap potential and the tail field-line stretching and associated increase in flux tube volume contribute substantially to undershielding following a southward turning of the IMF.

Plate 1 shows the evolution of the plasmapause in an RCM simulation of the event of 10 July 2000, for which IMAGE EUV data have been analyzed by Goldstein et al. [2003a]. The plasmapause evolution was modeled by representing the assumed initial plasmapause in terms of a string of test particles, then following the string as the particles $E \times B$ drift in the model electric field; test particles are added by interpolation when adjacent points get too far apart. The following features should be noted:

(i) There is always a drainage tail. Theoretical models of plasmapause shape based on the assumption of time-dependent convection have predicted such drainage tails for many years (e.g., Grebowsky [1970]), and early satellite observations showed regions of high density outside the main plasmasphere (Chappell [1972] and references therein). However, there was a long-running controversy about whether those outer high-density regions were detached from the main plasmapause or connected to it, as suggested by the models. EUV observations from IMAGE seem to have settled that controversy in favor of drainage plumes that extend out from the main plasmapause [Sandel et al., 2001].

(ii) In this simulation, a plasmapause protuberance that was evident near local noon at 0000 UT rotated east over the next four hours and grew somewhat. Then the strong convection caught it and made it into a second drainage tail. Though the protuberance at 0000 UT depended on the way the code was initialized and is not necessarily physical, some instances of double drainage tails have been observed [Goldstein et al., 2004a].

(iii) The long period of strong convection on 10 July 2000 caused the simulated drainage tail to become very thick, filling a large part of the dayside magnetosphere, a phenomenon that was first noted many years ago [e.g., Grebowsky, 1970; Chappell, 1972].

(iv) The plasma that filled the drainage tail and escaped to the magnetopause boundary layer came from the main plasmasphere, which has eroded substantially on the night side. The simulated plasmapause radius at local midnight decreased almost a factor of two between 0420 and 0800. EUV observations [Goldstein et al., 2003a] documented the severe erosion of the real plasmasphere in this event. The observed motion of the plasmapause to within about 3 $R_E$ of Earth's center is well reproduced by the model.

A southward turning of the IMF that leads to sustained and substantial southward IMF causes severe convection effects in the inner magnetosphere. Fresh plasma is injected into the ring current from the plasma sheet, a process that
has been extensively studied with several different ring-current models [e.g., Fok and Moore, 1997; Kozyra et al., 2002; Jordanova et al., 2003; Chen et al., 2003], and also by a set of models which calculate electric fields that are self-consistent with the ring-current plasma—the Rice Convection Model [Garner et al., 2004], the Comprehensive Ring Current Model [Fok et al., 2001; Ebihara et al., 2004], and the RAM model [Liemohn and Ridley, 2002]. Most of the self-consistent calculations exhibit two features that are in striking agreement with recently discovered observational features. The storm simulations of Garner et al. [2004], for example, show strong poleward/outward electric fields in the dusk-midnight sector, which were observed near the equatorial plane [Rowland and Wygant, 1998; Burke et al., 1998] and also in the subauroral ionosphere [Foster and Vo, 2002], where they are termed Subauroral Polarization Stream (SAPS) events. Self-consistent simulations [e.g., Fok et al., 2003] as well as calculations based on a high-resolution version of the AMIE empirical model supplemented by a penetration electric field [Jordanova et al., 2003] have shown a tendency for the main-phase ring-current-ion pressure to peak near local midnight (and sometimes east of midnight), in agreement with energetic-neutral-atom results from IMAGE [Brandt et al., 2002].

4. ELECTROMAGNETIC EFFECTS OF A NORTHWARD TURNING OF THE IMF

From an inner magnetosphere (RCM) point of view, the effect of a northward turning of the IMF is basically the opposite of the effect of a southward turning. The cross-polar-cap potential drop decreases, and the magnetic field configuration changes in such a way that the polar cap shrinks and the inner-plasma-sheet magnetic field lines become less stretched. Both of these changes lead to a condition of “overshielding.” In this condition, the region-2 Birkeland currents are stronger than necessary to shield the inner magnetosphere from the dawn-dusk convection electric field, resulting in a dusk-to-dawn-directed electric field in the inner magnetosphere. Figure 4 shows a typical RCM-computed overshielding pattern. The overshielding phenomenon was first identified in Jicamarca radar data by Kelley et al. [1979].

Although RCM calculations predict typical lifetimes of undershielding electric fields that are in good agreement with observations, RCM-computed overshielding electric fields have noticeably shorter lifetimes [Fejer et al., 1990], even when the time-dependent magnetic field effect is included [Sazykin, 2000]. In other words, when the polar-cap potential drop changes and magnetic field changes are symmetric for undershielding and overshielding cases, the response of the ionospheric penetration electric field is not.
A possible reason for this discrepancy is our lack of knowledge of how the magnetic field responds to IMF northward turnings. The problem can only be addressed with coupled RCM-MHD codes that compute the magnetic field in a self-consistent manner (see below).

One of the first discoveries from the IMAGE EUV instrument was the occasional development of a shoulder on the plasmapause [Goldstein et al., 2002], which was quickly interpreted as the result of overshielding. The near-Earth electric potential pattern of Figure 4 shows eastward electric field before dawn and westward electric field after dawn. Goldstein et al. [2002, 2003b] used the Magnetospheric Specification Model, which does not compute the electric field but uses a prescribed electric field pattern based on typical RCM results, to show that the pre-dawn eastward electric field moves the plasmapause out in that local time sector, while the westward post-dawn field moves it earthward; the result is development of a shoulder in the plasmapause during the period of overshielding. If northward IMF continues for some hours after the period of overshielding, convection near the plasmapause is weak, and the shoulder approximately corotates around into the day side. Goldstein et al. [2002] showed the effectiveness of overshielding in a case where the IMF switched quickly from southward to northward, while Goldstein et al. [2003b] showed a larger shoulder that resulted when the IMF underwent a longer and more gradual transition from southward to northward IMF.

Although the RCM has been used for many years to study prompt-penetration electric fields, it has never been possible using the RCM alone to make detailed predictions about the timing of these fields in response to solar-wind changes, because we lacked detailed information on the time-dependence of the RCM boundary conditions. For example, we typically assumed that the potential at the RCM poleward boundary switched suddenly in response to a sudden change in IMF, but the truth must be more complicated: the IMF change must be felt first near local noon and then gradually spread toward the night side. We have similarly lacked a quantitative representation of how the magnetic field configuration responds to an IMF change, as a function of time.

Embedding Rice Convection Model machinery in the BATS-R-US global MHD code [De Zeeuw et al., 2004] promises to allow more detailed theoretical analysis of how the inner-magnetospheric electric field reacts to a specified change in IMF, since the new coupled BATSRUS/RCM code treats solar-wind/magnetosphere coupling and the inner and outer magnetospheres self-consistently. The MHD code computes the time evolution of both the high-latitude potential distribution and the magnetic reconfiguration as a function of time and provides those inputs to the RCM. The RCM uses its many-species
representation to keep track of the inner-magnetospheric particle distribution and passes its pressure distribution back to the MHD code, which nudges its pressures to maintain approximate agreement with the RCM.

Plate 2 shows the time-dependent ionospheric-potential distribution after a northward turning of the IMF. The results displayed are similar to those reported by De Zeeuw et al. [2004], except that, in the present run, the RCM uses its own computational machinery to compute Birkeland currents and electric potential in its modeling region. For the earlier run, the RCM used MHD-computed Birkeland currents and potentials. The two procedures should give the same results in principle, but the RCM uses a finer grid in the ionosphere, for better numerical accuracy. In order to study the penetration-electric-field problem, the present run computes ionospheric potentials down to the equator, whereas the low-latitude boundary for the earlier run was set at about 51 degrees latitude.

For the present simulation, the solar wind was assumed steady for eight hours, with \( n=5 \text{ cm}^{-3} \) (protons), \( V=400 \text{ km/s} \), \( B_x=B_y=0, B_z=-5 \text{ nT} \). At 0800 UT, \( B_z \) was switched to +5 nT at the sunward boundary of the MHD modeling region (\( X=32 R_E \)). In the simulation, the northward IMF hit the dayside magnetopause at about 0809 UT. The simplest way to get a theoretical estimate for when the northward IMF should arrive at the dayside magnetopause would be to divide the geocentric distance of the sunward edge of the modeling region by the solar wind speed, which gives a time delay of 8.5 minutes. There are two obvious sources of error in this simple estimate: (i) the magnetopause stands upstream from the Earth; (ii) the speed slows drastically as the flow passes through the bow shock and approaches the magnetopause. Since the simple estimate agrees well with the simulation, apparently effects (i) and (ii) approximately cancel in the present case.

It is clear from Plate 2 that the effect of the northward turning on the polar-cap electric field distribution begins at local noon and gradually propagates across the polar cap to the night side. Remarkably, the same is not true of the penetration field: it intensifies and then de-intensifies but maintains basically the same spatial pattern throughout the event. This may be due, in part, to the fact that the overshielding electric potential is basically a 2D dipole pattern. The higher multipole moments that describe the concentration of the effect in the local-noon region shortly after 0809 UT die off more rapidly with increasing colatitude than the dipole term does and consequently do not strongly affect the field that penetrates to the low-latitude ionosphere.

Figure 5 shows a quantitative index of electric-field penetration, in the form of the total potential difference along the low-latitude ionospheric boundary of the RCM at 9.84 degrees latitude. The penetration potential increases
gradually over the first ten minutes after the northward turning at the magnetopause, peaks 12-25 minutes after the northward turning, then decays on a time scale ~30 minutes.

Considerable work has been done with the EUV instrument on the IMAGE spacecraft, comparing the time-dependence of electric fields at the nightside plasmapause with IMF $B_z$ or solar wind $E_y$ (e.g., Goldstein et al., 2003a, 2003c, 2004c, Goldstein and Sandel, 2004). That work concentrates mostly on southward turnings of the IMF and concludes that plasmasphere erosion is delayed about 30 minutes from the arrival of the IMF turning at the magnetopause. Examination of sharp northward turnings in the plots from Goldstein et al. [2004c] suggests that a time delay ~30 minutes applies also to northward turnings. It is not clear how much significance to attach to the difference between the IMAGE-observed time delay (~30 minutes) and our preliminary theoretical estimate (12-25 minutes). About 2-3 minutes of the difference can be explained by the fact that Goldstein and collaborators assume that plasma travels at full solar-wind speed between the upstream spacecraft and the magnetopause, whereas we use the MHD model to calculate the magnetopause arrival time. More realistic modeling with realistic ionospheric conductances, plus more detailed study of measured time profiles of the plasmapause electric field for specific northward-turning events, will be needed to determine whether there is a meaningful discrepancy between theory and observations with regard to the magnitude of time delay.

Dayside and nightside plasmapause responses often seem to occur with comparable delays (J. Goldstein, private communication), in agreement with the simulation. In some substorm events, the effect seems to propagate from night side to day side [Goldstein et al., 2004b, c, Goldstein and Sandel, 2004]. Of course, our present simulation does not include substorm effects.

It should be noted that this simulation, the first in which the coupled BATSRUS/RCM calculated electric fields in the low-latitude ionosphere, assumed uniform ionospheric conductance (4 S per hemisphere Pedersen conductance, zero Hall). Thus the results shown in Figures 6-7 must be regarded as preliminary, since experience has shown the importance of conductance variations on the local-time distribution of the electric penetration potential. Nonetheless, these results represent an important first step in fully self-consistent modeling of prompt-penetration electric fields.

5. EFFECT OF PLASMA-SHEET $P_{\phi}^{5/3}$

As discussed in Section 2, considerable effort has been expended in development of empirical algorithms for
estimating polar-cap potential drop and magnetospheric magnetic fields as functions of solar-wind parameters. Much less effort has been devoted to algorithms that would allow empirical estimation of $nV$ and $PV^{5/3}$ at the RCM's tailward boundary. Garner et al. [2003] produced a first set of estimates by combining a Tsyganenko [1989] magnetic field model with several statistical studies of plasma-sheet parameters. That study has recently been redone using a Tsyganenko and Stern [1996] magnetic field and the new Tsyganenko-Mukai [2003] empirical plasma model. Sample results for the most crucial parameter $PV^{5/3}$ are shown in Figure 6 for two different solar-wind conditions, one with southward IMF and one with northward.

Figure 6 illustrates two difficulties involved in using presently available empirical models to estimate $PV^{5/3}$ at any given time:

(i) For southward IMF, $PV^{5/3}$ shows a huge maximum near $X=−28, Y=0$ in the case of southward IMF, which is due to very weak equatorial magnetic fields in that region in the T96 model; that makes the flux-tube volume large. It is not clear whether such a peak is ever typical of the real plasma sheet for southward IMF. Its occurrence in the Tsyganenko and Stern [1996] magnetic field model might result from inclusion, in the averaging process, of periods when $B_z$ is southward at $X∼−28$ due to occurrence of a neutral line earthward of the observing spacecraft. A configuration where $PV^{5/3}$ decreases tailward, as in a region tailward of $X=−28$ in the bottom panel of Figure 6, would be strongly interchange unstable, so it is not clear that such a gradient in $PV^{5/3}$ could actually exist for extended periods.

(ii) $PV^{5/3}$ systematically increases tailward through the inner plasma sheet, which means that the value supplied to the RCM depends substantially on where the boundary is placed. This is a symptom of the pressure-balance inconsistency [Erickson and Wolf, 1980]. Nevertheless, it is clear from Figure 6 that $PV^{5/3}$ values in the inner plasma sheet ($−20 < X < −10$) are generally larger for southward IMF than for northward. This suggests that a northward turning of the IMF would cause a reduction in $PV^{5/3}$ at the RCM tailward boundary, if that boundary is held fixed in space. This implies that, shortly after a northward turning of the IMF, low-$PV^{5/3}$ flux tubes may exist tailward of higher-$PV^{5/3}$ tubes. Such a configuration is interchange unstable.

Plate 3 shows results from an RCM simulation of the March 31, 2001 magnetic storm, in which $PV^{5/3}$ at the tailward boundary was varied in time, based on estimates from the Tsyganenko [2003] storm-time magnetic field model and the Tsyganenko-Mukai [2003] plasma model. Strong interchange instability occurs several times in the simulation, and Plate 3 shows snapshots from one such period. Low-$PV^{5/3}$ flux tubes (green in the figure) are
supplied through the tailward boundary, and interchange fingers develop, with the low-$PV^{5/3}$ flux tubes swept rapidly into the near-Earth part of the plasma sheet. Differential gradient/curvature drift, which becomes increasingly important near the Earth, tends to blur the fingers when they get to the inner magnetosphere. It should be remarked that the north-south component of the IMF is not the only solar-wind parameter that affects $PV^{5/3}$, according to the Tsyganenko/Tsyganenko-Mukai combined models. Solar-wind density and velocity also have effects, which were included in the simulation shown in Plate 3.

We should also note that if the reduction in plasma-sheet $PV^{5/3}$ occurs near the end of the main phase of a magnetic storm, when $PV^{5/3}$ is high in the ring-current region, then the interchange instability extends deeper into the inner magnetosphere and is able to transport the higher density main-phase ring current plasma outward [Sazykin et al., 2002], speeding storm recovery.

From these results we infer that a northward turning of the IMF may generate interchange instability in the plasma sheet, a possibility that was pointed out earlier by Golovchanskaya et al. [2002] in the context of explaining auroral-arc structures. However, our theoretical argument rests on the highly uncertain assumption that the Tsyganenko/Tsyganenko-Mukai combined models can provide a valid estimate of time variations in plasma-sheet $PV^{5/3}$ in the period immediately after a northward turning of the IMF.

6. SUMMARY

Some effects of IMF $B_z$ changes on the inner magnetosphere are well-established and can be understood, at least to zero order, in terms of changes in the electromagnetic inputs to the RCM, particularly the polar-cap potential and the magnetic-field configuration. These effects include overshielding and undershielding, SAPS events, ring-current injection, as well as plasmaspheric erosion, drainage tails, and shoulders.

One detail that is not yet well established, but is ripe for both theoretical and observational investigation, is the exact time dependence of the prompt-penetration electric field in response to a step function change in IMF $B_z$. We have made a theoretical prediction concerning this time dependence, based on a simulation with the new BATSRUS/RCM coupled code.

Another area of current study is the effect of IMF changes on plasma parameters in the plasma sheet. Empirical models suggest that a northward turning of the IMF may reduce inner-plasma-sheet $PV^{5/3}$ and trigger interchange instability in the plasma sheet.
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FIGURE AND PLATE CAPTIONS

Figure 1. Equipotential diagrams just before and just after a sudden increase in polar cap potential from 45 keV to 90 kV. The view is of the equatorial plane, with the Sun to the left. The corotation electric field is not included in the display, though it was included in the simulation. From Sazykin [2000].

Figure 2. Comparison of RCM-calculated prompt-penetration-induced downward drifts with those derived statistically from observations with the Jicamarca radar. Observational results are shown for times just after an increase in AE and 60 minutes later (bottom plot). RCM results are shown for times just after a 33 kV increase in potential and 10 minutes later (middle plot), then 60 minutes later (bottom plot). Adapted from Fejer and Scherliess [1997].

Figure 3. Magnetic field lines in the noon-midnight meridian. The top diagram shows a Tsyganenko model, relaxed to equilibrium. The lower diagram shows how 50 minutes of strong adiabatic convection affects the configuration. The dashed curve in each diagram maps to 68 latitude. From Toffoletto et al. [2000].

Figure 4. RCM-computed equatorial equipotentials immediately after a factor-of-two reduction in polar-cap potential. From Sazykin [2000].

Figure 5. Total magnetospherically generated potential drop along the equator as a function of UT, after the northward turning of the IMF.

Figure 6. The top and middle panels show equatorial contour plots of \( \log_{10}(PV^{5/3}) \) for northward and southward IMF, in units of nPa(R_E/nT)^5/3. The assumed solar wind parameters are \( n=5 \) cm\(^{-3}\), \( V=400 \) km/s, \( B_x=B_y=5 \) nT, for both panels, but \( B_z=+5 \) nT in the top panel and \( -5 \) nT for the middle panel. The bottom panel shows \( \log_{10}(PV^{5/3}) \) along the \(-X\) axis.

Plate 1. RCM simulation of plasmapause evolution for an event that occurred 10 July 2000. In each panel, the upper plot shows model inputs (polar cap potential (blue) and \( Dst \) (black)) as a function of time, with the red bar indicating the time for the plasmapause plot. In the lower part of each panel, orange indicates the computed plasmasphere, and black contours show instantaneous streamlines for cold plasma. The view is of the equatorial plane, with the Sun to the left. The connected points shown in blue are IMAGE EUV measurements of the plasmapause location. The five panels represent times (a) UT=0, more than 4 hours before the beginning of the strong convection; (b) UT=0420, just before the strong convection; (c) UT=0520, after about an hour of strong convection; (d) UT=0800, the end of strong convection; (e) UT=0930, in a low-convection period.
Plate 2. Ionospheric potentials computed by the coupled BATSRUS/RCM code after a northward turning of the IMF. The views are from high above the north pole, with the Sun to the left. The black circles represent 30 and 60 degrees latitude. The northward turning was imposed at the sunward boundary of the simulation box (X=32 R_E) beginning at 0800 UT. The color bar shows electric potential values ranging from –20 kV to +20 kV. The orange-yellow colors on the dusk side at low- and mid-latitudes represent overshielding, as do the blue colors on the dawn side.

Plate 3. Equatorial contour plots of RCM-computed $Pr^{5/3}$ for 12:30, 12:40, and 13:00 UT in a simulation of the March 31, 2001 magnetic storm.
Figure 1. Equipotential diagrams just before and just after a sudden increase in polar cap potential from 45 keV to 90 kV. The view is of the equatorial plane, with the Sun to the left. The corotation electric field is not included in the display, though it was included in the simulation. From Sazykin [2000].

Figure 2. Comparison of RCM-calculated prompt-penetration-induced downward drifts with those derived statistically from observations with the Jicamarca radar. Observational results are shown for times just after an increase in AE and 60 minutes later (bottom plot). RCM results are shown for times just after a 33 kV increase in potential and 10 minutes later (middle plot), then 60 minutes later (bottom plot). Adapted from Fejer and Scherliess [1997].

Figure 3. Magnetic field lines in the noon-midnight meridian. The top diagram shows a Tsyganenko model, relaxed to equilibrium. The lower diagram shows how 50 minutes of strong adiabatic convection affects the configuration. The dashed curve in each diagram maps to 68° latitude. From Toffoletto et al. [2000].

Figure 4. RCM-computed equatorial equipotentials immediately after a factor-of-two reduction in polar-cap potential. From Sazykin [2000].

Figure 5. Total magnetospherically generated potential drop along the equator as a function of UT, after the northward turning of the IMF.

Figure 6. The top and middle panels show equatorial contour plots of log_{10}(PV^{5/3}) for northward and southward IMF, in units of nPa(R_E/nT)^{5/3}. The assumed solar wind parameters are n=5 cm^{-3}, V=400 km/s, B_x=B_y=5 nT, for both panels, but B_z=+5 nT in the top panel and -5 nT for the middle panel. The bottom panel shows log_{10}(PV^{5/3}) along the -X axis.

Plate 1. RCM simulation of plasmapause evolution for an event that occurred 10 July 2000. In each panel, the upper plot shows model inputs (polar cap potential (blue) and Dst (white)) as a function of time, with the red bar indicating the time for the plasmapause plot. In the lower part of each panel, orange indicates the computed plasmasphere, and white contours show instantaneous streamlines for cold plasma. The view is of the equatorial plane, with the Sun to the left. The connected points shown in blue are IMAGE EUV measurements of the plasmapause location. The five panels represent times (a) UT=0, more than 4 hours before the beginning of the strong convection; (b) UT=0420, just before the strong convection; (c) UT=0520, after about an hour of strong convection; (d) UT=0800, the end of strong convection; (e) UT=0930, in a low-convection period.
Plate 2. Ionospheric potentials computed by the coupled BATSRUS/RCM code after a northward turning of the IMF. The views are from high above the north pole, with the Sun to the left. The black circles represent 30 and 60 degrees latitude. The northward turning was imposed at the sunward boundary of the simulation box ($X=32\ R_E$) beginning at 0800 UT. The color bar shows electric potential values ranging from -20 kV to +20 kV. The orange-yellow colors on the dusk side at low- and mid-latitudes represent overshielding, as do the blue colors on the dawn side.

Plate 3. Equatorial contour plots of RCM-computed $PV^{5/3}$ for 12:30, 12:40, and 13:00 UT in a simulation of the March 31, 2001 magnetic storm.
Figure 1
Figure 2
Penetration potential

Figure 5
Figure 6
Plate 2