Long-period magnetospheric-ionospheric perturbations during northward interplanetary magnetic field

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Abstract. In this paper we present observations of long-period magnetospheric-ionospheric perturbations during northward interplanetary magnetic field (IMF). On November 10-11, 1998, the IMF was northward for 29 hours. The solar wind and IMF parameters were relatively steady. After the IMF had been northward for 14 hours, strong ionospheric velocity (or electric field) perturbations were observed by the Iceland West HF radar in the postmidnight/dawn sector. The velocity perturbations showed periods in the range 50-60 min, with a mean value ~54 min. The Super Dual Auroral Radar Network observed periodic changes of nightside ionospheric convection. For each cycle a large-scale convection cell formed around 0200 magnetic local time (MLT) near magnetic latitude 70° and grew for ~30 min. The convection cell then moved eastward with a mean velocity of ~1.4 km s⁻¹. The final position of the cell focus was around 0600 MLT near magnetic latitude 77°. Ground magnetometers recorded weak magnetic perturbations with periods 50-60 min in both the premidnight and postmidnight sectors. The GOES 8 satellite also observed magnetospheric magnetic field perturbations with similar periods at L ~ 6 on the nightside. The satellite and the key radars which observed the convection oscillations are nearly magnetically conjugate, so the good temporal correlation between the satellite and radar data indicates that the magnetospheric and ionospheric perturbations have a common source. We propose that the magnetospheric-ionospheric perturbations originated within the magnetosphere. The transformation of the magnetospheric tail from an extended to a more dipolar shape during northward IMF is associated with 40-60 min period global tail oscillations which ultimately result in the generation of field-aligned currents and nightside ionospheric convection vortices near X = -10 R_E. If the proposed mechanism is correct, it will be possible to infer the magnetospheric cavity shape from the measured periodicity of the tail oscillations during northward IMF.

1. Introduction

The Earth's magnetosphere can support a variety of oscillations with a very large spread of periods, including long periods of about 1 hour. Quasiperiodic recurrence of magnetospheric substorms has been observed during southward interplanetary magnetic field (IMF). Borovsky et al. [1993] determined the time interval between consecutive substorm onsets from particle injection events monitored on geosynchronous satellites. They found that the most probable time between substorm onsets was ~2.75 hours; this was interpreted to be the period between substorms when the IMF remains southward for extended periods of time so that the driving of the magnetosphere is uninterrupted. Farrugia et al. [1993] studied substorm activity during the passage of an interplanetary magnetic cloud during which the IMF was southward for approximately 18 hours. In total, 23 substorm onsets were identified during this period. The onsets were fairly evenly distributed with an average recurrence frequency of one substorm every ~50 min; the shortest interval between substorms was ~25 min and the longest was 100 min. Klimas et al. [1994] studied substorm recurrence with a Faraday loop model. Given a steady loading rate from the solar wind, the model showed that substorms are activated with a recurrence time of ~1 hour, which is interpreted to be a natural unloading period in the magnetospheric dynamics. Siscoe et al. [1994] and Shodhan et al. [1996] presented Geotail observations of long-period (~100 min) oscillations in plasma density and velocity between magnetosheath-like and lobe-like values. They suggested that these oscillations were measured when the tail boundary moved back and forth over the satellite. The boundary oscillations might be caused by the expansions and contractions of the cross-sectional area of the tail during substorms; this internally driven motion was termed "breathing."

Long-period fluctuations have been observed in both the magnetosphere and the ionosphere. Chen and Kivelson [1991]
studied ultralow frequency waves in the lobes of the magnetotail and found fluctuations of magnetic field with a nominal period of \( \sim 35 \) min. Rinnert [1996] found quasiperiodic enhancements of electron density in the auroral \( E \) region in the European Incoherent Scatter (EISCAT) radar data. The periods were typically 40-60 min. These events could occur at all local times of day with a maximum probability in the morning sector. Lessard et al. [1999] presented ground and satellite observations of monochromatic (1-2 min) magnetic pulsations, spanning more than 8 hours in local time and from \( L = 5.9 \) to \( L = 9.6 \). The pulsations were modulated with a 45-min periodicity. It is not clear whether these long-period fluctuations were caused by fluctuations in the solar wind/IMF or by some processes intrinsic to the magnetosphere.

Huang et al. [2000a] recently reported quasiperiodic ionospheric disturbances that occurred during northward IMF. After the IMF turned northward several hours, ground magnetometer magnetic deviations with a periodicity of \( \sim 40 \) min were observed in the magnetic latitude range 74°-80° over an extended longitudinal region in the morning sector. The high-latitude oscillating currents were closely associated with the generation of gravity waves with similar periods; these were observed by HF radars at lower latitudes. The solar wind and IMF were relatively stable; there were no obvious source perturbations in the upstream solar wind for the ionospheric disturbances. They suggested that the source of the long-period ionospheric disturbances might be within the magnetosphere. Since the magnetic deviations recorded with ground magnetometers were quite weak (an amplitude of \( \sim 10 \) nT), it was not possible to determine from the magnetometer record whether the disturbances traveled along some specific direction and whether the ionospheric convection showed corresponding changes.

In this paper, we present HF radar, ground magnetometer, and satellite observations of magnetospheric-ionospheric perturbations with periods 50-60 min within a 29-hour interval of northward IMF. We will study the quasiperiodic changes of global convection and discuss the mechanism responsible for the perturbations.

2. Observations

We study an event that occurred on November 11, 1998. Figure 1a shows the IMF \( B_z \) component and 3-hour \( Kp \) index on November 10-11. \( B_z \) became positive at 1300 UT on November 10 and remained positive for 29 hours. After 0600 UT on November 10, the \( Kp \) index was smaller than 2 for the rest of the

![Figure 1](image-url)
Table 1. Locations of Radars and Ground Magnetometers

<table>
<thead>
<tr>
<th>Stations</th>
<th>Abbreviation</th>
<th>Geographic</th>
<th>Magnetic</th>
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<td></td>
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<td>Lat.</td>
<td>Lon.</td>
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Plate 1. (a) The line-of-sight velocities measured by the Iceland West HF radar beam 9 between 0300 and 1000 UT on November 11, 1998, plotted as a function of range (in kilometers) and time. (b) The line-of-sight velocities from beams 8 and 9. Magnetic local time at the radar site is approximately equal to UT.
same day [Huang et al., 2000b]. This paper focuses only on the nightside oscillations and does not include the simultaneous variations in the dayside convection.

Plate 1 shows the seven cycles of the ionospheric line-of-sight Doppler velocity perturbations. The two-dimensional ionospheric convection pattern derived from all the Northern Hemisphere radars shows corresponding quasiperiodic changes. We first present the convection plots for one cycle, as shown in Figure 2. The radar data are averaged over 4 min (two radar scans) for each plot. The IMF orientation in the Y-Z plane is illustrated on the bottom right corner of each plot, with the inferred 30-min delay. In Figure 2a the meridional component of the ionospheric flow is poleward between 0300 and 0600 MLT and becomes equatorward between 0000 and 0300 MLT. The high-latitude counterclockwise flow must be closed at lower latitudes; Figure 2d indeed shows such flow closure between magnetic latitudes 70° and 75°. It is reasonable to assume that a counterclockwise convection cell exists in the postmidnight/dawn sector, although the radar data do not show the complete structure of the cell. At the beginning of each cycle the cell starts to form, centered around 0200 MLT near magnetic latitude 70°, as shown for 0504 UT in Figure 2a. The location of the cell remains almost unchanged for ~30 min, as shown for 0536 UT in Figure 2b. However, the flow associated with the cell intensifies between 0504 and 0536 UT. The cell then begins to move eastward, as shown in Figure 2c at 0548 UT. Finally, at 0604 UT the cell focus is located between 0500 and 0600 MLT in the magnetic latitude range 75°-80°; this represents the final

Figure 2. Ionospheric convection plots observed with the SuperDARN HF radars in the Northern Hemisphere between 0504 and 0608 UT on November 11, 1998. The radar positions are indicated by capital letters: T, Saskatoon; K, Kapuskasing; G, Goose Bay; W, Stokkseyri (also termed Iceland West); E, Pykkvibaer (also termed Iceland East); F, Hankasalmi, Finland.
position of the cell for each cycle. The convection in the premidnight/dusk sector is not as clear because of the lack of data there. Our analysis will be confined to the convection in the postmidnight/dawn sector only. For each cycle a counterclockwise convection cell forms around 0200 MLT near magnetic latitude 70°, intensifies for ~30 min, takes ~20 min to move eastward, and is finally focused around 0600 MLT near magnetic latitude 77°.

Figure 3. Same as Figure 2, but for six different times.
Figure 4. (a) The GOES 8 satellite orbit in the equatorial plane during 0000-1200 UT on November 11, 1998, (b) the geomagnetic field components measured by GOES 8, and (c) the band-pass (3-100 min) filtered data of the geomagnetic field.

We now take a look at the measurements of the Geostationary Operational Environmental Satellite GOES 8. Figure 4a shows the orbit of GOES 8 in the equatorial plane during 0000-1200 UT on November 11, 1998; the distance in the Z coordinate was small (<2 Re). During the period of interest, GOES 8 was on the nightside. Figure 4b shows the geomagnetic field components measured with the magnetometer on the satellite. The vector magnetic field is given as 1-min averaged values in the local coordinate system. The magnetic field componentHp is perpendicular to the satellite orbital plane or parallel to the Earth’s spin axis in the case of a zero degree inclination orbit, Hr is perpendicular to Hp and directed earthward, and Hz is perpendicular to both Hp and Hr and is directed eastward. It is clear that Hz shows perturbations with a periodicity of 50-60 min superposed on the half-day variations. The Hp component is the strongest; it is difficult to see small perturbations superposed on it. The Hr component also shows some perturbations.

In order to identify the perturbations which are of interest, we apply a band-pass filter (3-100 min) to the GOES 8 data to remove the half-day variations. Since the quasiperiodic perturbations in the radar velocity occur between 0300 and 1000 UT (Plate 1), the filtered GOES 8 data are also given for this interval, as shown in Figure 4c. Between 0300 and 0700 UT, the Hp and Hz perturbations are almost in phase; the Hz perturbations appear to have a phase delay. After 0700 UT the Hp and Hz components show some shorter-period perturbations. We will not discuss the relationship among the three components in detail. The important result for our purpose is that the magnetospheric magnetic field shows perturbations with periods similar to the ionospheric velocity (or electric field) perturbations.

We compare the measurements of the magnetospheric magnetic field perturbations and the ionospheric electric field perturbations. Figure 5 shows the comparison between the Doppler velocities measured by the Iceland West radar beams 8 and 9 at range 1665 km and the filtered Hz component. In Figure 5 the GOES 8 Hz is inverted with positive values at the bottom and negative values at the top. There happens to be a phase difference of about 180 degrees between the ionospheric velocity...
and $H_n$, but this is not of any particular significance because of the difference in latitude and longitude between the radar observation points and the conjugate point to the GOES 8 satellite. The important result is that for the entire interval of about 7 hours the radar and satellite data exhibit similar temporal fluctuations. The coincidence between the satellite and radar data implies that the magnetospheric perturbations observed by the satellite and the ionospheric perturbations observed by the radar have a common source.

The ionospheric velocity perturbations shown in Plate 1 represent perturbations in ionospheric electric field which can cause corresponding perturbations in ionospheric currents, detected as magnetic fluctuations by ground-based magnetometers. Figure 6 shows the $H$ (northward) component of the magnetic perturbations recorded with the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS), Magnetometer Array for Cusp and Cleft Studies (MACCS), and Greenland West Coast magnetometer chains on November 11,
1998. The locations of the magnetometer stations are given in Table 1. The magnetic local time at the CANOPUS and MACCS chains is approximately UT minus 7 hours, while for the Greenland West Coast chain it is approximately UT minus 2 hours. For the interval 0200-1000 UT shown in Figure 6 the local time is approximately 1900-0300 MLT at the CANOPUS and MACCS chains and 0000-0800 MLT at the Greenland chain. Therefore these magnetometer chains recorded the magnetic perturbations in the premidnight and postmidnight sectors, respectively. The magnetic perturbations are quite weak (~5 nT), possibly caused by weak conductivity in the quiet nightside ionosphere. The perturbations at higher latitudes (GH, BL, UMQ, and ATU) appear to have a periodicity of ~1 hour. This result is expected on the basis of the ionospheric screening effect [Hughes and Southwood, 1976a, 1976b] in which the magnetospheric hydromagnetic wave magnetic perturbations seen on GOES 8 in the eastward component $H_e$ are, as a result of the ionospheric Hall currents resulting from the electric field of these hydromagnetic waves, rotated by 90 degrees and seen best in the northward $H$ component of the magnetometers on the ground. An interesting feature in Figure 6 is that the long-period perturbations are clearer at magnetic latitudes above 70° and become almost unidentifiable at lower latitudes, such as at GILL and ISLL. Because the high-latitude areas in the nightside ionosphere map along geomagnetic field lines to the magnetotail, it can be inferred from Figure 6 that the corresponding magnetospheric perturbations originate in the tail.

Finally, we compare the magnetometer records at different longitudes. In Figure 7, magnetic perturbations at three stations located at nearly equal magnetic latitudes are shown. The longitudinal separation is ~600 km between ATU and MCG and ~1200 km between ATU and DNB. As shown in Figure 2, the ionospheric convection cell moves eastward, with an average velocity of ~1.4 km s$^{-1}$. If this velocity applies to the magnetometer perturbations, one would expect a time delay of ~7 min between ATU and MCG and ~14 min between ATU and DNB. However, it is very difficult to identify these delays between the stations from Figure 7, since the magnetic perturbations are too weak.

3. Discussion

As mentioned in Introduction, magnetospheric substorms may have a recurrence period of about 1 hour in the substorm onsets [Farrugia et al., 1993; Klimas et al., 1994; Siscoe et al., 1994; Shodhan et al., 1996]. A possible mechanism for the periodic recurrence of substorms is the pressure balance in the magnetotail. When the IMF is southward, dayside merging of the IMF and geomagnetic field lines transfers dayside flux onto the tail lobes, which increases the pressure on the plasma sheet. When the pressure reaches some critical value, a substorm is initiated, and the energy stored in the tail is released. If the IMF remains southward, this energy loading-unloading process can occur repeatedly. However, substorms occur during southward IMF and result in large perturbations in the nightside ionospheric currents. In the event presented in this paper the perturbations occurred during northward IMF, and the nightside ionospheric current perturbations were very weak. Obviously, the perturbations and corresponding mechanisms in the present event are different from those associated with substorms.

For southward IMF the magnetotail is highly stretched. With a long cylindrical model of the tail, McClay and Radliski [1967] and Ershkovich et al. [1972] showed that the tail might have some eigenmode fluctuations with periods 10-40 min. Chen and Kivelson [1991] observed fluctuations of magnetic field with a period ~35 min in the lobes of the magnetosphere. They suggested that the 35-min fluctuations could be one of the magnetotail eigenmode fluctuations but indicated that more cases are needed to draw a conclusion. Furthermore, the 35-min fluctuations were observed during substorms and should occur for southward IMF. Rinnert [1996] reported observations of quasiperiodic (40-60 min) enhancements of electron density in the auroral $E$ region and suggested that the periodic density enhancements were caused by periodic particle precipitation controlled by oscillations in the magnetotail. It was mentioned that no events could be found after long quiet intervals. At least a short period of increased geomagnetic activity must have happened before the periodic density enhancements were observed. In contrast, the periodic perturbations presented in this paper were observed after the IMF turned northward for 14 hours and were not associated with the increased geomagnetic activity prior to the quasiperiodic density enhancements. In addition, $E$ region density enhancements should increase the ionospheric conductivity and cause obvious magnetic deviations, but the magnetic perturbations in our event were very weak. In the event reported by Lessard et al. [1999], nearly monochromatic short-period (~2 min) magnetic pulsations observed at the ground and on satellite were modulated with a 45-min periodicity. They suggested that a global disturbance could induce a radially polarized electric field in the $L$ value range of 6-10; both the electron flux modulation and monochromatic pulsations were the consequence of the global disturbance. However, it was not possible to determine whether the source of the 45-min fluctuations in their event was in the solar wind or whether this frequency was intrinsic to the magnetosphere. The magnetometer at the south pole station showed oscillations with half the period of the magnetospheric electron flux modulations in their case. In
our event, the magnetospheric and ionospheric perturbations showed the same periodicity.

For northward IMF quasisinusoidal fluctuations in the Pc5 period range (1-10 min) were observed on the magnetopause [Kivelson and Chen, 1995] and were interpreted as Kelvin-Helmholtz surface waves. Papitashvili et al. [1996] presented observations of ground magnetic disturbances in the southern polar cap during a several-hour interval of northward IMF. The spectra of the disturbances showed peaks at ~15 min and ~60 min, while that study dealt with 15-min pulsations. Huang et al. [2000a] first focused upon long-period (40-60 min) ionospheric disturbances during an extended interval of northward IMF. In the event reported by Huang et al. [2000a], ionospheric disturbances and atmospheric gravity waves with a period of ~40 min were observed after $B_z$ was small ($|B_z| \leq 1$ nT) for 17 hours and then became positive for 4 hours. The $K_p$ index was 0 when the ionospheric disturbances occurred. In the event presented in this paper, $B_z$ was positive for 14 hours before the magnetospheric-ionospheric perturbations with periods 50-60 min were observed; the $K_p$ index was also near 0 (see Figure 1).

We think that the ionospheric perturbations in the previous event [Huang et al., 2000a] and in the present event could be associated with the same or similar source mechanism; the difference in the periodicity could be caused by different solar wind/IMF parameters and resultant extent of the magnetospheric tail.

In the event of Huang et al. [2000a], it was not possible to determine whether the ionospheric disturbances traveled along some specific direction. In the event presented in this paper, during the last half of each oscillation the ionospheric convection cell traveled eastward with a mean velocity of ~1.4 km s$^{-1}$, as shown in Figure 2. However, it was not possible to determine the propagation delay from ground magnetometer records because the magnetic perturbations were too weak. This is not surprising, given that the ionospheric conductivity would be very low in the nightside winter auroral zone after the extended period of northward IMF.

We now discuss the source mechanism of the long-period perturbations. It is well known that perturbations in the solar wind/IMF can result in similar perturbations in the magnetosphere and ionosphere. In the present event we are interested in the interval of 0230-0930 UT on November 11, 1998, as indicated by the vertical dashed lines in Figure 1. During this interval the solar wind velocity and density were relatively stable. The IMF components showed some fluctuations between 0500 and 0700 UT, but these fluctuations did not exist for the entire interval. In contrast, periodic perturbations were observed for the 7-hour interval in the magnetospheric and ionosphere, as shown in Plate 1 and Figures 4 and 5. Therefore we do not think that the magnetospheric-ionospheric perturbations were driven directly by solar wind/IMF perturbations. Instead, we suggest that the long-period perturbations are a natural oscillation mode in the magnetosphere; the initiation of the oscillations might be associated with solar wind/IMF perturbations.

We think that the tail acts as a large three-dimensional cavity within which various standing wave patterns can occur and that during northward IMF, some of the natural periods associated with those patterns will be from 40 to 60 min. The shape of the cavity has been the subject of several studies. Sibeck et al. [1985] found that there is an elliptical cross section of the tail in the Y-Z plane (GSM coordinates), with the tail being flattened in the Z direction and more extended by a factor of 3 in the Y direction, for a strong 12 nT draping field. For a 5 nT draping field the major axis was only 50% more than the minor axis [Sibeck et al., 1986]. More recently, Shodhan et al. [1996] considered the reasons for the Geotail mantle crossings in the tail at about $X = -170 R_E$ and found evidence for both windsock and breathing modes in the Y-Z plane, with timescales of some tens of minutes.

For northward IMF the MHD models of Barge et al. [1999] show that a cut of the tail in the Y-Z plane shows a rounded shape that looks quasidipolar but is really quite distorted from dipolar shape. It is certainly much different from the highly stretched tail shapes associated with southward IMF, as discussed by McBlay and Radiski [1967] and Ershkovich et al. [1972]. In the X-Z plane the Barge et al. [1999] MHD model shows that the X-extent of the closed field line region is strongly dependent on the $B_z$ value of the IMF, and varies from about $X = -88 R_E$ for $B_z = 2.5$ nT to $X = -40 R_E$ for $B_z = 5$ nT and finally to about $X = -29 R_E$ for $B_z = 10$ nT. In the simulations of Song et al. [1999] the tail lengths are 56 and 32 $R_E$ for $B_z = 5$ and 10 nT, respectively. For the conditions in the present paper, namely, a northward $B_z$ component in the range 3-6 nT, the tail length of the closed cavity would be about 50-80 $R_E$. The fact that the closed field region is so sensitive to IMF changes means that a variable IMF will lead to very extensive expansions and contractions of the outer magnetosphere, even with relatively minor IMF variations.

The above results show that the three-dimensional shape of the magnetotail cavity is critically dependent on IMF conditions. In general, one would expect a complex set of standing wave modes in the magnetospheric cavity. The standing wave modes in such a cavity could be excited by various mechanisms, both internal and external to the magnetosphere, including the breathing, windsock, and wrenching mechanisms suggested by Shodhan et al. [1996]. Another example involves the simulations of Usadi et al. [1993]. They showed that large-scale twin vortices can be generated in the equatorial plane of the magnetosphere after the IMF turns northward for ~1 hour (their Figure 12a). They argued that the twin vortex structure is caused by the deformation of the magnetosphere from a stretched-tail shape to a more dipolar shape, but not due to a Kelvin-Helmholtz instability. The tail convection associated with the twin vortex structure maximizes around $X = -30 R_E$ and has the vorticity associated with the region 1 currents.

Let us now concentrate on the generation of long-period oscillations due to standing waves in the X-Z plane of the tail. We propose that the periodic oscillations are excited by the movements of the closed tail boundary in response to the IMF. Such oscillations would lead to compressional waves. In turn, these waves would be reflected back at the near-Earth large pressure gradient region at about $X = -8 - 10 R_E$, with the result that a standing wave pattern is produced.

In the proposed scenario the oscillations of the tail boundary can be excited by the deformation and overshoot of the magnetosphere from a tail shape to a more dipolar shape or by IMF perturbations. Since the size of the closed magnetosphere is mainly determined by the magnitude of $B_z$, a large change in $B_z$ can cause the expansion and/or contraction of the closed magnetosphere and subsequent oscillations. This is also similar to the compression of the dayside magnetosphere by a solar wind pressure enhancement and subsequent oscillations at some intrinsic period. For the present event the IMF perturbations might play a role. The periodic ionospheric perturbations were observed 14 hours after $B_z$ turned northward. The tail oscillations excited by the first contraction of the magnetosphere could have been damped. As shown in Figure 1b, there were fluctuations in...
the three IMF components between 0030 and 0230 UT; these IMF fluctuations might have been capable of exciting the tail oscillations. After excitation the magnetospheric oscillations would continue at the natural resonant period, until they are damped due to energy dissipation. The IMF perturbations between 0500 and 0700 UT might have enhanced the tail oscillations. We suggest that the magnetospheric oscillations occur at an intrinsic frequency determined by the tail length; the function of IMF perturbations is to excite or enhance the magnetospheric oscillations.

We can estimate the period of the tail oscillations by assuming that the magnetotail cavity resonates due to the standing waves produced by compressional (magnetosonic) waves propagating between the near-Earth and distant boundaries. Under this approximation the period is given by

\[ T = \frac{2l}{v_c}, \quad (1) \]

where \( l \) is the distance between the boundaries, and \( v_c \) is the velocity of the compressional wave.

In the simulations of Bargatze et al. [1999], the outer boundary of the closed tail is at \( X = -40 R_E \) for IMF \( B_z = 5 \) nT and at \( X = -88 R_E \) for IMF \( B_z = 2.5 \) nT. The plasma pressure at the outer boundary of the closed tail is \( -0.5 \times 10^{11} \) Pa for IMF \( B_z = 5 \) nT and \( -3 \times 10^{11} \) Pa for IMF \( B_z = 2.5 \) nT, increases toward the Earth, and reaches a peak value \( -8 \times 10^{11} \) Pa at about \( X = -10 R_E \). The average pressure is \( -3 \times 10^{11} \) Pa between the outer boundary and the peak position. The geomagnetic field is almost constant \((-11.5 \) nT for IMF \( B_z = 5 \) nT and \(-3.5 \) nT for IMF \( B_z = 2.5 \) nT) between the outer boundary and the pressure maximum but suddenly increases at about \( X = -10 R_E \). In the simulations of Usadi et al. [1993], the plasma temperature in the closed magnetosphere is almost constant at \(-200 \) eV after a 90-min interval of northward IMF.

In the present event, \( B_z \) was 3-4.5 nT with a mean value of 3.2 nT over the interval 0230-0930 UT. Using a linear interpolation of the simulation results of Bargatze et al. [1999], we find that the outer boundary of the tail should be about \( X = -75 R_E \) and the geomagnetic field about 6 nT. We assume an isothermal plasma with \( T = T_e = 200 \) eV and average plasma pressure of \( 3 \times 10^{11} \) Pa. This average ion density is \(-0.5 \) cm\(^{-3}\). Accordingly, the Alfvén velocity is \( 185 \) km s\(^{-1}\). The assumed ion density and Alfvén velocity agree with estimates by other authors. For example, the typical near-tail plasma density given by Hughes [1995] is 0.01 cm\(^{-3}\) in the tail lobe, 0.1 cm\(^{-3}\) in the plasma sheet boundary layer, and 0.3 cm\(^{-3}\) in the central plasma sheet; McClay and Radisky [1967] took the Alfvén velocity to be 200 km s\(^{-1}\) in their calculations of magnetic fluctuations in the magnetotail. In the present case the magnetotail would have been highly contracted after the extended interval of northward IMF. Consequently, the plasma density could have been higher, and the Alfvén velocity could have been lower.

The relationship between the compressional wave velocity and Alfvén velocity is given by [Kivelson, 1995]

\[ v_c^2 = \frac{1}{2} \left[ v_A^2 + v_s^2 \pm \left( v_A^2 + v_s^2 \right)^{1/2} \right], \quad (2) \]

where \( v_c \) is the Alfvén velocity, \( c_s \) is the ion acoustic velocity, and \( \theta \) is the angle between the magnetic field and wave vector. The ion acoustic velocity is given by

\[ c_s = \left[ \frac{\gamma k_B T_e}{m_p + m_e} \left( \frac{T_p}{T_e} + T_e \right) \right]^{1/2}, \quad (3) \]

where \( \gamma \) is the ratio of specific heats, \( k_B \) is the Boltzmann constant, \( m_p \) (\( m_e \)) is the proton (electron) mass, and \( T_p \) (\( T_e \)) is the proton (electron) temperature. With \( T_p = T_e = 200 \) eV and \( \gamma = 1 \) (isothermal plasma), the ion acoustic velocity is 196 km s\(^{-1}\). Using \( v_c = 185 \) km s\(^{-1}\) and \( c_s = 196 \) km s\(^{-1}\) and taking \( \theta = 90^\circ \), we find that the velocity of the fast-mode wave is 270 km s\(^{-1}\). We assume that the compressional waves propagate between the outer boundary of the closed tail at \( X = -75 R_E \) and the near-Earth boundary at \( X = -10 R_E \) over a distance \( l = 65 R_E \). Therefore the period of the standing wave tail oscillations would be about 51 min, which is double the 25.5-min one-way travel time of the compressional waves from \( X = -75 R_E \) to \( X = -10 R_E \). This agrees reasonably well with the observations.

We can now address the question of why the ionospheric convection patterns observed by the radars are seen to exhibit the long-period oscillations at lower latitudes rather than at the high latitudes that would map out to the tail at 50-80 R\( E \). The answer may be similar to the effect found in the simulations of Birn and Hesse [1996] for substorm conditions. They showed that, although midtail reconnection during substorms occurred near \( X = -23 R_E \), the resulting field-aligned currents to the ionosphere were concentrated near \( X = -13 R_E \) far from the reconnection site, even though the reconnection is the ultimate energy source for the currents.

This type of scenario could be extended to the standing wave pattern in the \( X-Z \) plane that we propose above for positive \( B_z \) conditions. If the waves are not completely reflected at \( X = -10 R_E \), that is, if the boundary there is not totally fixed but is partially free, then it would be likely that some energy would be transferred from the standing wave pattern to the convection pattern at these near-Earth distances. Suppose that there is a global earthward electric field [Lessard et al., 1999]. This electric field will drive plasma to move eastward in the magnetosphere and ionosphere. The resulting lower-latitude convection pattern would exhibit the eastward motion caused by the radially inward electric field, and the convection would certainly be strongly influenced by the periodicity of the standing wave mode.

In our event the ionospheric convection vortex formed around 0200 MLT near magnetic latitude 70\(^\circ\). For a dipolar geometry the relationship between the \( L \) value in the equatorial plane and the magnetic latitude \( \theta_0 \) of the field line on the Earth's surface is given by

\[ \theta_0 = \cos^{-1} \left( \frac{1}{\sqrt{L}} \right). \quad (4) \]

For \( \theta_0 = 70^\circ \), the \( L \) value is \(-8.5 \). This is consistent with the assumed inner reflection boundary of the compressional waves and the location with large change in plasma pressure and geomagnetic field in the simulations of Bargatze et al. [1999].

The combined radar, magnetometer, and satellite observations presented in this paper have revealed some significant characteristics of the long-period magnetospheric-ionospheric perturbations during northward IMF. As discussed above, the magnetospheric-ionospheric perturbations in the present event and the previous event of Huang et al. [2000a] might have the same or similar generation mechanism. However, the period of the perturbations is \(-40 \) min in the previous event and \(-54 \) min in the present event. If the mechanism suggested in this paper is
The final position of the cell focus was around 0600 MLT and moved eastward. The eastward motion of the cell took 20 min; it remained nearly unchanged. The convection cell then started to move southward near magnetic latitude 70°. The flow intensity associated with the convection cell grew for 30 min, while the cell position remained nearly unchanged. The periodicity of magnetospheric oscillations during prolonged northward IMF, if the periodicity is indeed determined by the size of the cavity and if the field and plasma parameters in the magnetosphere are measured.

However, many questions remain unanswered. For example, it is not clear whether the ionospheric convection is symmetric with respect to the noon-midnight meridian; the radar data showed only the portion of the convection in the postmidnight sector. The present studies use radar and magnetometer data only from the Northern Hemisphere; it is necessary to investigate the conjugate properties of the perturbations in both hemispheres if the magnetospheric-ionospheric perturbations are truly a global oscillation. It is also unclear how other IMF components (B_{y} and B_{z}) and solar wind pressure play a role in determining the period of the perturbations. The assumed earthward electric field in the magnetosphere has not been verified. It is not fully understood why the convection cell does not move for the first 30 min of each cycle and what determines the final position of the cell at ~0600 MLT. It is necessary to compare the distinctive regions in the magnetosphere predicted by the simulations [Bargatze et al., 1999; Song et al., 1999] with direct measurements. More observational and simulation efforts are required to verify the proposed mechanism. We plan further studies in the above areas in the future.

4. Summary

The IMF turned northward at 1300 UT on November 10, 1998, and remained northward for 29 hours. The Kp index was not larger than 1+ over the entire interval. We have observed, for the first time, long-period magnetospheric-ionospheric perturbations with HF radars, ground-based magnetometers, and satellite magnetometers, during this prolonged interval of northward IMF. The major findings are as follows.

1. After the IMF turned northward for 14 hours, the Iceland West HF radar observed periodic F region ionospheric velocity perturbations in the postmidnight/dawn sector between 0300 and 1000 UT on November 11, 1998. Seven cycles of velocity perturbations were clearly identifiable. The velocity perturbations showed periods 50-60 min, with a mean period ~54 min. The amplitude of the line-of-sight velocity perturbations was ~500 m s^{-1}, corresponding to electric field perturbations with an amplitude ~30 mV m^{-1}.

2. For each cycle of the convection perturbations, a large-scale, counterclockwise convection cell formed around 0200 MLT near magnetic latitude 70°. The flow intensity associated with the convection cell grew for ~30 min, while the cell position remained nearly unchanged. The convection cell then started to move eastward. The eastward motion of the cell took ~20 min; the final position of the cell focus was around 0600 MLT between magnetic latitudes 75° and 80°. The mean eastward velocity of the cell shift was ~1.4 km s^{-1} during this 20-min interval.

3. Ground-based magnetometers recorded quasiperiodic magnetic perturbations with periods 50-60 min in both premidnight and postmidnight sectors. The magnetic perturbations had an amplitude 3-5 nT above magnetic latitude 70° and became very weak below that latitude. The low conductivity of the quiet nightside ionosphere would not allow effective coupling of the wave through the ionosphere, with the result that the signal seen on the ground would be significantly attenuated.

4. At the GOES 8 satellite which was nearly in the equatorial plane of the magnetosphere during the period of interest, magnetic field perturbations were also observed with periods 50-60 min at L ~ 6 on the nightside. The magnetospheric magnetic field perturbations were well correlated with the ionospheric electric field perturbations, indicating that the magnetospheric and ionospheric perturbations had a common source.

5. We propose the following mechanism for the generation of the long-period magnetospheric-ionospheric perturbations. After the IMF turned northward for a few hours, the magnetosphere becomes largely closed. The deformation of the magnetosphere from a tail shape to a dipolar shape or IMF fluctuations can excite oscillations in the closed tail. The period of the global tail oscillations is determined by the radial extent of the closed tail. The oscillations at the outer boundary of the tail are transmitted earthward at the speed of compressional waves, forming a standing wave pattern when there is partial reflection at a "leaky" boundary at about X ~ -10 Re. As a result of energy leakage at this boundary, some of the compressional wave energy may couple into convection and field-aligned currents. The latter are generated at tail distances near the leaky inner boundary because there is an interface there between two distinct flow regions, as inferred from the corresponding radar flows in the ionosphere. The field-aligned currents result in the generation of large-scale ionospheric convection vortices on the nightside. For an average B_{z} value of 3-6 nT over several hours, consistent with the observations, the period of the magnetospheric-ionospheric perturbations is expected to be in the range 40-60 min. This period is determined by a natural resonant period of the magnetic cavity, possibly associated with the compressional wave travel time between the inner and outer boundaries of the cavity.

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