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EASTWARD PROPAGATION OF A PLASMA CONVECTION ENHANCEMENT FOLLOWING A SOUTHWARD TURNING OF THE INTERPLANETARY MAGNETIC FIELD

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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 eastward, around the afternoon magnetic local time sector, at a speed of the order of 1 kms^{-1}. 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) (eg. 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 of the IMF impinged upon the Earth's bow shock. McPherron and Manka(1985) and Clauer and Kamide (1985) have recently reported similar delays. Enhancements in convection speeds in response to IMF changes have been observed using the Sondrestromfjord incoherent scatter radar with a time resolution of about 25 min. (Clauer et al.,1984).

EISCAT observations of 2.5-minute resolution allow the lag between the IMF change and the response of F-region convection to be quantified for the first time. Rishbeth at al. (1985) observed a delay which was roughly twice the time expected for the IMF effect to reach the ionosphere. In this letter the same EISCAT data are analysed at even higher time resolution (post-integration periods of 30 seconds). It is shown that the additional delay is consistent with the initial expansion of a new enhanced convection pattern.

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Observations

The U.K. Special Programme "POLA" uses the EISCAT radar to study high-latitude plasma convection in the F-region of the ionosphere at invariant latitudes between about 71° and 75°. The experiment uses a monostatic beam-swinging technique, signals being transmitted and received at Tromsø along two azimuths 24° apart (see figure 1). The line-of-sight velocity component, v_T, is measured in each beam direction with resolution in invariant latitude of about 0.5°. Data for the third range gate are presented here; other gates give similar results but have lower signal-noise ratios. The azimuths were chosen such that, for the same range, the two scattering volumes are centred at the same invariant latitude (van Eyken et al.,1984). Gate 3 is at an invariant latitude of 72.0° and the spatial separation of the scattering volumes for the two azimuths, Δx, is 281 km. Observations are made in a 5-minute cycle: eight 15-second pre-integrated data dumps are recorded for azimuth 1; these are followed by thirty seconds during which the Tromsø antenna is in motion and a further eight 15-second data dumps for azimuth 2 ; the cycle ends with a second 30-second period during which the antenna returns to azimuth 1. In van Eyken et al. (1984) and Rishbeth et al. (1985) line-of-sight components were combined to derive velocity vectors with 2.5-minute resolution. In this letter only the directly-measured line-of-sight velocity components and the ion temperatures are studied, but at higher (30-second) time resolution.

For a nine-hour period on October 27th, 1984, simultaneous observations of the IMF were obtained from the UK satellite (UKS) of the Active Magnetospheric Particle Tracer Explorer (AMPTE) mission. At 1107UT the IMF abruptly turned southward, having been predominantly northward for the previous three hours. At this time, the UKS was near $18R_E$, upstream of the Earth's bow shock, and the EISCAT scattering volumes were at an MLT of about 1400hrs. Subsequent correlation analysis has shown that the strong increase in westward convection (see figure 1 of Rishbeth et al,1985) occurred 11 ± 1 minutes after the southward turning. The initial onset of high convection velocities caused a sharp rise, and subsequent decay, in ion temperatures due to the enhanced ion-neutral frictional heating. The velocity vectors observed before and after the enhancement are drawn from different convection patterns; the data set appears to show

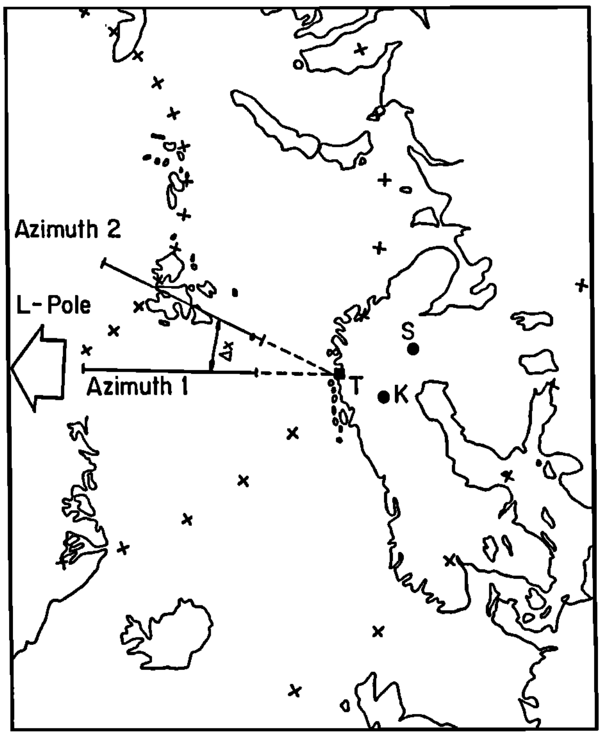

Fig. 1. Map of the EISCAT radar showing the two beam directions employed in the U.K. Special Programme POLA.

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 (a), T_i and (b), v_T, and the respective $|z/\sigma|$ values, where z is the Fisher-z variable and σ is the variance. The significance levels ascribed to the r values, from these $|z/\sigma|$, are overestimates as they assume normal distributions of samples and do not account for the persistence in the T_i and v_T time series. Values are given as a function of lag Δt, introduced between the two time series for the two azimuths; the convention adopted for the sense of Δt is such that for positive Δt the observations for azimuth 2 are lagged: azimuth 1 data for 1115-1139 UT are always used (as marked in figure 2) and are correlated with azimuth 2 data for $(1115+\Delta t)$-$(1139+\Delta t)$ UT. It can be seen that, for positive Δt, no correlation coefficients greater than 0.6 are obtained and none are significant at more than the nominal 99% level. However for negative Δt, peak correlation coefficients greater than 0.95 are obtained for both v_T and T_i at nominal significance levels greater than the 99.99% level. This effect was revealed by all gates having sufficient signal-noise ratio to allow 30-second analysis of the signal spectrum.

Fits were made to the r-Δt curves shown in figure 3, weighted according to the number of samples used to obtain each value of r. From these fits, the lags of the peak correlation, Δt_p, were found to be 1.8 ± 0.2 minutes and 3.1 ± 0.2 minutes for the T_i and v_T enhancements respectively, giving mean eastward velocities, $\Delta x/\Delta t_p$, of 2.6 ± 0.3 kms^{-1} and 1.5 ± 0.1 kms^{-1}. Similar correlation analyses between data from different range gates, for each of the two azimuths, give delay estimates, Δt_p 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, dayside field line merging would cause flux tubes sunward of the old polar cap to

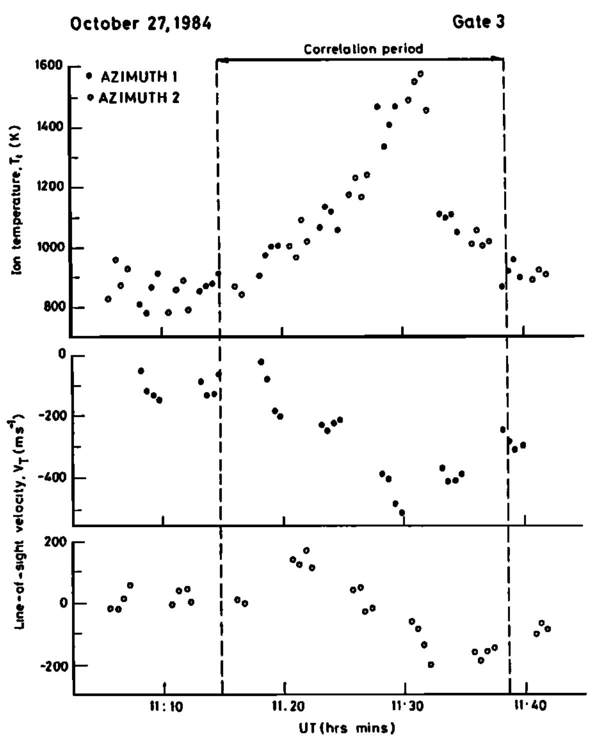

Fig. 2. Ion temperatures, T_i , and line-of-sight velocities, v_T , observed for the two POLA azimuths in gate 3 (height=277 km, invariant latitude = 72.0°). The southward turning of the IMF was observed by the AMPTE UKS at 11:07UT.

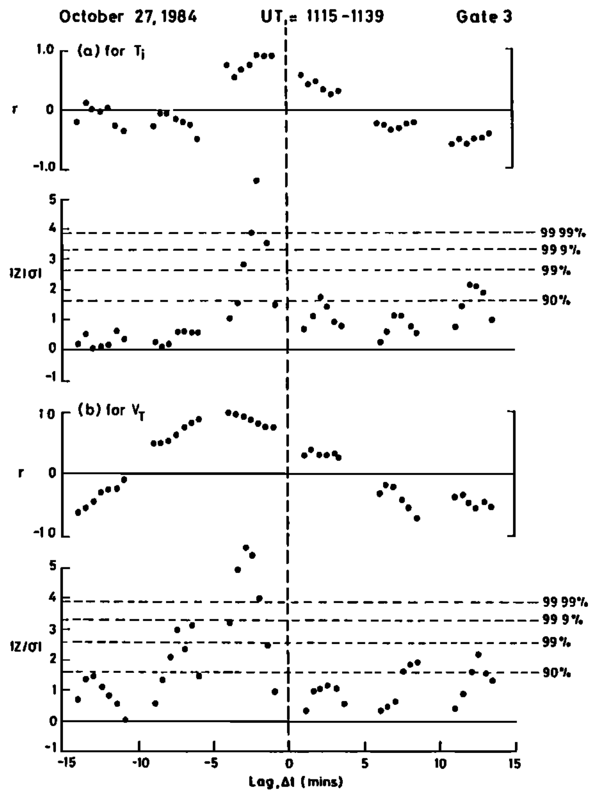

Fig. 3. Correlation coefficients ,r, between the two azimuths as a function of lag , Δt, for (a), T_i and (b), v_T. For positive Δt, the time series for azimuth 2 has been lagged. Also shown are the values of $|z/\sigma|$ (see text).

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 ϕ, 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 a×c 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 :

$$B_i \, \pi c a^2 = \phi t \qquad (1)$$

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 :

$$v = \frac{ds}{dt} = \frac{1}{2}\sqrt{\frac{\phi}{B_i \pi t} \; \frac{\cos^2\theta + c^2\sin^2\theta}{c}} \qquad (2)$$

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

From the AMPTE data, the energy coupling factor, ε (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, ϕ_S, as a function of ε. The values of ε before and after the southward turning give ϕ_S of 30kV and 170kV respectively, hence a value of 140kV is taken here for ϕ.

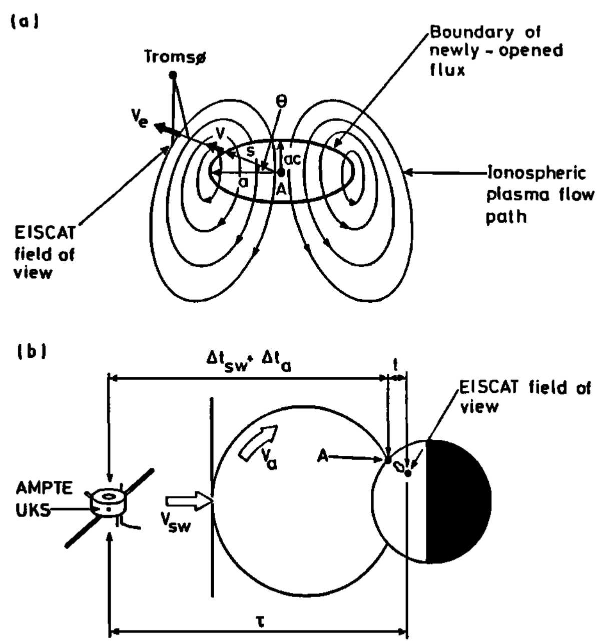

Fig. 4. (a) A twin vortex pattern of the kind set up by an elliptical region of open flux centred on the point A. (b) Schematic illustration of the origin of the delay, , between the IMF change seen at the AMPTE UKS and the apparent F-region response seen by EISCAT. From the solar wind and Alfvén propagation speeds, v_{sw} and v_a respectively, Δt_{sw} and Δt_a can be estimated, giving t, 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 Δt_{sw} = 4 ± 1 minutes, and the propagation time of Alfvén waves along geomagnetic field lines from the magnetopause to the cusp ionosphere to be Δt_a = 2 ± 1 minutes. As the temperature and convection enhancements are first observed τ (=11 ± 1) minutes after the IMF change seen by the UKS, t can be estimated to be ($\tau - \Delta t_{sw} - \Delta t_a$) = 5 ± 3 minutes. Using B = 5 × 10^{-5} Tesla, equation (2) yields a range for v between 1.4 and 0.7 kms^{-1} for a circular region of open flux (c=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 θ = 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 4, 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 $\theta \simeq 0$ 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 $1 kms^{-1}$. 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.

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