

A possible explanation for rapid, large-scale ionospheric responses to southward turnings of the IMF

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Abstract. We have examined the dayside high-latitude convection response to a sudden southward turning of the Interplanetary Magnetic Field (IMF) and found that the response is nearly instantaneous (<2 min) over a spatial region extending from $\sim 75^\circ$ to 85° and from ~ 9 to 16 MLT. Observations of the magnetic field were made with the WIND spacecraft in the solar wind and the GEOTAIL and IMP8 spacecraft in the magnetosheath. In the high-latitude ionosphere, the HF radars of the Super Dual Auroral Radar Network (SuperDARN) were used to monitor the convection. Based on the magnetosheath flow of the gas dynamic approximation, the field lines of the new IMF state were draped over a large portion of the dayside magnetopause when the first significant indication of convection response was measured in the ionosphere. Significant magnetic field line draping accompanied by extended reconnection on the dayside magnetopause may help explain the rapid, large-scale response of ionospheric convection.

Introduction

The dependence of high-latitude ionospheric convection on the orientation of the Interplanetary Magnetic Field (IMF) is an important part of understanding the fundamental processes which determine our space weather. Many studies have addressed how the convection responds to a change in the orientation of the IMF [e.g., *Nishida and Maezawa*, 1971; *Lockwood et al.*, 1986; *Etemadi et al.*, 1988; *Saunders et al.*, 1992; *Taylor et al.*, 1998, and references therein]. A standard model of the convection response to a change in the IMF has emerged, whereby reconnection of the new IMF state initiates a change in the plasma flow at the ionospheric footprint of the new X line. The new convection flow then expands dawnward and duskward in a twin-vortex pattern at a phase speed of $<\sim 5$ km s $^{-1}$ resulting in a newly-established global convection pattern after ~ 15 min [*Cowley and Lockwood*, 1992].

Recently several studies have reported observations that apparently contradict this model [*Ridley et al.*, 1997, 1998; *Ruohoniemi and Greenwald*, 1998]. These studies seem to indicate that the ionospheric convection response to a sudden change in the IMF is globally instantaneous, i.e., that the entire polar ionosphere responds nearly simultaneously (<2 min) to reconnection of the new IMF state at the magnetopause.

In all of these studies the IMF is monitored using a spacecraft, typically upstream of the Earth's bow shock. Changes in the IMF are propagated to the Earth's bow shock and through the magnetosheath to the subsolar magnetopause, where reconnection is believed to initiate. Several minutes ($\sim 1-3$) are added to the subsolar magnetopause impact time to account for the communication between newly reconnected field lines at the magnetopause and their ionospheric footprints. The lagged (positive or negative) IMF is then compared to the observations of the ionospheric plasma convection, obtained by a variety of different techniques, and conclusions about the ionospheric response are inferred. Critical to the validity of this method is the ability to determine precisely when the IMF arrives at the magnetopause. *Ridley et al.* [1998] describes in detail some of the uncertainties involved in such techniques and conclude that typical time estimates may be uncertain to ± 8 min.

We believe that additional difficulties exist in determining when a change in the IMF impacts the magnetopause and that the uncertainty can be even greater. A potentially important element missing from this type of analysis is the detailed plasma flow in the magnetosheath, in particular, the extent to which field lines are draped over the magnetopause when reconnection of the new IMF state occurs. Instead of trying to precisely measure the time when a change in the IMF impacts the subsolar magnetopause, which may or may not be the site of reconnection, we are suggesting that the amount of field line draping may significantly influence the nature of the convection response. In some cases field lines of the new IMF state may be draped over a significant portion of the dayside magnetopause and reconnection may occur over a larger region of the dayside than was previously thought.

In order to address this issue we have selected an event which was marked by a large and rapid (<2 min) southward turning of the IMF that was observed by the WIND spacecraft upstream of the bow shock and the GEOTAIL and IMP8 spacecraft in the magnetosheath. To determine the convection response we use the Northern Hemisphere array of SuperDARN radars which monitor a large portion of the dayside high-latitude ionosphere. The approach we take is to observe the IMF change at the various satellites and estimate the degree to which field lines of the new IMF state are draped over the magnetopause at the time when new reconnection is believed to occur, or 2 min before the first significant ionospheric convection response is observed.

Our findings for this event are consistent with field lines of the new IMF state draping over the entire dayside magnetopause. Such a configuration of field lines at the magnetopause would help to explain the observed nearly simultaneous (~ 2 min) response over the dayside ionosphere with the SuperDARN array, similar to the recent results

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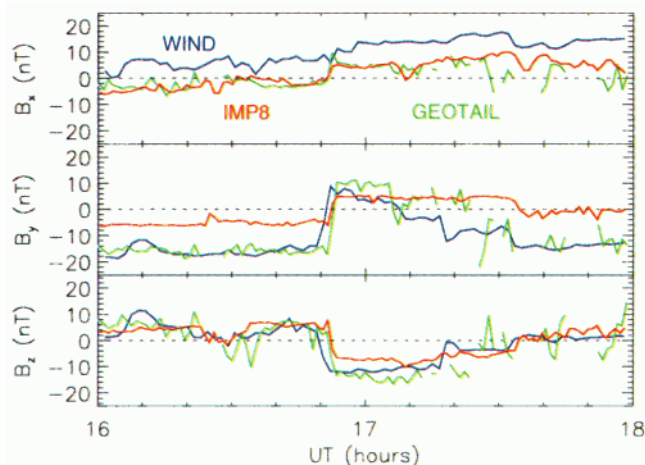


Figure 1. Magnetic field components recorded on November 25, 1997 by the WIND (blue), GEOTAIL (green), and IMP8 (red) spacecraft, plotted in GSM coordinates. The WIND data have been shifted by +60 min and scaled by a factor of 4, while the IMP8 data have been shifted by -20 min.

presented by other researchers [Ridley *et al.*, 1997, 1998; Ruohoniemi and Greenwald, 1998]. The draping provides a mechanism for the rapid, large-scale onset of convection over the dayside ionosphere.

Analysis

The event to be studied occurred on November 25, 1997. Figure 1 shows the three components of the magnetic field observed by each of the three spacecraft. At GEOTAIL, located near the computed subsolar magnetopause at $12.5 R_E$, the B_z component of the magnetic field changes abruptly (~ 2 min) from +3 nT to -13 nT at ~ 1651 UT. The B_y and B_x components also change during this transition from -17 nT to +10 nT and from -1 to +6 nT, respectively. A similar change in the IMF was measured at both WIND (~ 60 min earlier) and IMP8 (~ 20 min later), increasing confidence that the change at GEOTAIL was spatially extended and of IMF origin. The IMF data have been shifted appropriately in Figure 1. During this period the solar wind density and velocity measured at WIND were steady, implying that no pressure pulses were associated with this structure.

We use the Northern Hemisphere component of the SuperDARN radar network [Greenwald *et al.*, 1995] to determine the high-latitude convection pattern. During the period of the event being studied, line-of-sight (LOS) velocity measurements were available from 5 of the 6 northern SuperDARN radars currently in operation.

Figure 2 shows LOS velocities from 2 of the 5 radars. Each panel displays the data from one beam and a series of range gates. This format is the same as that presented by Ruohoniemi and Greenwald, [1998]. The particular beams were chosen to illustrate the wide MLT range of the first observed transition in the convection. The invariant latitude of the selected range gates are listed to the right of each panel. The vertical dotted line drawn through each panel at 1702:49 UT indicates the first discernible transition in convection attributable to the change in IMF observed at GEOTAIL, seen most clearly in Figure 2c. This time was determined from careful examination of the radar scans.

Prior to the transition at 1702:49 UT only minor variations in the ionospheric LOS velocities were seen on 2-min time scales. A significant increase in these velocities of 200–500 m s^{-1} is seen in all the range gates in Figure 2 within 2 min of the identified onset time. To further characterize this transition the increase in velocities exceeded 750 m s^{-1} within 6 min in some of the range gates. The response occurs nearly simultaneously in the ~ 10 MLT and ~ 15 MLT sectors (Figures 2a and 2c). A response is not seen in the ~ 12 MLT sector (Figure 2b) until the following scan at 1704 UT, because the beam in that sector is sampled ~ 30 s earlier than those in Figures 2a and 2c. Thus, within ~ 30 s, the transition occurred simultaneously over nearly 7 hours of MLT.

To show the extent of the convection onset the SuperDARN data has been combined in a manner described by Ruohoniemi and Baker [1998] to produce 2-min convection maps. Figure 3a shows the scan preceding the transition (1700–1702 UT) and Figure 3b shows the scan following the transition (1704–1706 UT). The fitted velocity vectors in Figure 3b show an enhanced flow over all MLTs where ionospheric scatter is present and a change from northeastward to northwestward flow in the prenoon sector near 80° , both

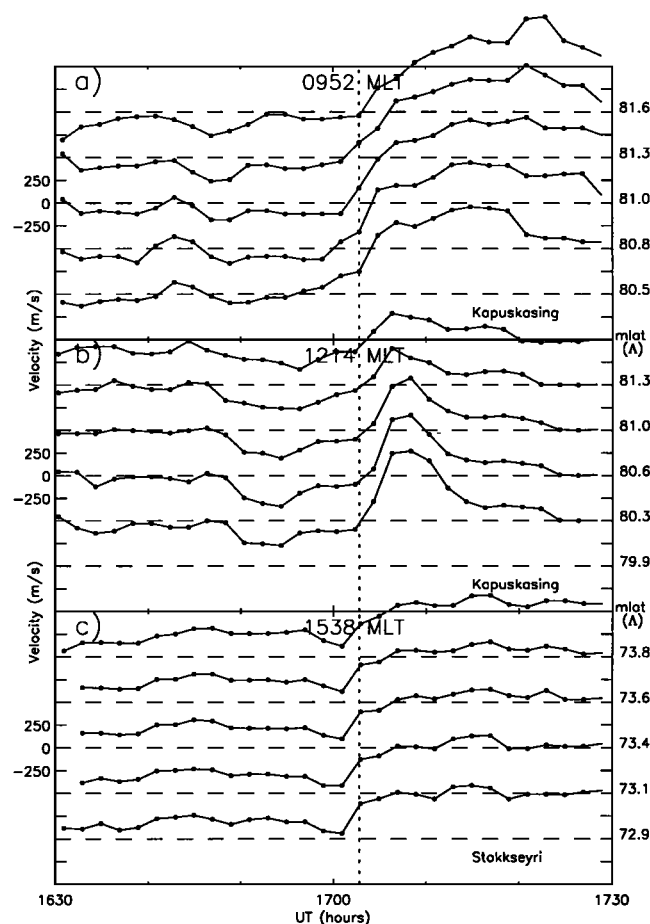


Figure 2. Stackplots of LOS velocities from three SuperDARN radar beams and several range-gates chosen to represent a wide range of MLT. The vertical dotted line indicates the earliest observed change in the ionospheric convection. It is evident from the dramatic changes in all the LOS velocities that the ionospheric response to the change in IMF is nearly instantaneous across the MLT range covered.

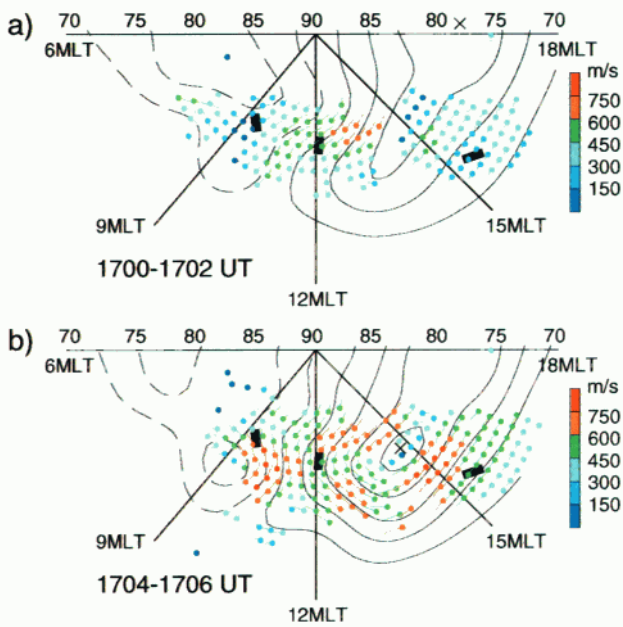


Figure 3. 2-min convection maps as measured by the Northern Hemisphere component of SuperDARN from a) 1700 to 1702 UT and b) 1704 to 1706 UT showing a transition of ionospheric convection consistent with a $+B_Z, -B_Y$ to $-B_Z, +B_Y$ IMF change. The cross polar cap potential increased from 35 kV to 49 kV during this period. The coverage of ionospheric echos shown was typical during the hour preceding and following the first significant response to the sudden change in the IMF.

typical of a $+B_Z, -B_Y$ to $-B_Z, +B_Y$ IMF change [Greenwald *et al.*, 1990]. The black rectangular boxes show the locations of the stackplot Doppler data shown in Figure 2.

The CANOPUS magnetometer at Taloyoak, NWT ($\Lambda \approx 79^\circ$) showed a change consistent with the onset of enhanced northwestward flow across 12 MLT. The transition occurred within 1 min of the time identified by the radar measurements, confirming the near-noon ionospheric response to ± 1 min. Magnetometer stations located further equatorward showed no discernible change.

Discussion

We have identified the ionospheric response to a sudden southward turning of the IMF and found that the response is nearly instantaneous (< 2 min) over a large portion of the dayside ionosphere. Prior to the identified transition, there was no indication in the high-latitude convection pattern that a change in IMF had occurred at the magnetopause. Subsequent to this time, there was a rapid enhancement of convective flow velocities that spread over the high-latitude ionosphere on a time scale of less than 30 s.

Observations from the GEOTAIL spacecraft, located near the subsolar magnetopause, WIND located in the upstream solar wind, and IMP8 located down the flank of the magnetosheath, provide evidence that the field lines of the new IMF state were draped over a large portion of the dayside magnetopause when reconnection began. To illustrate the draping of the new IMF at the time of reconnection at the magnetopause a minimum variance analysis was per-

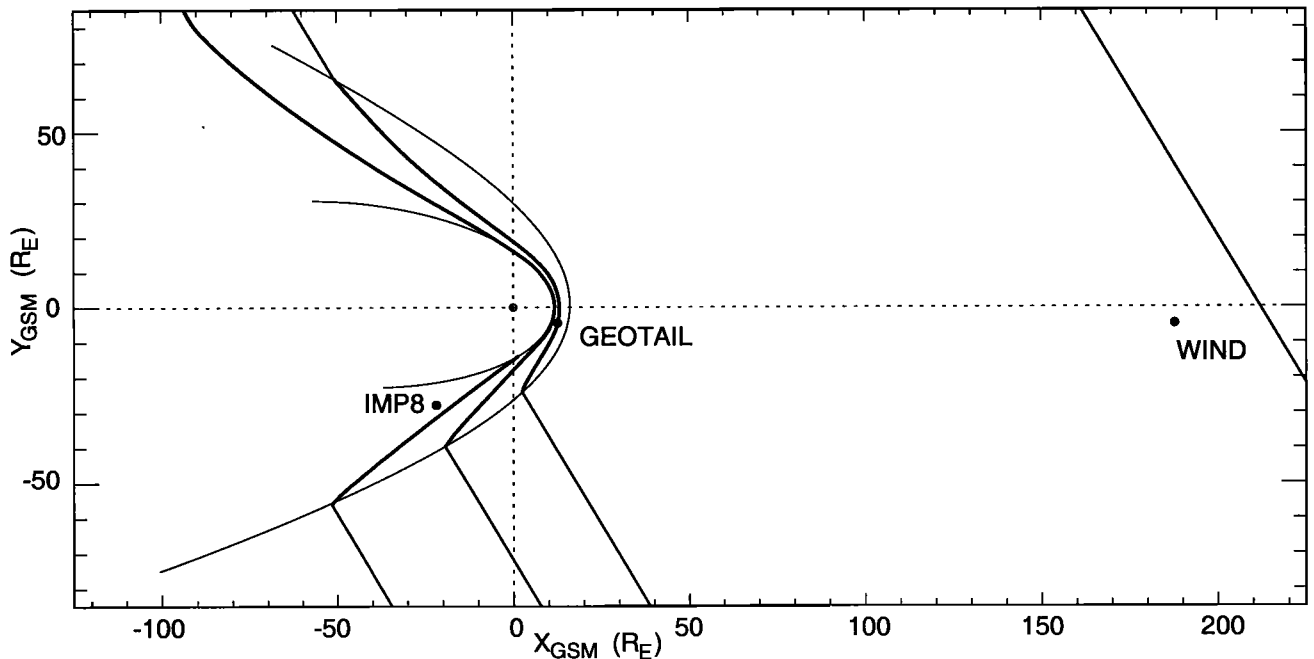


Figure 4. The X - Y_{GSM} plane showing the locations of the spacecraft (WIND, GEOTAIL, and IMP8) which observed the B_Z - B_Y change (shown in Figure 1), a model bow shock after Peredo *et al.* [1995], a model magnetopause after Roelof and Sibeck [1993], and the intersection with planes containing the IMF at four propagation times from WIND; the time of the WIND observation, the time of the GEOTAIL observation, 2 minutes prior to the enhanced ionospheric convection observation, and the time of the IMP8 observation.

formed on the WIND magnetic field data and a planar surface containing the field lines determined. The planar structure was propagated at the solar wind speed, measured at WIND, for three time intervals. Where the planar structure passed into the magnetosheath it was propagated in a manner consistent with the flows predicted by the gas dynamic model of Spreiter and Stahara [1980]. Figure 4 shows the intersection of this plane with the X - Y_{GSM} plane for four times: 1551 UT, the observation time at WIND; 1652 UT, the observation time at GEOTAIL; 1701 UT, two minutes prior to the time that enhanced ionospheric convection was observed; and 1713 UT, the observation at IMP8.

The lines drawn in Figure 4 are undoubtedly somewhat in error due to the difficulties in determining the orientation of an assumed planar structure in the solar wind, propagating such a feature in the solar wind, and the unknown details of the flows in the magnetosheath near the magnetopause. However, even considering these errors it is apparent that, for this case, the field lines were significantly draped over a large portion of the dayside magnetopause when reconnection began. The draping was most dramatic in the northern hemisphere due to the vertical tilt of the magnetic plane (not shown). Our analysis does not require any delay in the onset of reconnection once the new IMF state has contacted the magnetopause.

In this particular case the draping of magnetosheath field lines over a large portion of the dayside magnetopause and an associated extended line of reconnection, could explain the observed nearly instantaneous, large-scale convection response to a change in the IMF. This picture is inconsistent with earlier models of single-point reconnection causing ionospheric responses that spread anti-sunward at a few km s^{-1} . We do not dispute that the latter situation may, on occasion, occur, but we believe that our observations may help to resolve some of the ongoing controversy regarding rapid, large-scale ionospheric responses following changes in the IMF.

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References

- 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.
- Etemadi, A., S. W. H. Cowley, M. Lockwood, B. J. I. Bromage, D. M. Willis, and H. Lühr, The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF: A high time resolution correlation analysis using the

- EISCAT 'POLAR' and AMPTE UKS and IRM data, *Planet. Space Sci.*, **36**, 471, 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 observations of dynamic variations in high-latitude dayside convection due to changes in IMF B_y , *J. Geophys. Res.*, **95**, 8057, 1990.
- Greenwald, R. A., W. A. Bristow, G. J. Sofko, C. Senior, J.-C. Cerisier, and A. Szabo, Super Dual Auroral Radar Network radar imaging of dayside high-latitude convection under northward interplanetary magnetic field: Toward resolving the distorted two-cell versus multicell controversy, *J. Geophys. Res.*, **100**, 19,661, 1995.
- Lockwood, M., A. P. van Eyken, B. J. I. Bromage, D. M. Willis, and S. W. H. Cowley, Eastward propagation of a plasma convection enhancement following a southward turning of the interplanetary magnetic field, *Geophys. Res. Lett.*, **13**, 72, 1986.
- Nishida, A., and K. Maezawa, Two basic modes of interaction between the solar wind and the magnetosphere, *J. Geophys. Res.*, **76**, 2254, 1971.
- Peredo, M., J. A. Slavin, E. Mazur, and S. A. Curtis, Three-dimensional position and shape of the bow shock and their variation with Alfvénic, sonic and magnetosonic Mach numbers and interplanetary magnetic field orientation, *J. Geophys. Res.*, **100**, 7907, 1995.
- 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.
- Roelof, E. C., and D. G. Sibeck, Magnetopause shape as a bivariate function of interplanetary magnetic field B_z and solar wind dynamic pressure, *J. Geophys. Res.*, **98**, 21,421, 1993.
- Ruohoniemi, J. M., and K. B. Baker, Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, **103**, 20,797, 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 field oscillations: Determination of the ionospheric phase velocity, *J. Geophys. Res.*, **97**, 19,373, 1992.
- Spreiter, J. R., and S. S. Stahara, A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res.*, **85**, 6769, 1980.
- Taylor, J. R., et al., SuperDARN studies of the ionospheric convection response to a northward turning of the interplanetary magnetic field, *Ann. Geophysicae*, **16**, 549, 1998.

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