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PRODUCTION OF POLAR CAP ELECTRON DENSITY PATCHES BY TRANSIENT MAGNETOPAUSE RECONNECTION

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Abstract. Some implications are considered of recent theoretical work concerning the excitation of dayside ionospheric convection by magnetic reconnection at the dayside magnetopause. In particular, transient bursts of such reconnection ('flux transfer events') are considered as a cause of polar cap 'patches' of enhanced plasma density. Examples of such patches, as observed at European longitudes by the EISCAT radar, are presented and used to discuss the implications of the proposed mechanism.

Introduction

Polar cap 'patches' are regions of enhanced F-layer plasma density, observed convecting antisunward in the polar cap, particularly in winter at sunspot maximum (e.g. Buchau et al., 1985). Their high densities and UT dependence verify that they are produced by solar photoionisation on the dayside and convected into the polar cap. The time constant for the decay of the enhancement is typically comparable with, or larger than, the transpolar convection time and hence such patches can be observed throughout the polar cap, even on the nightside. Steady convection can draw solar-produced plasma into the polar cap; however, this would yield a spatially continuous 'tongue' of enhanced plasma across the polar cap. Hence the fact that the enhanced plasma is frequently observed as a series of drifting patches, rather than a continuous tongue, indicates that the convective flow is not steady (Anderson et al., 1988).

Recent observations of convection bursts in the dayside auroral ionosphere, accompanied by transient auroral forms, have been interpreted in terms of transient magnetopause reconnection ('flux transfer events', FTEs). This is because their occurrence and motion is controlled by the interplanetary magnetic field (IMF) in a manner consistent with that expected for newly-opened flux tubes (e.g. Lockwood et al., 1989). These events are broadly consistent with recent theoretical considerations of the ionospheric signatures of FTEs (Cowley et al., 1991; Smith et al., 1992), based on observations of the response of convection to changes in the IMF (see Cowley and Lockwood, 1992). In this paper, we consider how this theory can predict the occurrence of polar cap patches, with reference to EISCAT observations of electron density.

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EISCAT Observations of Patches

Figure 1 presents EISCAT observations of the F-region plasma density, made using the 'Polar' experiment. In this mode the radar points poleward, at 20° elevation, along two azimuths, one 12° to the west of the magnetic meridian and the other 12° to the east. Almost identical results were obtained along the two azimuths: here only data for the western azimuth are shown. The data are displayed as a function of invariant latitude Λ but, because of the slant path of the beam, the altitude of observation increases from 200 km to 650 km as Λ increases from 71° to 78°. All latitudes were sampled simultaneously. Each panel shows the data for one whole day. The local MLT is approximately UT+2.75 hours. Note that for panels 1 and 2, the plots start at 10 UT (12:45 MLT), but panel 3 starts at 15:15 UT (18 MLT) in order to show features around noon as well as midnight. Near midnight (observed at about 21:15 UT), (a), (b) and (c) provide examples of a continuous plasma tongue, discrete patches and no significant polar cap densities, respectively. However (c) does show patches near noon.

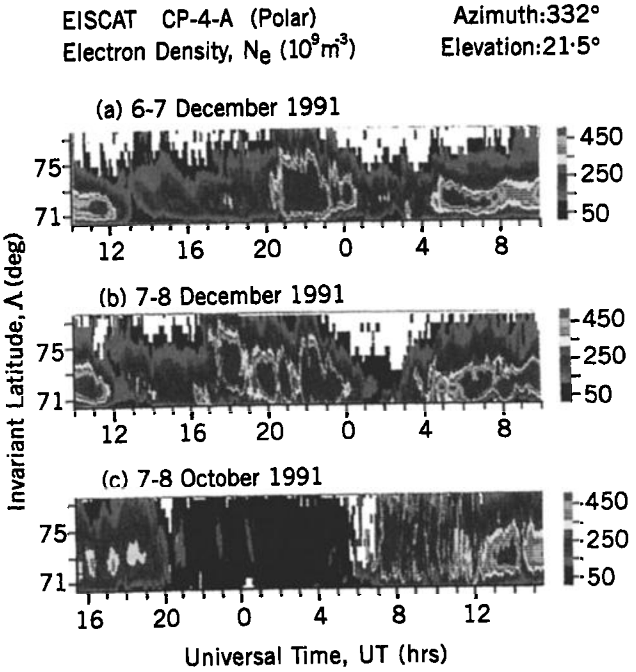

Fig. 1. Plasma densities observed by the EISCAT 'Polar' experiment on (a) 6 December 1991, (b) 7 December 1991 and (c) 7 October 1991.

On 6-7 December 1991, the highest plasma densities are near local midnight. This is commonly the case in the EISCAT winter data. The plasma vector flow, derived from the two azimuths, is antisunward at these times, showing these data to be in the nightside convection polar cap. The region of high density is broadly continuous for about 2.5 hours, showing structure only after about 22:30 UT. This is then initially a tongue-like polar cap plasma feature.

On the next day, 7-8 December 1991, EISCAT again observed the highest plasma densities near midnight. However this time they are observed as a series of equatorward-moving patches. The density enhancements approach the radar at about 0.5-1 km s^{-1} (along both azimuths), consistent with the simultaneously measured plasma convection. Note that the patches are less clear at the furthest latitudes because the altitude is greater there.

The 7-8 October 1991 data near midnight show neither a plasma-tongue, nor a series of significant patches. However, starting at about 07 UT (09:45 MLT) on 8 October, a series of poleward moving patches are observed. Again the patch motion and the plasma drift velocity are both about 1 km s^{-1}. This behaviour persists between about 7 and 11 UT (09:45-13:45 MLT), yielding 9 discrete patches and hence a mean repetition period of about 25 min. Patches of a similar kind were observed moving poleward by the Chatanika radar, using a similar observation mode (Foster and Doupnik, 1984). In that case the repetition period was shorter (about 7 min.) but the patches had smaller north-south extent.

The Effects of Transient Magnetopause Reconnection

Figure 2 considers what happens during a burst of magnetopause reconnection which applies a voltage (in its own rest frame) along the X-line, AB, in the low-latitude magnetopause (dashed line). In the absence of any significant field-aligned voltage drop, this must equal the voltage along the ionospheric projection of the X-line, the merging gap ab, in its own rest frame (i.e. that of ab). As discussed by Lockwood and Cowley (1992), this can be achieved in two ways. Firstly, there could be no initial ionospheric flow in the Earth's frame, but the merging gap would move equatorward; alternatively, the merging gap could remain static in the Earth's frame, and then there would be poleward flow across the boundary in the Earth's frame. In either case, flux is transferred across the boundary, in its own rest frame, at a rate equal to the applied voltage along the X-line. In general, both may occur to some extent.

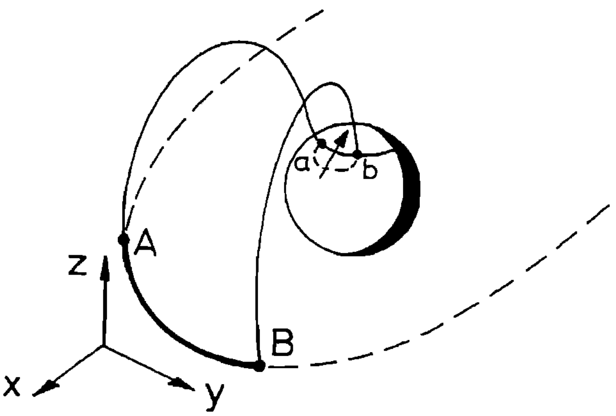

Fig.2. Projection of magnetopause reconnection X-line (AB) to ionospheric merging gap (ab). A pulse of reconnection voltage along AB can drive poleward ionospheric flow in the Earth's frame of reference or can move ab equatorward, or both (adapted from Lockwood and Cowley, 1992).

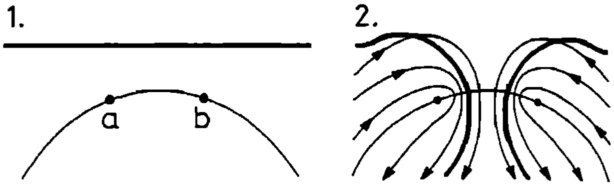

Fig. 3. Dayside ionospheric flow patterns for pulsed magnetopause reconnection if the merging gap is stationary in the Earth's frame: (1) between the pulses; (2) during the pulse. Noon is at the top and dawn to the right in both cases. The solid line shows a plasma density contour in its initial location (1), and after repeated pulses in (2): high plasma densities are sunward of this contour (see text for details).

In this section we consider the effects of a series of such reconnection pulses, between which the reconnection X-line becomes fully dormant. Magnetopause signatures usually interpreted in terms of such transient reconnection typically occur with a 2-20 min. repetition period (Elphic,1988), averaging about 7 min. To clarify presentation of the effects, we shall consider pulses lasting 5 min. and repeating with an above-average period of about 20 min. We shall also omit complications introduced by a non-zero IMF B_y component. Many of the features discussed here will apply to larger $|B_y|$ cases; however, the stronger zonal flows produced by the 'magnetic tension' force will tend to deplete the plasma and complicate the resulting density distribution.

In figure 3, the merging gap (ab) is considered to remain fixed in the Earth's frame. In this case, there is no flow in the dayside ionosphere between the reconnection pulses (all other sources of flow being considered inactive) as shown in part (1). During the reconnection pulses, the flow pattern is as in part (2), with the full reconnection voltage appearing as flow across the merging gap, ab, in the Earth's frame. The solid line in part (1) is a line of constant plasma density. In the absence of plasma flow (for sufficient period) this will be broadly aligned with a line of constant zenith angle. The density falls steeply with distance antisunward across this line for two reasons; the decay of solar photoionisation rate with increased zenith angle across the day/night terminator and the decreasing time of exposure of more poleward flux tubes to ionizing solar radiation. The figure therefore describes a winter situation at a certain UT and with a certain polar cusp latitude, such that the merging gap ab lies slightly antisunward of the day/night terminator. In the absence of motions of the polar cap boundary (and hence the merging gap ab), the ionospheric flow would repetitively be enhanced during the reconnection bursts. Hence flux tubes would move along the streamlines shown in (2), but in a stop-start manner. The non-steady nature of the motion may alter the plasma densities somewhat (via the velocity dependence of the reaction rates) but, because the plasma decay time is considerably greater than the reconnection burst repetition rate, the plasma distribution would be similar to that for steady reconnection at the average rate. Hence a tongue of plasma will be produced, extending into the polar cap, as solar-enhanced plasma is moved anti-sunward by the convection, as shown in (2) and this mechanism alone does not appear likely to give patches within the polar cap.

In figure 4, the merging gap ab is allowed to migrate equatorward during the reconnection pulses. The theory presented by Cowley and Lockwood (1992) predicts that when the reconnection ceases, the open-closed boundary will relax back poleward toward an equilibrium configuration. From both theory and observation, this relaxation time is thought to be about 10-15 min. Because the electric field along ab, in its own rest frame, is zero at these times (i.e. no reconnection is taking place) the plasma around the boundary moves with the boundary (i.e. it is said to be 'adiaroic'). The flow patterns in figure 4 are similar to those derived by Cowley et al. (1991), other than that the reconnection pulses are considered to be longer and less frequent.

From the same initial conditions as in figure 3, figure 4 considers conceptually the evolution of the flows and regions of high plasma density, with snapshots 2.5 min. apart. Starting from the same initial conditions as in figure 3 at time t=0 in (1), the burst of reconnection starts at time t=2 min. At t=2.5 min (2), the merging gap is moving equatorward, and there is some weak flow excited. Because the enhanced reconnection is envisaged as occurring first at the centre of the X-line and subsequently spreading away from noon, the merging gap has moved furthest near its centre. In (3) the flow has increased and is starting to significantly move the high-density plasma on the dayside, distorting the plasma density contour as shown. Indeed, in this snapshot, the reconnection burst has begun to reconnect field lines on which the F-region plasma density is high because it previously resided in sunlight. At time t=7 min. the reconnection burst ends. Hence the merging gap begins to return poleward with the local plasma flow. As with the onset of reconnection, this is envisaged to commence at the centre of the merging gap and then spread east and west. The distortion of the plasma density contour continues in (4) and (5) as the flows decay, and the magnetosphere-ionosphere system tends towards an equilibrium with the new amount of open flux. By t=15 min., the flows have returned low density plasma sunward of high density plasma and the patch is "pinched off" by the time the flows have ceased (8). In principle, the flows shown in fig. 4 would leave the patch connected to the dayside by a narrow tongue between the two flow cells. However, in practice small movements of the zero-potential contour (e.g. due to fluctuations in IMF B_y) will probably act to disperse such a feature. At t=19.5 min. the next reconnection burst commences and the flows in (9)-(12) are the same as in (2)-(5). While producing a second patch, these flows are also moving the first patch poleward and tending to elongate it in the dawn-dusk direction (for this case with zero IMF B_y).

Discussion

Figure 4 demonstrates a mechanism whereby discrete patches of enhanced plasma density are produced in the polar cap by transient bursts of dayside reconnection. To illustrate the mechanism we have considered reconnection bursts 17.5 min apart, and lasting 5 min. Although there is little doubt that such periods can and do occur, shorter intervals are more commonly inferred from the ISEE and AMPTE magnetopause data (Elphic, 1990). To consider their effect, we must recall that the density varies significantly over a few 100 km transverse to the single contour discussed in figures 3 and 4. Hence we would expect shorter-lived events to give less equatorward motion of the merging gap and to cause smaller differences in density between inside and outside the patch. For FTE repetition rates which are very short (1-2 min.), it is possible that the resulting density fluctuations

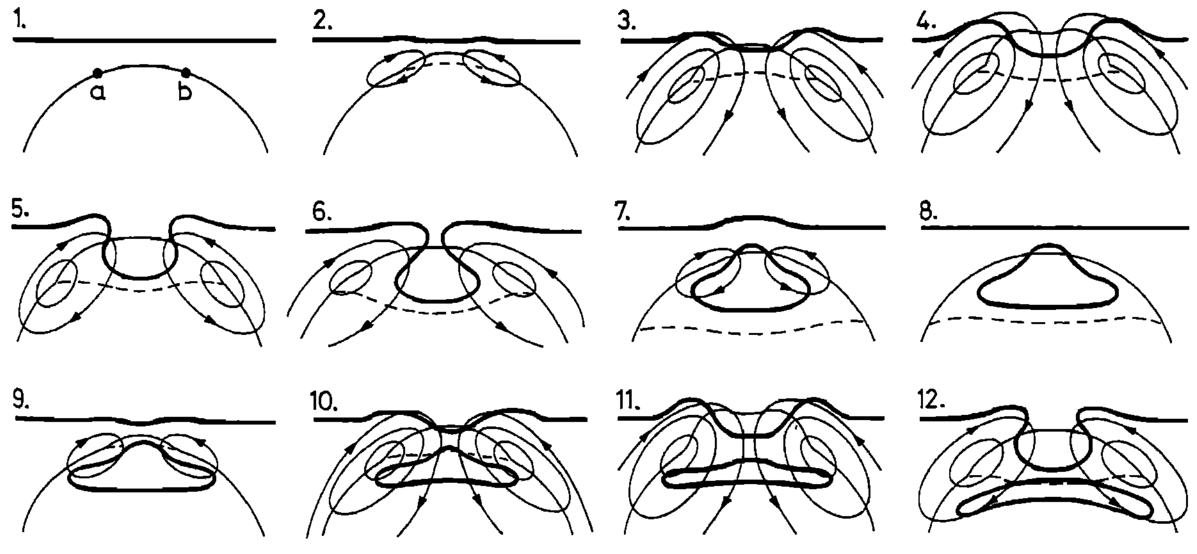

Fig. 4. Sequence of flow snapshots 2.5 min apart, for a sequence of reconnection pulses during which the merging gap migrates equatorward (adapted from Cowley et al., 1991). The solid line is a high plasma density contour.

would not be defined as patches at all, and such reconnection would produce a polar cap tongue, as if the reconnection and convection were completely steady. In this case, the occurrence of large density fluctuations would reflect only the occurrence of larger, longer-lived and less frequent of the spectrum of reconnection rate variations. The periods discussed here are very similar to those required to explain the patches seen moving poleward on the dayside on 7 October 1991 (figure 1, panel 3). However, the same mechanism would be applicable to the shorter repeat period events reported by Foster and Doupnik (1984).

We also note that this mechanism for allowing high density plasma into the polar cap in patches relies on a certain position of the dayside open/closed field-line boundary, relative to the contours of solar zenith angle. Hence the occurrence of patches will depend upon season, UT, and polar cap size. Because the mean plasma density at a given zenith angle also depends on the sunspot number, there will be a solar cycle dependence also. These variations are largely independent of the convection mechanism invoked to bring dense, solar-produced plasma into the polar cap.

Because of the above factors, the optimum time for patch production is, for typical polar cap radii, around 18 UT. At these times, the EISCAT Polar experiment is observing the nightside polar cap, where patches would be expected to arrive at around 20 UT, allowing for a 2-hour transpolar travel time. Hence behaviour of the kind shown in the top panel of figure 1 is expected to be typical. The occurrence of a tongue, rather than a discrete series of patches, on 6 December 1991 could for instance be due to a reconnection rate that was more steady than on the following day, or simply arise because the polar cap was more inflated on 6 December. In the latter case the merging gap would always be sunward of the day/night terminator, and then even transient reconnection would only give a tongue of ionisation.

In addition, we would expect the dayside polar cap boundary latitude to show variations with the phase of the substorm cycle (Lockwood and Cowley, 1992). Reconnection, proceeding as a series of bursts, will move the dayside polar cap boundary equatorward in a stepwise manner, if unopposed by nightside reconnection. Hence during the growth phase of a substorm the boundary may move from a location which gives no high plasma densities within the polar cap, through one which yields patches to one which generates a continuous tongue. Similarly, during the expansion/recovery phase the opposite sequence may occur as the polar cap is deflated by dominant reconnection in the geomagnetic tail. Hence the morphology of patches may show a dependence on the phase of the substorm cycle. This could, for example, explain the onset of patch formation around 23 UT on 6 December 1991 (figure 1a). Alternatively, this may be simply a UT effect.

The absence of any high densities on the nightside on 7 October 1991 suggests weak or contracted convection cells at those UTs. However, the IMF must have swung strongly southward before 07 UT on 8 October, when the convection observed by 'Polar' (at 09:45 MLT) was strong (>1 km s^{-1}) and poleward (antisunward), placing the convection boundary close to 71° invariant. At this time, patches were observed moving poleward throughout the experiment field of view.

Conclusions

A mechanism whereby transient bursts of dayside magnetopause reconnection produces polar cap patches has been presented. An important feature is that the reconnection burst causes the merging gap (the ionospheric projection of the reconnection X-line) to migrate equatorward. Without motion of the polar cap boundary, the flow would tend to generate a tongue of ionisation rather than patches, even if the reconnection is pulsed. Examples of patches observed by EISCAT in the polar cap are presented. They exhibit the range of behaviour of plasma density predicted by this mechanism in the convection polar cap.

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