Forecasting ionospheric electric fields: An interplanetary coupling perspective

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Understanding of the temporal and spatial development of interplanetary-driven ionospheric convection is evolving rapidly. Detailed comparisons of the IMF measurements by Wind with ionospheric electric field observations by sounding rockets and the Polar spacecraft conclusively demonstrate that signals can interact with the magnetosphere on significantly longer or shorter than nominal advection lag time scales. The antiparallel merging hypothesis of Crooker provides a unifying perspective for interpreting measurements. The timing and location of interactions depend on IMF B_X in such a way that merging can occur simultaneously in the northern and southern hemispheres with interplanetary features that are significantly separated in time on a single streamline. The measurements also show that small-scale variations of the interplanetary electric field couple to the magnetosphere and ionosphere more directly than has been previously reported. These variations are plausible sources of commonly seen temporal and spatial deviations from statistical dayside convection patterns. To quantitatively apply this new understanding to improve space weather forecasting requires multiple satellites in the solar wind.

1. INTRODUCTION

Electric fields produce significant space weather effects on the propagation of transionospheric electromagnetic signals and, through Joule heating, on satellite drag. Predictions of these effects require a thorough grasp of electrical interactions between the interplanetary medium and the Earth's magnetosphere-ionosphere (M-I) system. In some average sense the interplanetary magnetic field (IMF) components in the $Y - Z$ plane affect the sizes, shapes and intensities of ionospheric convection (potential) patterns [*Heppner and Maynard*, 1987. *Weimer* [2001] has developed detailed statistical models for high-latitude potential patterns that use time-averaged values of IMF clock angles and magnitudes, as well as the solar wind densities and velocities as input parameters. Data from monitors upstream in the solar wind allow these models to make one-half- to one-hour predictions of global convection patterns. Experience teaches that significant variability in the intensities and distributions of convective electric fields cannot be accounted for by the statistical parameters. The purpose of this paper is to summarize results from two recent sounding rocket experiments that suggest (1) the dayside ionosphere responds on a much finer scale to interplanetary variations than previously thought, and (2) the timing of near-cusp auroral events depends on all three IMF components [*Maynard et al.*, 2000a]. To help understand the significance of our new results we begin with a brief overview of electric field driven plasma flows in the high-latitude M-I system.

Cowley and Lockwood [1992] developed a conceptually simple picture of how merging between the IMF and earth-bound magnetic field lines adjacent to the dayside cusps drive ionospheric plasma convection. Magnetic tension forces associated with the polarity of IMF B_Y initially cause plasma to move toward the east or west across the cusp before turning into the polar cap [*Heppner and Maynard*, 1987]. Flows continue as newly opened flux tubes are dragged tailward by the solar wind as it propagates a few tens of R_E beyond the Earth. The addition of new open flux to the polar caps expands the adiaroic portion of the open-closed boundaries, thereby communicating the flow to the whole pattern. As used by *Siscoe and Huang* [1985], the term"adiaroic" describes a boundary across which there is no flux transfer. After 5 to 10 min, the "new" open flux becomes "old." While it continues to move tailward as more open flux is added through the cusp, its influence on the flow pattern diminishes. Reconnection of open flux in the magnetotail produces analogous affects on nightside convection patterns that also depend on the IMF orientation, but with a further 30 to 60 min delay.

Originally magnetic merging was assumed to occur along the subsolar magnetopause between antiparallel components of the IMF and the Earth's dipole field [e. g. *Sonnerup*, 1974]. *Crooker* [1979] suggested that many observations were easier to explain if merging were confined to regions on the dayside magnetopause where internal and external magnetic field vectors were completely antiparallel. A consequence of the antiparallel merging hypothesis is that in cases where the IMF has a significant B_Y component the merging line splits into two segments located near the two dayside cusps [*Crooker*, 1985]. For IMF $B_Y > 0$ the merging-line segments are on the evening side of the northern hemisphere cusp and the morning side of the southern hemisphere cusp. The opposite spatial relations between the cusps and the merging-line segments maintain when IMF $B_Y < 0$. While questions relating to the dominance of antiparallel or component merging are not yet resolved, recent sounding rocket results support the antiparallel hypothesis [*Maynard et al.*, 2000a, 2000b].

Two independent sets of observations bear on the problem. *Ridley et al.*, [1997, 1998] investigated responses to changes in the IMF by examining differences from base convection patterns previously esablished using the AMIE technique [*Richmond and Kamide*, 1988]. They found that difference patterns acquired characteristic shapes that depended on the orientation of the new IMF conditions and appeared over most of the polar cap region simultaneously. The difference-pattern magnitude increased linearly with time, maintaining both its position and shape. The communication lag between the time when changed interplanetary conditions first contacted the magnetosphere and difference patterns were established in the ionosphere was 8.4 (±8.2) min. The large variation indicates that interaction processes are still not well defined. The average time for reconfiguration after the change started was 12 min. The second set of response time measurements utilized SuperDARN radar capabilities. *Ruohoniemi and Greenwald* [1998] and *Shepherd et al.*, [1999] showed that changes in convection patterns appeared nearly simultaneously at all local times after abrupt switches in the IMF direction. *Shepherd et al.*, [1999] suggested that draping of the IMF around the magnetopause delays the onset of interactions until they can happen simultaneously along the whole merging line. Their experimental results were viewed as being inconsistent with models requiring single-point reconnection that spreads antisunward at a few km/s.

2. FOUNDATIONS FOR A NEW DIRECTION

On December 2 and 3, 1997, two sounding rockets were launched to the geographic west from the SvalRak range at Ny-Ålesund (78.92° N, 11.95° E). The experimental payloads of both rockets included energetic particle spectrometers to measure the energy distributions of downcoming electrons and ions, double-probe antennas to measure electric field vectors and fluxgate magnetometers to detect signatures of field-aligned currents and propagating magnetohydrodynamic waves [*Maynard et al.*, 2000a]. Supporting ground-based measurements of auroral luminosities at 557.7 and 630.0 nm were made by meridian scanning photometers and all-sky imagers. Measurements from the SuperDARN radar in Finland and from the ion drift meter on a Defense Meteorological Satellite Program (DMSP) satellite provided useful synoptic views of the prevailing large-scale convection patterns. Both launches occurred near magnetic noon while B_X was the dominant IMF component. On December 2, IMF $B_Y < 0$ and B_Z was mostly northward. At the time of the December 3 flight the polarities of all three components were reversed but their magnitudes were comparable to those of the first flight. The antiparallel merging hypothesis required that on December 2 the evening/morning convection cell would be driven by merging in the southern/northern hemisphere. The converse relationships prevailed at the time of the December 3 flight.

Most previous research emphasized the roles of the Y and Z components of the IMF in determining the magnitude and timing of the interactions. However, IMF B_X also can be important. *Maynard et al.*, [2000a] compared data from the first sounding rocket from Svalbard with IMF and solar wind velocity measurements from the Wind and IMP 8 spacecraft and with ground-based optical and radar measurements to help distinguish spatial and temporal variations. The rocket's westward trajectory carried it toward auroral forms associated with morningside boundary layers. The rich set of vector dc electric and magnetic fields and energetic particle fluxes gathered by the rocket revealed a complex electrodynamic picture of the cusp/boundary layer region. Four factors were important in separating temporal and spatial effects: (1) near the December solstice the Earth's north magnetic pole tilts away from the Sun; (2) at the UT of launch the dipole axis was rotated toward dawn; (3) B_X was the dominant IMF component; and (4) the variability of interplanetary driving was low. The first three factors affect how the dayside magnetopause presents itself to the oncoming solar wind and thus the locations of the merging sites. The fact that the interplanetary variability during the flight was low allowed us to use small but distinctive changes in the IMF as timing markers for electric field variability in the dayside ionosphere. No signatures of dayside merging at a northern hemisphere site were detected by either the rocket or ground sensors. From an interpretive point of view, the key observations were of electric field variations in the interplanetary medium that correlated directly with those observed by the sounding rocket. However, the rocket detected the signals about 10 min earlier than expected with lag times estimated for simple advection between Wind and the Earth.

The effective interplanetary electric field (IEF) was calculated using the formula $E_{KL} = V_X B_{YZ} sin^2(\theta/2)$ where θ is the IMF clock angle [*Kan and Lee*, 1979]. This formula was initially derived by *Sonnerup* [1974] for the maximum rate of component merging in the subsolar region. The correlated rocket and Wind measurements required that planes of constant IEF phase be tilted toward the Earth, and that first contact with the magnetopause occurred in the southern hemisphere. Using correlations of electric field measurements at the rocket with those at the Wind and IMP-8 satellites *Maynard et al.*, [2000a] estimated the polar and azimuthal tilt angles of IEF phase fronts as they propagated toward the Earth in the solar wind. Figure 1 schematically shows the deduced merging site in the southern hemisphere and the two tilt angles of the constant-phase planes. The interaction at the measured correlation time was only possible with merging in the southern hemisphere. Consequently, the observed northern hemisphere convection pattern was stirred in part by merging of the IMF with closed field lines near the poleward edge of the southern hemisphere cusp thereby adding open flux to the northern polar cap. Subsequent motions of adiaroic polar cap boundaries were detected in the rocket electric field measurements, [*Siscoe and Huang*, 1985]. The observations indicate that IMF B_X significantly affected the location and timing of merging interactions. Implicit in our placing of the merging site is the antiparallel merging hypothesis [*Crooker*, 1979].

Figure 1

On the following day the second rocket flight was launched under southward IMF conditions. As mentioned above, the rocket was launched to the west while Svalbard was near magnetic noon, and the signs of all three IMF components were reversed from their values on December 2. Background electric fields measured by the rocket and a DMSP satellite indicate that the rocket entered the prenoon convection cell. Again a detailed correlation was found between electric field variations detected at different times by the rocket, Wind, and IMP 8. Figure 2 shows the correlation between E_{KL} and the meridional component of the electric field detected at the location of the rocket. The correlation coefficient between the two data sets was 0.79. Again the lag time for signal detection in the ionosphere was much less than that required for normal advection between Wind and the Earth [*Maynard et al.*, 2000b]. The combined rocket, Wind and IMP 8 data also required that the constant IEF phase fronts be similarly tilted and that first contact occured at the magnetopause on the morningside of the southern hemisphere cusp.

Figure 2

Auroral acivity in the vicinity of the rocket occurred in the prenoon convection cell and had to be driven at a southern hemisphere merging line. *Maynard et al.*, [2000b] used this inference to distinguish afternoon and morning convection cell portions of all-sky images that were driven by processes in the northern and southern hemispheres, respectively. This allowed a separation of spatial and temporal effects. The key to understanding the data was applying the antiparallel merging hypothesis of *Crooker* [1979].

Plate 1

Plate 1 shows a cartoon from *Maynard et al.*, [2000b]. The top two plots show how a tilted phase front first impacts the magnetosphere on the dawn side of the southern cusp, and later interacts near the northern cusp. The magnetosphere shape was determined with the Tsyganenko-96 magnetic field model *Tsyganenko and Stern*, 1996]. The subsolar magnetopause coincides with the last closed field line surface. Open field lines behind the cusp provide the full outline of the magnetopause. If component merging had been dominant, interactions would have occurred near the equator and affected both hemispheres at about the same time. If antiparallel merging dominated, the northern hemisphere should respond much later than the southern hemisphere. Thus, it is possible to have the two hemispheres reacting to different segments of the solar wind data stream associated with different lag times. This was in fact the case. Newly opened field lines at the southern hemisphere merging point drape over the edge of the northern hemisphere in the region of the yellow dots. The orange line in the top right plot represents possible antiparallel sites for positive B_Y and smaller B_Z of both polarities. The bottom left plot of Plate 1 shows the approximate field of view of the all-sky image overlaid onto a *Weimer* [2001] convection pattern displayed in inertial coordinates [*Maynard et al.*, 1995]. The approximate ionospheric footprints of the merging sites are represented by the yellow dots and the orange line. The westward rocket trajectory is indicated by a heavy black line. The bottom right plot overlays the same possible merging sites on an all-sky image. The white line shows the direction of the meridian scanning photometer measurements taken at the same time.

Plate 2c-d

Plate 2c-d shows two all-sky images acquired during the time of the second rocket flight when the correlation with Wind IEF data was established. The approximate area of emissions originating from merging in the southern hemisphere is represented by an open-ended hook. The size and position of the hook were approximated from the locations of bright auroral emissions observed during the rocket flight. The cusp is clearly bifurcated in the left image. This same break point is evident at other times, depending on the relative activity occurring to the east of the Ny-Ålesund observatory. During this interval the intensities of both E_{KL} and auroral emissions within the hook increased. The rocket trajectory, represented by a light line on the figure, passed just poleward of the most intense emissions. Auroral emissions from east of the hook originate from northern hemisphere merging events. The traces at the bottom (top) display E_{KL} properly lagged for merging in the southern (northern) hemisphere. The difference in time between interactions with the same E_{KL} features in the two hemispheres was $\sim$14.5 min.

The lag time for northern hemisphere interactions in the afternoon convection cell was determined using auroral signatures as fiduciaries that are characteristic of three brief intervals when IMF B_Z turned northward or approached zero. All-sky images acquired during one of the northward IMF intervals are shown in Plate 2a-b. Auroral forms characteristic of northward IMF [*Sandholt et al.*, 1998] were observed at the poleward edge of the cusp region (noted by the top orange dashed arrows). They appeared at that location, rather than originating to the east and propagating westward across the cusp, clearly identifying their origin. Attention is also directed to the markedly lower level of auroral emissions from the region controlled by southern hemisphere merging (inside of the hook). This is consistent with the low levels of E_{KL} at the times keyed by the two bottom dashed arrows.

Returning to Plate 2c-d, we note that much weaker auroral emissions emanated from the region at the end of the top set of red arrows, referring to northern hemisphere merging. Also there is a general lack of auroral emissions to the east, even though E_{KL} in the top trace is large. The antiparallel criterion explains this lack of aurora to the east. At the appropriate interaction time IMF B_X had decreased, tilting the IMF more toward the vertical. Since the phase front had already passed the subsolar magnetopause, there were no possible antiparallel sites for the new orientation. Thus, merging and the auroral emissions turned off even though the IEF intensity was high. Using the antiparallel hypothesis *Maynard et al.*, [2000b] harmonized 40 min of all-sky and meridian scanning photometer data with the same time lags.

3. CONCLUSIONS

In summary, the data presented here have opened new avenues for understanding interplanetary coupling to the M-I system. They show that interaction timing depends strongly on IMF B_X. This probabaly accounts for some of the variability in the initial response times reported by *Ridley et al.*, [1998]. The orientation and propagation of the phase front is a three-dimensional problem that cannot ignore B_X. Applying the antiparallel merging hypothesis harmonizes extremely complex data sets. Small details in the IEF have counterparts in the ionospheric electric field, confirming that the ionosphere responds directly to interplanetary driving. Northern hemisphere convection is in part driven at merging sites on the magnetopause near the northern and southern hemisphere cusps. As a result, it becomes possible to separate spatial from temporal variability derived from two hemispheric sources, which respond to different segments of the solar wind data stream. We believe that resultant source-bifurcation of the cusp is a common feature that arises in direct consequence to antiparallel merging.

The interactions differ according to the presentation of the magnetopause to the solar wind and the IMF. The rocket measurements, especially with northward IMF, support the concept of expanding/contracting adiaroic boundaries for the polar cap. In the vicinity of the cusp, under B_Y dominant conditions with southward IMF, coupling to the solar wind results in direct tugging of the field lines as open flux is carried tailward. Even though flux tubes opened in the north and in the south are tugged in the same direction, there is a natural break between the two. Inertial coordinates logically separate the two cells. It thus follows that the small convection cell is driven from the opposite hemisphere. How long the IMF directly couples to the ionosphere through the lobes remains to be determined. *Cowley and Lockwood* [1992] postulate that after ~10 min the newly opened flux no longer acts as a driver of convection patterns. *Farrugia et al.*, [2000] also found that small variations in the IMF coupled to particle precipitation, field-aligned currents, and ionospheric currents in the closed field line region that maps to a sunward flowing mixing layer near the flanks of the magnetosphere. In this case, however, the lag was longer than the normal advection time, indicating that the different merging locations and physical processes affect coupling.

4. FORECASTING APPLICATIONS

Since the M-I system responds in detail to interplanetary drivers, a model could in principle be constructed for forecasting if we could determine how the IEF engages the magnetopause under a wider variety of conditions. This is a long-term goal toward which we have only taken a few steps. As a whole the ionosphere serves as an integrator that feeds back actively into the magnetosphere. How coupling modifies the driving must be understood before detailed modelling becomes practical.

In the near term, predictions of convection patterns using the statistical models driven by data from an upstream monitor could logically be improved by treating the propagation as a 3-D problem. The influence of B_X on the timing and driving rate can be factored in. The distance that the upstream monitor is away from the Sun-Earth line in both Y and Z, as well as the tilt of the phase front, must be considered when determining the timing of the interaction at the magnetopause. We also need to understand the differences between large changes in the IMF and shocks versus the small-scale variations discussed above.

There is growing evidence that through optical techniques we will be able to predict large geomagnetic events with a day or more warning [*Fox et al.*, 1998]. However, for detecting the relatively small interplanetary variations needed to predict substorm occurrences, we will be limited to the shorter time scales required for information to propagate from monitors near the first libration point (L_1) to the Earth. The coherence of interplanetary parameters between the halo orbit of ISEE 3 to the Earth ranged from good to poor [*Russell et al.*, 1980]. The correlation between L_1 and Earth improved if the distance between the Sun-Earth line and the observing spacecraft ($d_\perp$) was less than a few tens of R_E [*Crooker et al.*, 1982; *Lyons et al.*, 1997] and if interplanetary variability was relatively high. Working within the $d_\perp$ limitation, our finding that surfaces of constant IEF phase are tilted with respect to the Sun-Earth line appears to introduce an insuperable error of $\sim \pm 10$ min for predicting when an interplanetary structure will reach the magnetopause. With a single satellite near L_1, it is impossible to determine the tilt angles. However, since three points determines a plane, with two near-Earth satellites such as IMP 8 and Geotail in the solar wind, the two tilt angles can be specified using standard correlation techniques [*Russell et al.*, 1980]. We are encouraged by the examples presented by *Russell et al.*, [1980] indicating that once established, high correlations (constant tilt angles?) lasted for hours. In fact, *Maynard et al.*, [2000b] were able to show agreement between IEF and dayside auroral variations by assuming that the tilt angles remained constant during the 50 min period shown in Plate 2.

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Figure 1. Schematic representation of merging site and depiction of phase plane tilts from *Maynard et al.*, [2000a].

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Plate 1. Cartoon illustrating the various merging sites in the magnetosphere and ionosphere and their relationship to the aurora from *Maynard et al.*, [2000b]. The top two panels shows a 3-D representation of the magnetopause. The yellow phase plane is shown abutting the Southern-Hemisphere-merging site in the left panel and encountering the northern-hemisphere cusp region in the right panel. Newly opened field lines in the Southern Hemisphere would pass by the dotted yellow region in the Northern Hemisphere in the top left. The orange line in the top right schematically delineates possible Northern Hemisphere merging sites, applying the antiparallel criterion. The bottom two panels translate the merging sites to the ionospheric configuration of convection and aurora.

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Plate 2. All-sky images of 630.0 emissions over Ny-Ålesund acquired at (a) 0907:04, (b) 0907:34 UT, (c) 0909:34, and (d) 0910:04 UT projected to 200 km in altitude. E_{KL} for the two different lags determined to be the best for the northern (southern) hemisphere correlations are shown in the top (bottom) data traces, with the image times keyed by the arrows to the respective images. The open curve in each image approximates the region controlled by southern hemisphere merging. Auroral enhancements in (to the right of) this region are in response to increases in E_{KL} in the bottom (top) trace. For reference, the DMSP F13 orbit and the rocket trajectory mapped to 200 km altitude have been superposed on the image (adapted from *Maynard et al.*, [2000b]).

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14

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