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MHD simulations of the response of high-latitude potential patterns and polar cap boundaries to sudden southward turnings of the interplanetary magnetic field

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Abstract. 3-D MHD simulations were used to investigate the behavior of the high-latitude convection and the polar cap variations during two events characterized by sudden southward IMF turnings. In agreement with recent observations the simulation results indicate that the convection pattern across the entire polar cap begins to change a few minutes after the arrival of the southward IMF. In contrast, the onset of the equatorward motion of the open closed field-line boundary depends on the local time, with equatorward motion of the midnight boundary delayed by about 20 minutes relative to the the onset of the boundary motion at noon. We interpret this delay as the time required to convect newly merged flux from the dayside to the nightside. We belive that these two different responses can reconcile apparent contradictions in studies of ionospheric reconfigurations in response to changes in the IMF.

1. Introduction

Potential and convection patterns in the high latitude ionosphere are strongly influenced by the orientation of the Interplanetary Magnetic Field (IMF), as has been shown in a number of studies *[e.g., Ruohoniemi and Greenwald, 1996, and references therein]*. Recently, observations by *Ridley et al. [1997] and Ruohoniemi and Greenwald [1998]* indicate that the response of the convection pattern to a sudden southward turning is essentially simultaneous, on the minute time scale, over the entire high-latitude region. These results conflict with earlier studies that observed time delays in the convection dynamics as one moved away from the noon sector *[e.g., Saunders et al., 1992]*.

In this study we used 3D MHD simulations to study the dynamic response of the convection pattern to sudden changes in the IMF from northward to southward. The accuracy of the simulations has been benchmarked against observations from spacecraft and groundstations *[Lopez et al., 1998; Lyon et al., 1998; Goodrich et al., 1998]*.

In this paper we focus on the change in the polar cap potential patterns and the motion of the boundary between open and closed field lines in response to sudden southward turnings of the IMF in event simulations. It will be shown that contrary to the pattern of the potential the polar cap boundary exhibits signicant time delays as a function of local time. We present first a brief description of the code used study, followed by a discussion of two events of a sudden southward rotation of the IMF, and then our conclusions.

2. Code Description

The Lyon-Fedder-Mobarry 3D MHD simulation code *[e.g., Fedder and Lyon, 1995]* models the solar wind and the magnetosphere by numerically solving the ideal MHD equations. The outer boundaries are at x=30 and -300 R_E and $(y^2 + z^2)^{1/2} = 100R_E$. Outflow conditions are applied on the rear (tailward) boundary where the plasma flow is supersonic. Elsewhere, external boundary conditions were specified using solar wind data propagated to points on the front and cylindrical sides of the grid. The application of the WIND data to the grid boundaries sets the registration of simulation time to actual (UT) time. In this paper we examine results from runs made for March 9, 1995 and January 10, 1997.

The inner boundary was set at $r = 3.5\ R_E$ for the March 9 run. In the January 10 run the inner boundary was set at $r = 2.0\ R_E$ because the magnetosphere experienced a major compression during the period simulated code *[e.g., Goodrich et al., 1998]*. At the inner boundary, the magnetospheric quantities are mapped along the dipole field to a 2-D ionospheric simulation. The details of empirical model used to calculate the anisotropic height-integrated conductivity tensor can be found in *Fedder et al. [1995]*. In short, the conductivity is dependent on the solar EUV flux and the particle precipitation from the magnetosphere. During one of the runs discussed here (January 10), the simulations were performed in the Solar Magnetic (SM) coordinate system, allowing the rotation of the Earth's magnetic dipole to be included. In the other run (March 9), the dipole tilt was constant.

3. March 9, 1995

The substorm early on March 9, 1995 is an ideal case for simulation. The event followed an extended period of northward IMF that allowed the magnetosphere to settle into its ground state. Our previous analysis of this event demonstrated that the global substorm activity was reproduced with remarkable fidelity in the simulations *[Lopez et al., 1998; Lyon et al, 1998]*. We are therefore confident that this simulation run can be used for quantitative analysis, and even for controlled experiments to determine possible factors in substorm triggering *[Wiltberger et al., 1998]*.

The top panel Figure 1 presents the input solar wind Bz, propagated to the Earth. The middle panel shows the position of the boundary between open and closed field lines for the noon and the midnight meridians. The bottom panels show the polar cap pontetial contours at three different

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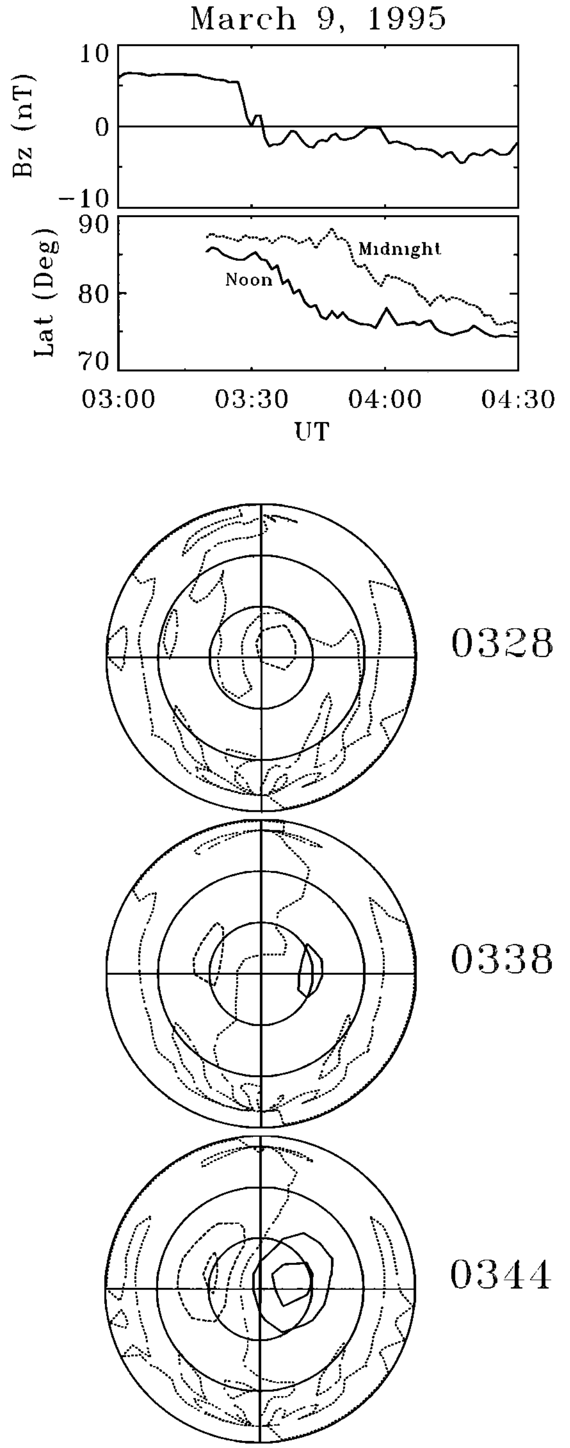

Figure 1. Solar wind B_Z (top panel), simulated polar cap boundaries (middle panel), and three snapshots of the ionospheric potential pattern - one just before the arrival of the southward B_Z, and two in close sequence just after the arrival of the southward B_Z, on March 9, 1995. The contours on the plot are drawn at 10 kV intervals; the circles are drawn at 10 degree intervals, beginning at 60 degrees.

times: the uppermost of the three is taken at a time just before the arrival of the southward IMF, and the lower two are taken at times shortly after the arrival of the southward IMF. The contours on the potential patterns are plotted at 10 kV intervals.

At 0330 UT, the IMF turned southward, leading to a growth phase that was registered by a number of ground stations *[Lopez et al., 1998]*. There was also a large negative B_Y component that was larger than the southward component (not shown). Thus the geoeffectiveness of the southward IMF was limited. In fact, the substorm that eventually developed was relatively small, with a maximum AE of just over 350 nT. In order to allow the potential to build up and produce easily visible potential patterns we have chosen times for polar cap potential patterns several minutes after the first arrival of the southward IMF.

The potential pattern prior to the arrival of the southward IMF is consistent with weak convection during magnetically quiet time. Just after the southward field arrived, a two-cell pattern began to emerge, and it strengthened as the southward field intensified. It is important to note is that the potential pattern does not show significant local time evolution as one might expect if the change in convection had a significant delay between noon and midnight. The pattern did not move - it just strengthened as the potential increased.

Figure 1 also shows that at the time that the southward IMF arrived, the dayside polar cap boundary immediately began to move equatorward. The motion of the midnight boundary, on the other hand, was delayed by about 25 minutes relative to the dayside.

4. January 10, 1997

The January 10 event was a very well observed magnetic storm driven by a magnetic cloud resulting from a coronal mass ejection *[e.g., Goodrich et al, 1998]*. Again, the simulation produced an excellent reflection of reality, reproducing major periods of activity driven by the cloud.

Prior to the arrival of the main cloud, there was a sudden southward rotation of the IMF that, when propagated to Earth, arrived at 0230 UT. Figure 2 shows shows the Z component of the IMF, the boundaries between open and closed field lines, and the potential contours in the same format as in Figure 1.

The potential pattern prior to the arrival of the southward IMF is consistent with a quiet magnetosphere. Immediately after the southward IMF arrived, a two-cell potential pattern began to emerge, and by 0236 UT it had strengthened considerably. As in the March 9 case, there is no evidence that the pattern moved or evolved in local time - it just got stronger as the cross-polar cap potential increased.

This event also shows a local time delay associated with the polar cap boundary motion. The boundary at noon responded immediately to the arrival of the southward IMF, and it began to move equatorward in respons to dayside merging. The equatorward motion of the midnight boundary was delayed by 15 minutes.

5. Summary

We have presented two cases of sudden southward rotations of the IMF, and the effect that these events have in MHD simulations driven with solar wind data. In each case we see the same pattern. At the time of arrival of the southward IMF, the change in the potential patterns did not show a delay from day to night. Instead, the change was essentially simultaneous across the high-latitude ionosphere. Thus our finding is in complete agreement with the results of *Ridley et al. [1997] and Ruohoniemi and Greenwald [1998]* that the change in the ionospheric convection happens quickly and in a global fashion. Moreover, just as *Ridley et al. [1997]* found, the potential pattern itself does not move, but increases in magnitude as the cross-polar cap potential grows. We take this agreement as additional support for our original supposition that the simulations results, properly benchmarked againsts real data, are useful tools for investigating the global response of the magnetosphere to changes in solar wind conditions.

On the other hand the motion of the polar cap has a strong local time dependence. The dayside boundary begins to move equatorward when the southward IMF arrives at the Earth, but there is a significant delay before the nightside boundary begins to move. For one of our periods, March 9, we have some independent confirmation that the delay was real *[Lyon et al., 1998]*. Therefore we take the delay in the boundary motion at midnight as an accurate reflection of reality. We interpret the delay to be the time needed for newly merged flux on the dayside to be transported to midnight. This explanation accounts for the difference in the time delay between the two events we examined bere. On March 9, the southward IMF was relatively weak, so that the convection was slow and it took more time for newly merged flux to be transported to the nightside as compared to January 10.

Our result also shows some agreement with *Saunders et al. [1992]*. At first reading one might consider this odd, since that paper is generally take to support the notion that there is a progressive delay away from noon in the reconfiguration of the high-latitude convection. Our interpretation is that there is an aspect of the reconfiguration, namely the motion of the open-closed field line boundary, that does lag as a function of local time. *Saunders et al. [1992]* used ground-based magnetometers to determine the correlation lag between magnetic variations at two high latitude stations in the CANOPUS chain. However, our results would suggest that these stations would, after a period of northward IMF, lie well well equatorward of the open-closed boundary. If the magnetic perturbation used to establish the phase delay were related to currents flowing at or near that boundary there would be a time delay progressively away from noon as the boundary expanded and the current moved to lower latitutdes. And in fact the time delays discussed by *Saunders et al. [1992]* are comparable to the delays one would expect for the expansion of the polar cap and the currents flowing near the separatrix as a function of local time. Thus our study, we believe, provides a possible explanation for the apparent contradiction. Further study should be able to confirm if the our proposition is indeed correct.

The simulations allow us to put this behavior into physical context. The first point to note is that on the time scale of minutes the ionosphere is incompressible because of the high Alfven speed in and above the ionosphere. Thus, much as when a cup of coffee is stirred, the response of the ionosphere should be global in extent. This global response can be calculated using the height integrated equation for the ionospheric potential,

$$\nabla \cdot \underline{\Sigma} \cdot \nabla \Psi = J \sin d \qquad (1)$$

where Ψ is the ionospheric potential, Σ is the conductivity tensor, J is the field-aligned current, and d is the dip angle. This equation has no time-dependence; changes in J and the conductance cause immediate, global consequences. Until the nightside conductance is modified by substorms the conductance is fairly constant. Thus, changes in the potential are primarily caused by changes in the field-aligned current. The "stirrers" in this case are the dayside Region 1 currents. These begin to be important at the beginning of

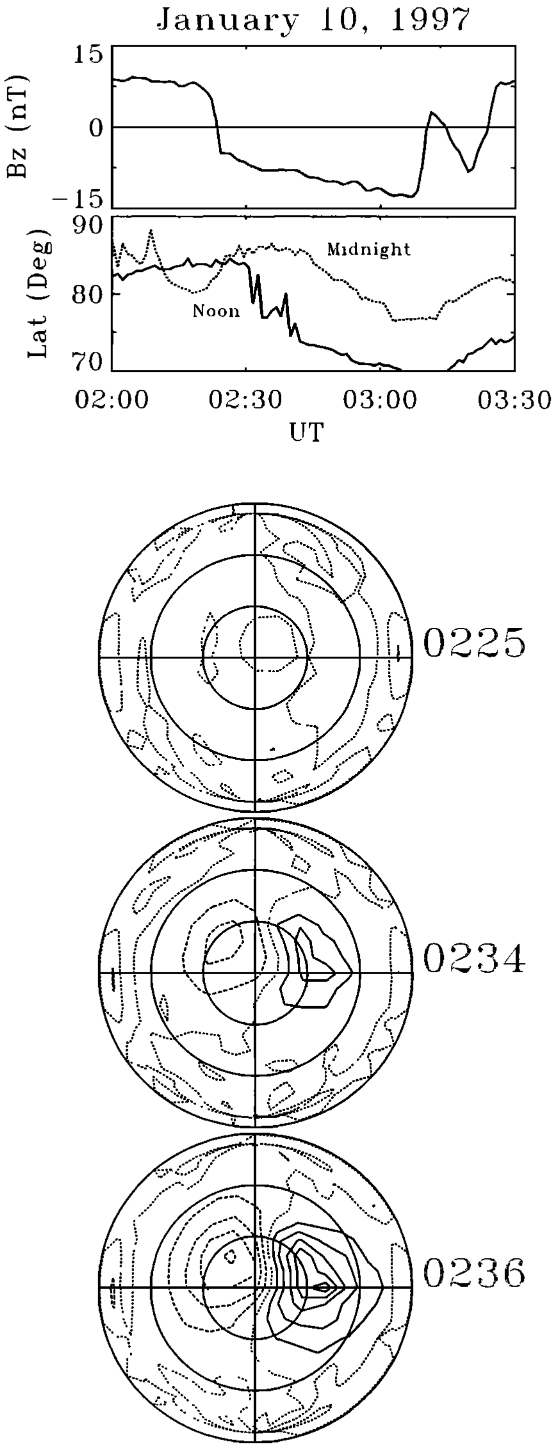

Figure 2. Solar wind B_Z (top panel), simulated polar cap boundaries (middle panel), and three snapshots of the ionospheric potential pattern - one just before the arrival of the southward B_Z, and two in close sequence just after the arrival of the southward B_Z, on January 10, 1997 in the same format as Figure 1.

dayside reconnection, and increase in strength as time goes on. They do not, however, shift much in position. They mark the boundary between field lines sheared by reconnection and those which are not. Since the reconnection site does not change, the position of the region one currents does not change either. The strength of the Region 1 system changes with the amount of energy transport from the solar wind to the magnetosphere.

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