Eastward propagation of a plasma convection enhancement following a southward turning of the interplanetary magnetic field

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Published version at: http://dx.doi.org/10.1029/GL013i001p00072
To link to this article DOI: http://dx.doi.org/10.1029/GL013i001p00072

Publisher: American Geophysical Union

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Abstract. On October 27th 1984, high-latitude ionospheric convection was observed by the European incoherent scatter (EISCAT) radar. For a nine-hour period, simultaneous observations of the interplanetary magnetic field (IMF) were obtained sunward of the Earth's bow shock. During this period, the IMF abruptly turned southward, having previously been predominantly northward for approximately three hours, and a strong enhancement in convection was observed 11 ± 1 minutes later. Using the very high time resolution of the EISCAT data, it is shown that the convection enhancement propagated earthward, around the afternoon magnetic local time sector, at a speed of the order of 1 km/s. These results are interpreted in terms of the effects of an onset of steady IMF-geomagnetic field merging and are the first to show how a new pattern of enhanced convection is established in the high latitude ionosphere.

Introduction

Many studies have investigated the patterns of high-latitude F-region convection and E-region currents under a variety of orientations of the interplanetary magnetic field (IMF) (e.g. Heelis and Reiff, 1985; Friis-Christensen et al., 1985). For a northward IMF, the flows are generally much slower and are confined to higher latitudes than when the IMF is southward. In some of these studies the history of the IMF was not considered, and in most of the others the convection patterns were studied for periods when the IMF orientation had been stable over extended periods of up to several hours prior to the convection observations. Nishida (1968) noted that the DP 2 current system was enhanced at high latitudes 7 ± 1 minutes after a southward turning. The initial enhancement in convection was observed 11 ± 1 minutes later. Using the very high time resolution of the EISCAT data, it is shown that the convection enhancement propagated earthward, around the afternoon magnetic local time sector, at a speed of the order of 1 km/s. These results are interpreted in terms of the effects of an onset of steady IMF-geomagnetic field merging and are the first to show how a new pattern of enhanced convection is established in the high latitude ionosphere.

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the replacement of the low-speed pattern for northward IMF by a southward-IMF pattern.

Results

Figure 2 shows the ion temperatures, $T_i$, and line-of-sight velocities, $v_T$, observed in gate 3 for each of the two azimuths shown in figure 1, for 30-second post-integration periods. The southward turning of the IMF at 1107UT is marked ST. The change in $v_T$ following the IMF turning is seen for azimuth 1 slightly before it is seen for azimuth 2, i.e. the effect appears to be propagating eastward. To quantify this visual impression, a cross-correlation analysis was carried out for the line-of-sight velocities observed in the two beam directions. This analysis was repeated for the ion temperatures.

The results are given in figure 3 which shows the correlation coefficients, $r$, for $T_i$ and $v_T$, respectively, giving mean eastward velocities, $\Delta x/\Delta t$, of $2.6 \pm 0.3$ km$^{-1}$ and $1.5 \pm 0.1$ km$^{-1}$. Similar correlation analyses between data from different range gates, for each of the two azimuths, give delay estimates, $\Delta t$, which correspond to only a small southward component perpendicular to the L-shell. Hence the changes in $v_T$ and $T_i$ are propagated slightly south of eastward around the afternoon sector. In the following section these results are interpreted in terms of the expansion of the new enhanced convection pattern.

Discussion

After three hours of northward IMF, the pattern of convective flows in the polar ionosphere is known to be weak and contracted. Some open flux would still exist, mapping through the distant tail to the IMF. If a southward turning of the IMF then impinges on the magnetopause, daytime field line merging would cause flux tubes sunkward of the old polar cap to

Figure 1. Map of the EISCAT radar showing the two beam directions employed in the U.K. Special Programme POLA.
become open. As additional flux is connected to the IMF, the region of newly-opened field lines expands rapidly outward from a small initial area. Within this region field tension produces anti-solar flow and, as ionospheric flow is incompressible, this generates a new twin-vortex flow pattern, of the kind illustrated in figure 4a; this must also grow rapidly. The flow pattern would be established by the region of newly opened flux via Alfvén waves which propagate perpendicular to the geomagnetic field lines at a speed very much greater than the expansion speed of the open flux boundary. In this way, a new polar cap and a new twin-celled convection pattern might be established following a southward turning of the IMF.

In this section we shall discuss how the EISCAT data presented in the previous section are consistent with these concepts and with the motion of the equipotential contours over the field of view as the new convection pattern expands.

Consider a constant potential difference \( \Phi \), applied across a small region of the magnetopause at time \( t=0 \) by the onset of steady IMF - geomagnetic field merging. In this letter it is assumed that the the region of the ionosphere where flux is opened to the IMF is elliptical, of semi-axes \( a \) and \( b \) at time \( t \) (see figure 4a). Siscoe and Huang (1985) have performed calculations for the inflation of a circular cap \( (c=1) \), however for \( t \) near zero an elliptical form may be more general. The total flux connected to the IMF at the time \( t \) is given by:

\[
B_i \pi ac^2 = \Phi t
\]

(1)

where \( B_i \) is the geomagnetic flux density at ionospheric altitudes. This equation assumes that \( t \) is sufficiently small that no open flux is lost from the region by reconnection in the geomagnetic tail. Phenomena associated with enhanced tail reconnection are not observed until about 25-40 minutes after the IMF southward turning impinges on the magnetopause (eg. Baker et al., 1983). Hence the velocity of expansion of the boundary of the open flux region is:

\[
v = \frac{ds}{dt} = \frac{1}{2} \sqrt{\frac{\Phi}{B_i}} \frac{\cos^2 \theta + c^2 \sin^2 \theta}{c}
\]

(2)

The distance \( s \) and the angle \( \theta \) are defined by figure 4a, and \( c \) is assumed not to vary with \( t \).

From the AMPTE data, the energy coupling factor, \( \gamma \) (as defined by Reiff et al., 1981), can be computed for immediately before and after the southward turning, regression equations from Reiff et al. give a value for the cross polar-cap potential for a steady-state polar cap, \( \Phi_\gamma \), as a function of \( \gamma \). The values of \( \gamma \) before and after the southward turning give \( \Phi_\gamma \) of 30kV and 170kV respectively, hence a value of 140kV is taken here for \( \Phi_\gamma \).

In this figure 4a, A twin vortex pattern of the kind set up by an elliptical region of open flux centred on the point A. (b) Schematic illustration of the origin of the delay, \( \tau \), between the IMF change seen at the AMPTE UKS and the apparent F-region response seen by EISCAT. From the solar wind and Alfvén propagation speeds, \( v_{sw} \) and \( v_A \) respectively, \( \Delta t_{sw} \) and \( \Delta t_A \) can be estimated, giving \( \tau \), the delay between ionospheric flux tubes (at the point A) first becoming open to the IMF and the convection enhancement being observed at EISCAT.
Figure 4b demonstrates how a value for t can be estimated. From UKS observations of the solar wind speed, Rishbeth et al. (1985) estimated the delay between the IMF change passing the UKS and reaching the sub-solar magnetopause to be $\Delta t_{SW} = 4 \pm 1$ minutes, and the propagation time of Alfvén waves along geomagnetic field lines from the magnetopause to the cusp ionosphere to be $\Delta t_m = 2 \pm 1$ minutes. As the temperature and convection enhancements are first observed $t = (11 \pm 1)$ minutes after the IMF change seen by the UKS, $t$ can be estimated to be $t = (C - $ $\Delta t_{SW} - \Delta t_m ) = 5 \pm 3$ minutes. Using $B = 5 \times 10^5$ Tesla, equation (2) yields a range for $v$ between 1.4 and 0.7 km s$^{-1}$ for a circular region of open flux ($V = 1$), as used by Siscoe and Huang. These are of the same order of magnitude as the observed eastward velocities but are a factor of about 2 smaller; the difference could have arisen because EISCAT observes the velocity of expansion of the equipotential and ion temperature contours set up by the open field region ($V_e$ in figure 4a), rather than the velocity of the boundary of that region ($V$).

Equation (2) shows that higher $v$ would result from a non-circular open flux region (for example with $c < 1$ for $\theta = 0$).

From both the $T_i$ and the $v_T$ data, it is found that the centre of the new convection pattern (point A in figure 4a, which maps to the point on the magnetopause where merging commenced) was somewhere between 1120 and 1300 MLT. The EISCAT observations are near 1400 MLT and this analysis show that the additional lag between the sudden changes in the AMPTE and EISCAT data, as identified by Rishbeth et al. (1985), can be explained by this simple model of the expansion of the new, enhanced convection pattern from a centre which is located nearer to local noon. The predominantly eastward direction of the expansion implies that $\theta = 0$ and that the latitude of A is not far to the north of the POLA field of view.

Conclusions

Very high time resolution data from EISCAT show that ion temperature and line-of-sight velocity changes observed 11 minutes after a southward turning of the IMF, were propagated eastward around the afternoon sector with speeds of the order of 1 km s$^{-1}$. Such expansion speeds are expected from simple considerations of the onset of steady field line merging at the magnetopause and explain the additional delay before enhanced convection is observed at a location away from the ionospheric footprint of the initial merging region, i.e. outside the cusp region. These EISCAT data are the first of sufficiently high time resolution to show how a pattern of sluggish convective flow, characteristic of a northward orientation of the IMF, rapidly evolves into an enhanced pattern, of the kind expected for a southward IMF.

Acknowledgements. We thank the Director and staff of EISCAT for their help and Dr D.J. Southwood for the provision of the AMPTE-URS magnetometer data. EISCAT is supported by the U.K. SERC, French CNRS, West German MPG, Norwegian NAVF, Swedish NFR and Finnish SA. AMPTE is a collaborative project of NASA (USA), DFVLR and MPG of West Germany and SERC of U.K.

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(Received October 28, 1985; revised December 2, 1985; accepted December 2, 1985)