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On the possible role of cusp/cleft precipitation in the formation of polar-cap patches

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Abstract. The work describes experimental observations of enhancements in the electron density of the ionospheric F-region created by cusp/cleft particle precipitation at the dayside entry to the polar-cap convection flow. Measurements by meridian scanning photometer and all-sky camera of optical red-line emissions from aurora are used to identify latitudinally narrow bands of soft-particle precipitation responsible for structured enhancements in electron density determined from images obtained by radio tomography. Two examples are discussed in which the electron density features with size scales and magnitudes commensurate with those of patches are shown to be formed by precipitation at the entry region to the anti-sunward flow. In one case the spectrum of the incoming particles results in ionisation being created, for the most part below 250 km, so that the patch will persist only for minutes after convecting away from the auroral source region. However in a second example, at a time when the plasma density of the solar wind was particularly high, a substantial part of the particle-induced enhancement formed above 250 km. It is suggested that, with the reduced recombination loss in the upper F-region, this structure will retain form as a patch during passage in the anti-sunward flow across the polar cap.

Key words. Ionosphere (ionospheric irregularities; particle precipitation; polar ionosphere)

Introduction

Structures of enhanced F-region density at a variety of scale sizes are present in the polar-cap ionosphere. One class of features, commonly referred to as polar-cap patches, appear in the form of localised regions of enhanced F-region plasma density, drifting in the antisunward convection across the polar cap (Buchau *et al*., 1983; Weber *et al*., 1984, 1986). The patches were identified using ionosodes and all-sky imaging photometers, but subsequently have been studied by many other instrumental techniques, including incoherent scatter radar, HF radar and even radio scintillation. A comprehensive review by Crowley (1996) gives an excellent overview of current understanding of polar-cap patch morphology and formation. Comparison between different techniques is not always easy because of different criteria used to define patches. However Crowley (1996) reports an attempt to give formal definition, where plasma enhancements observed by radio techniques should only be called patches if they are at least a factor of two above the background density and at least 100 km in diameter. For observations of 630.0 nm airglow due to radiative recombination of O^+, a patch should be at least 50 R and more than 50% above the background brightness.

Polar-cap patches occur predominantly under active conditions when the B_z component of the interplanetary magnetic field (IMF) has a southward component (Buchau *et al*., 1983; McEwan and Harris, 1996). However, no single mechanism has been identified as being responsible for the creation of patches. Most of the proposed mechanisms rely on plasma transport, rather than in-situ production, and almost all of the reported experimental evidence is in the form of individual case studies. Several authors, including Foster and Doupnik (1984), Kelley and Vickrey (1984), Whalen (1994) and Pinnock *et al*. (1995), reported regions of enhanced F-layer plasma convecting from the solar-illuminated dayside into the cusp/throat region. Buchau *et al*. (1985) found that the electron densities in the patches were similar to those at dayside sub-auroral latitudes, leading to proposed production mechanisms whereby solar-produced plasma becomes entrained in the high-latitude convection system, feeding a 'tongue-of-ionisation' into the polar cap. It has been suggested that time-varying changes to the convection

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pattern segment the tongue of ionisation and hence generate patches. Variations in both the B_z and B_y components of the IMF have been cited as being responsible for the plasma structuring. Several modellers have demonstrated that simple, instantaneous switches in the IMF could result in discrete patches similar to those observed experimentally (e.g., Anderson *et al.*, 1988; Sojka *et al.*, 1993, 1994; Decker *et al.*, 1994). The transient reconnection associated with flux transfer events has been invoked by Lockwood and Carlson (1992) as a possible mechanism. However, it has been noted that typical latitudinal gradients in electron density may not be sufficient to explain patch formation by rapid changes in the IMF; a problem particularly acute in the Southern Hemisphere, where the terminator often lies well away from the convection throat (Rodger *et al.*, 1994). Other possible causes for break-up of the tongue of ionisation include more localised convection effects, like short-lived convection jets linked to flow-channel events (Rodger *et al.*, 1994) and travelling twin-convection vortices (Schunk *et al.*, 1994). The high-speed plasma flows associated with such phenomena generate localised Joule heating, with a rise in plasma temperature leading to an enhanced ion-recombination rate (Valladares *et al.*, 1996). It is suggested that the localised erosion of the plasma density causes segmentation of the tongue of ionisation into discrete patches. Additional sources of plasma enhancement have been considered, including in-situ production by particle precipitation. Weber *et al.* (1984) proposed the idea of 'spatial resonance', in which plasma and particle source convect together at the same velocity, thus allowing sufficient time for the plasma density to build-up. More recent work by Rodger *et al.* (1994) cites a combination of particle precipitation in the cusp coupled with flow-channel events to explain two case studies of patch formation over Antarctica. However, little work has been done to ascertain the possible contribution of particle precipitation to patch formation and there have been few experimental observations.

The current study addresses the issue of particle-impact ionisation associated with cusp/cleft precipitation. The spatial distribution of ionospheric plasma density near the polar-cap inflow region has been obtained by radio tomography above Svalbard. Two contrasting examples are reported in which structures in electron density are identified in the source region that have the characteristics of patches. In the first the particle-induced ionisation is situated mainly below 250 km, where the recombination rate is high, and is thus unlikely to be particularly long lived. The second example is characterised by a considerably higher flux of softer particles, resulting in substantial ionisation above 250 km, with the formation of a patch that has the potential to retain form in the convective flow across the polar-cap.

Instrumentation

The optical instruments used were a meridian scanning photometer (MSP) and an all-sky camera at the Auroral Station, Longyearbyen (78.2°N, 15.3°E). The MSP consists of a parallel assembly of six photomultiplier tubes, each with a tilting narrow-band interference filter to allow subtraction of background light from the peak emission (Romick, 1976). A mirror in front of the tubes scans essentially along the magnetic meridian from north to south (45° west of geographic north). A full meridian scan, with the background subtracted, is obtained every 16 s. Observations from two of the emission lines monitored by the instrument have been used here: the red (630.0 nm) and green (557.7 nm) wavelengths emitted by atomic oxygen, which are both stimulated by particle precipitation. The all-sky camera was filtered at 630.0 nm and provided an image every 20 s.

The radio tomography monitoring system comprises receivers at Ny Ålesund (78.9°N, 12.0°E), Longyearbyen (78.2°N, 15.3°E), Bjørnøya (74.5°N, 19.0°E) and Tromsø (69.8°N, 19.0°E). Measurements are made of total electron content using signals from satellites in the Navy Ionospheric Monitoring System (NIMS). The observations are then inverted in a reconstruction algorithm to create spatial images of electron density as a function of height and latitude. A fuller description of experimental ionospheric tomography can be found in Walker *et al.* (1996).

Observations

Two examples are described illustrating contrasting aspects of the influence of cusp/cleft precipitation on ionospheric electron density. Observations made on 14 December, 1996, were first reported by Walker *et al.* (1998) and interpreted in terms of the ionospheric effects of magnetopause reconnection. Figure 1 shows records from both the red- and green-channels of the MSP between 10:41 UT and 10:49 UT. There is clear evidence of auroral activity, with a sharply defined equatorward boundary lying to the south of Longyearbyen. The maximum peak intensity observed for the red-line was some 12.5 kR, with an average peak intensity of about 9 kR for the 30 scans made during this interval. The average ratio between the red- and green-line intensities was 4.9. There is some evidence for finer structure within the main band of the 630 nm emission and rebrightening of the auroral features. It must, of course, be emphasised that the red-line observations studied here are of intense auroral emissions, in contrast to the weak airglow used for many studies of patches in the polar cap.

The tomographic image in Fig. 2 shows the distribution of electron density as a function of height and latitude, obtained from a southward heading satellite pass that crossed 78°N latitude at 10:46 UT. The main feature of interest to the current study is the F-region density enhancement between about 77.5° and 79°N. It can be seen that the structure is bounded at its equatorward edge by a sharp gradient in density to the south of Longyearbyen, identified by Walker *et al.* (1998) as a signature of the open/closed field-line

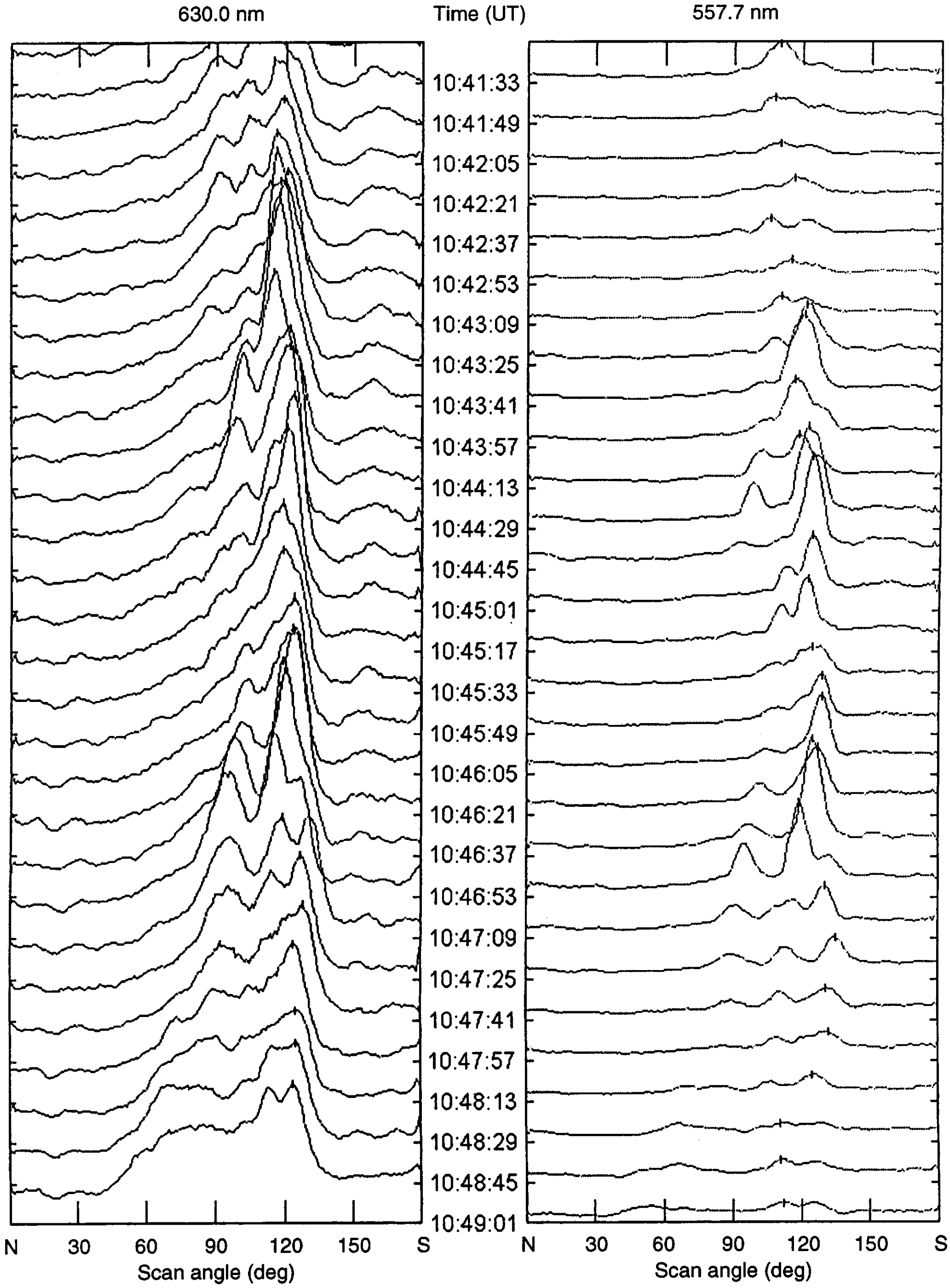

Fig. 1. Stacked plot of intensities of red (630.0 nm) and green (557.7 nm) emissions measured by the meridian scanning photometer between 1041 UT and 1049 UT on 14 December, 1996

boundary. The location of this boundary and the latitudinal extent of the feature are consistent with the band of 630 nm aurora seen in Fig. 1. The peak electron density is in excess of 2.75×10^{11} m^{-3} and the structure contains two, possibly three, localised enhancements. The peak height is below 200 km at 77.5°N rising to approach 240 km at 79°N. It can be noted for later comparison that the 2×10^{11} m^{-3} contour on the topside is at about the 250 km altitude level. Furthermore, the peak density in the enhanced region is almost an order of magnitude greater than that of the background ionisation just outside the polar cap in the trough to the south.

Measurements by the WIND spacecraft provide information about the IMF. The formula of Lockwood *et al.* (1989), for the time delay between the satellite measurements and the corresponding ionospheric response, gives a lag of some 27 min in this case. During the period of interest, B_z was established negative at about -3 nT, while B_y was around $+2$ nT and the plasma ion density of the solar wind was about 6 cm^{-3}.

The second example comes from observations made on the 10 December, 1997. Figure 3 shows the measurements from the red- and green-line channels of the MSP between 08:32 UT and 08:40 UT. The maximum peak intensity in the red-line was almost 27.5 kR, while

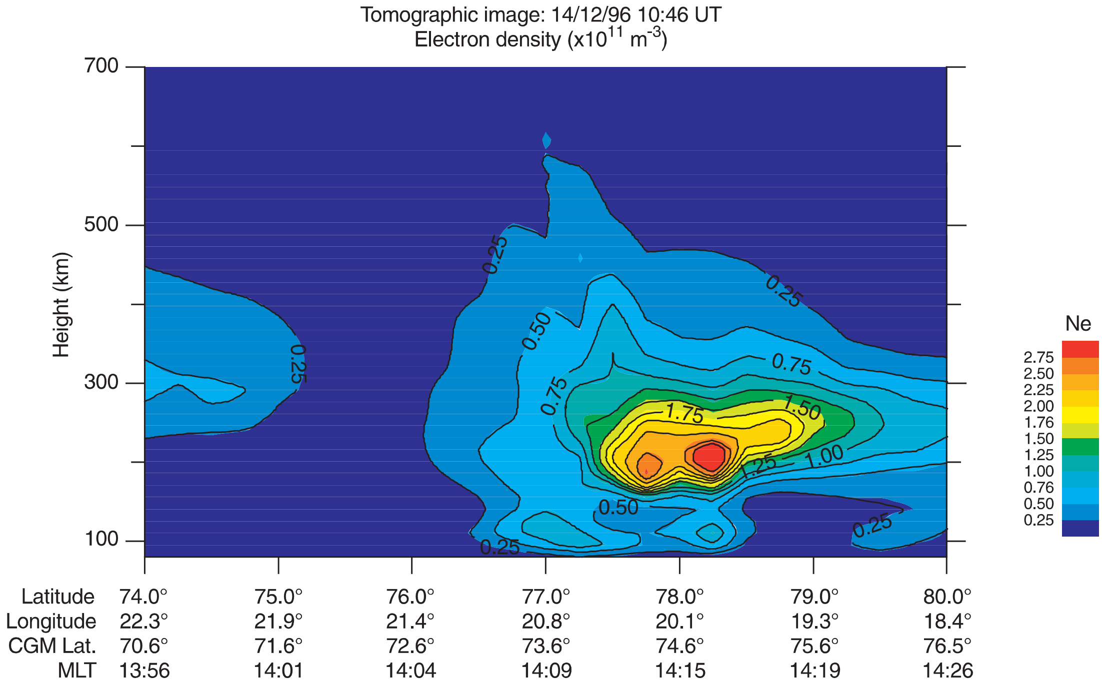

Fig. 2. Tomographic images of electron densities obtained from a satellite pass that crossed 78°N at 1046 UT on 14 December, 1996

the average peak intensity for the 30 scans during the interval was about 18.5 kR. The average red- to green-line intensity ratio was 8.6.

The tomographic image in Fig. 4 shows the electron density as a function of height and latitude, obtained from a southward satellite pass that crossed 78°N at 08:38 UT. The F-region in the north of the image exhibits clear structuring, with a feature that is contiguous with the red auroral emissions and containing two localised density enhancements between about 78°N and approximately 80.5°N. The peak densities, in excess of 4.5×10^{11} m^{-3}, are significantly larger than those observed in the image described earlier (Fig. 2) and, in the current example, the topside 2×10^{11} m^{-3} contour is generally above 325 km in the structure. The layer peak is at a height of around 250 km, with a density greater by a factor of almost five in comparison with that found in the trough to the south.

A broader picture of the 630.0 nm auroral activity at the appropriate time on 10 December, 1997 is presented in Fig. 5. This shows three images from the all-sky camera separated by 2 min intervals. The sub-ionospheric track of the NIMS satellite has been included in each panel. It can be seen that the red-line activity forms a narrow latitudinal band over Svalbard though with a broadening of the structure to the east. Fuller examination of the all-sky images showed that the cusp activity centre, with quasi-periodic intensifications, was located east of Svalbard. The NIMS satellite intersected one event in a sequence of intensifications.

IMF data from the WIND spacecraft, with an appropriate lag of some 75 min in this case, show that B_z was again established southwards with a value of about -3 nT, while B_y fluctuated around -13 nT. Significantly, the plasma density was about 33 cm^{-3}, more than five times larger than in the previous example.

Discussion

According to the classification scheme of dayside auroral activity given by Sandholt *et al.* (1998), the two cases presented here both belong to type 1 cusp aurora. Type 1 includes the classical sequences of moving auroral forms, which dominate the cusp/cleft activity picture under conditions of southward IMF. The event recurrence period for this activity is typically 5 to 10 min, and the movement of type 1 auroral forms has been found to follow the ionospheric convection pattern which is IMF controlled (Sandholt *et al.*, 1993, 1998; Moen *et al.*, 1995, 1999). This class of activity is widely accepted as a candidate footprint of time-varying reconnection at the dayside magnetopause (Lockwood *et al.*, 1998). The pulsed nature of cusp auroral activity indicates that ionospheric plasma, drifting into the polar cap through the cusp inflow region, is exposed to pulsed showers of magnetosheath particle precipitation.

The co-location of enhancements in ionospheric electron density with auroral activity implies that particle precipitation has played a direct role in the creation of the elevated densities (Moen *et al.*, 1998; Berry *et al.*, submitted 1999). While a consistent picture emerges from the two data sets, the red-line intensities observed on 10 December, 1997, were more than double those of 14 December, 1996. Similarly, the red-to-green intensity ratio was significantly enhanced in the 1997 case, implying a greater bias towards lower energy

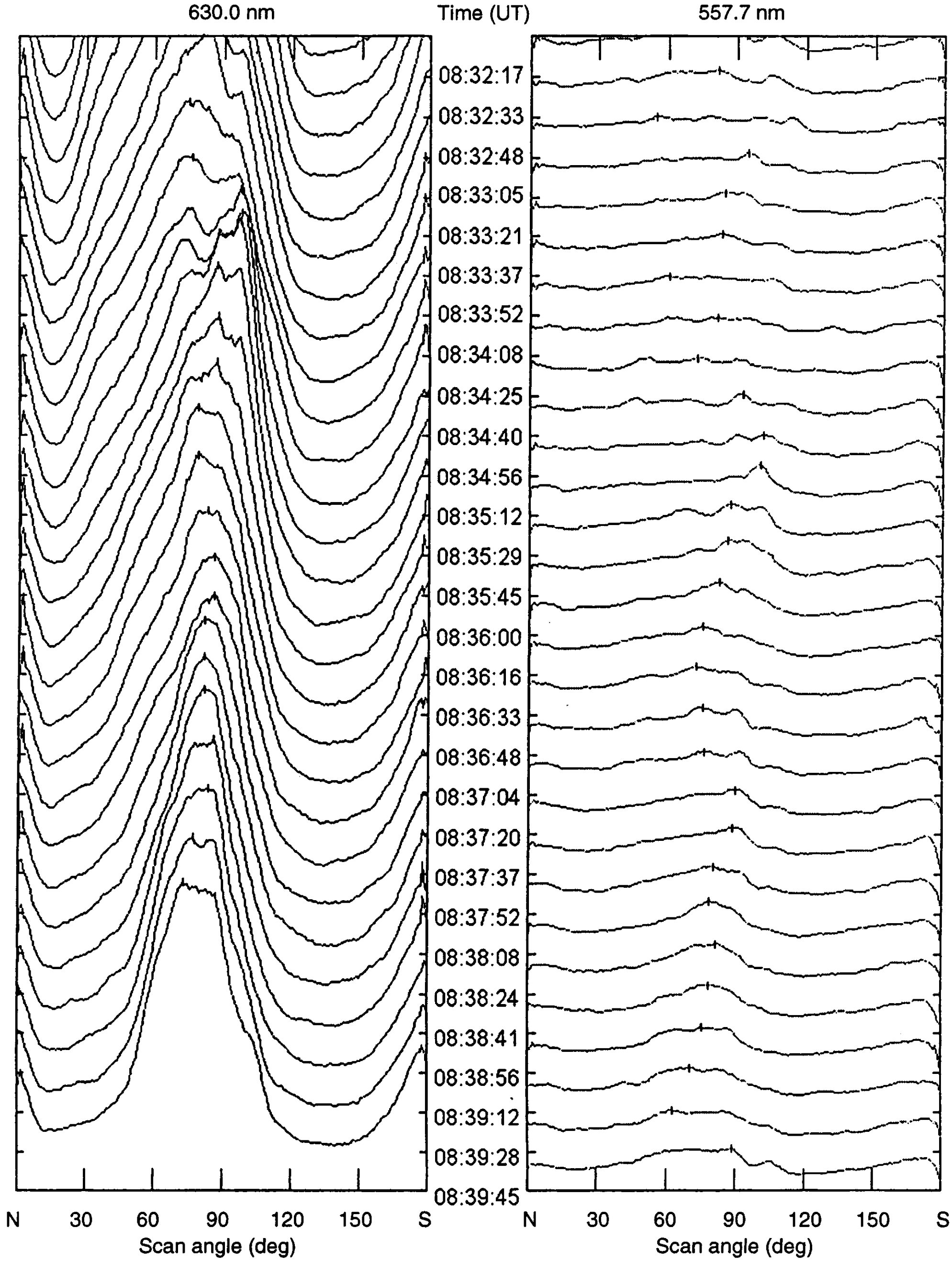

Fig. 3. Stacked plot of intensities of red (630.0 nm) and green (557.7 nm) emissions measured by the meridian scanning photometer between 0832 UT and 0840 UT on 10 December, 1997

ionising particles in the incoming spectrum. The spectral distribution, coupled with the significantly larger solar wind plasma densities on 10 December, 1997, suggest that the incoming particle flux was more likely to result in enhanced electron densities at higher altitude on that day than in the earlier example. This conclusion is confirmed by the tomographic images of electron density distribution, which show that the layer is at a higher altitude and with peak densities some 60% greater than in the example from 1997. In addition, there is clear evidence of enhanced levels of ionisation extending into the topside. The all-sky camera results confirm that the aurora, and hence the precipitation source for the ionospheric enhancement, is confined to a limited band of a few degrees latitude, consistent with the tomographic observations and with the accepted scale size of polar-cap patches. It should be noted that whilst the plane of the tomographic image is closer than the photometer scan to the cusp activity centre, the all-sky imager data reveals that both intersect regions exhibiting auroral phenomena typical of cusp dynamics. Extended observations from the all-sky camera also confirm the pulsating nature of the red-line aurora in this case even though this is not immediately apparent from Fig. 3. Furthermore, inspection of the green-line data recorded by the imager demonstrates the red-line dominance over the green aurora for the entire field of view.

Given the prevalent IMF conditions, with a southward B_z in both cases, it seems likely a two-cell

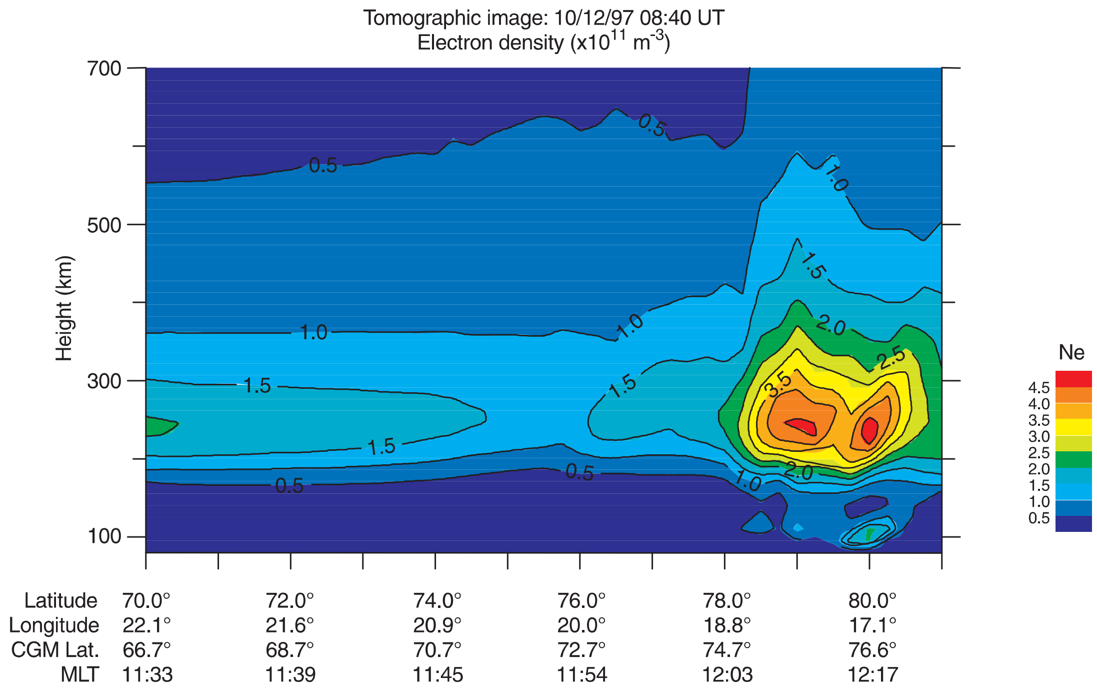

Fig. 4. Tomographic images of electron densities obtained from a satellite pass that crossed 78°N at 0840 UT on 10 December, 1997

convection pattern was established at the times of observation, with anti-sunward flow into the polar cap. Thus, it is reasonable to assume that in both cases the plasma enhancements formed by the precipitation will move with the background convection and eventually be carried across the polar cap. It should be noted, however, that release of the magnetic stress dominates the initial motion of a newly opened field line and when B_y is non-zero the plasma motion will have a zonal component. As tension is released and the line unbends the pull of the solar wind takes over. Given the dominance of B_y negative in the second example, the initial plasma motion will probably be eastward before the pull of the solar wind eventually brings the plasma into the polar cap outside the plane of the tomographic image. This view is supported by the all-sky measurements which show pulsed red-line emissions moving eastward. It is thus possible that initial flow along the L-shells keeps the plasma in the source region allowing the densities to build up.

In addition to transport, consideration must also be given to the lifetime of the F-region plasma. O^+ is the

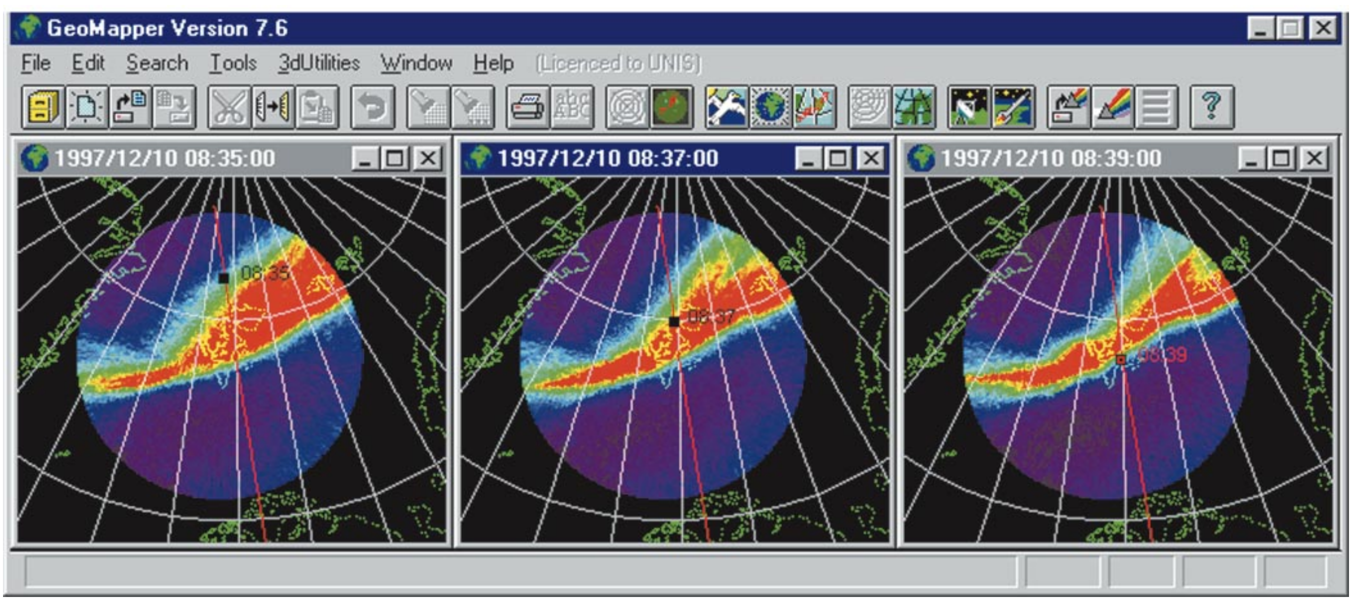

Fig. 5. A succession of false-colour images of red-line intensity obtained from the all-sky camera between 0835 UT and 0840 UT on 10 December, 1997

primary ion constituent above 250 km. The dominant mechanisms of chemical loss of O^+ is through slow ion-molecule reactions with N_2 and O_2 to form NO^+ and O_2^+, which in turn rapidly undergo dissociative recombination with electrons (Banks and Kockarts, 1973). Simple calculations have been made to estimate expected lifetimes. These have been based on the recombination rates given by Banks and Kockarts (1973), the MSIS-90 model for N_2 and O_2 density profiles versus height, and the measured electron densities. The decay time has been calculated for the F-region plasma enhancements to reach a density of 2×10^{11} m^{-3}; that is, still a factor two above the background level of 1×10^{11} m^{-3}. For the density feature on 10 December, 1997, the lifetime of the F-region structure was found to be ~40 s at 200 km, ~10 min at 250 km and increasing to ~1 h at 300 km. Thus, it seems probable that this feature will be long-lived as it convects with the background plasma away from the region of particle precipitation and across the polar cap in the form of a patch. However, for the feature observed on the 14 December, 1996, most of the enhanced density was found below 250 km altitude and hence it will have a lifetime limited to minutes after convecting away from the region of particle precipitation.

The present study has shown that particle precipitation in the cusp/cleft region can be responsible for the creation of structures in electron density with magnitude, scale and transport consistent with the known characteristics of polar-cap patches. While limited information can be obtained from a case study it must be recalled that almost all of the other proposed patch mechanisms have their origins in case studies and little work has been possible to date on the difficult task of assessing the importance of the various candidate processes. However, the particular conditions prevalent in the present study can be examined. The observations on 10 December, 1997, were made on a day when the ion density of the solar wind measured by the WIND satellite was very large, exceeding that for the earlier example by a factor of about 5. The 630 nm intensities measured on this day were typically doubled with respect to the earlier case, while the ratio of the red-to-green emission intensity ratio was some 75% larger. Another important difference was that the 1997 case was observed near magnetic noon around 1150 MLT, while that in 1996 was observed postnoon around 1350 MLT; the auroral station at Longyearbyen crosses magnetic noon about 0850 UT. It is suggested that in the former case the reconnection is near the sub-solar point, while the latter example is a candidate for reconnection on the flanks. For reconnection on the flanks, the injected plasma has to swim against a substantial anti-sunward movement of the newly opened flux tube, so that the softest particles will not be able to penetrate down to the ionosphere, with a consequent hardening of the auroral spectrum. It appears likely that the density of the magnetosheath source plasma and the location of plasma injection (MLT-hours) are two critical parameters in determining whether or not cusp/cleft precipitation can lead to the creation of ionospheric plasma structures at sufficiently high altitudes to persist in the convective transport across the polar cap.

Conclusion

The combination of optics and radio tomography provides a new opportunity to study experimentally the ionisation impact of cusp precipitation in the F-region ionosphere, and hence the possible role in patch formation. The two examples presented here demonstrate that precipitation of soft particles into the cusp/cleft region can play a potential role in the formation of structures in electron density with the characteristics of polar-cap patches. Both cases show that the precipitation can create F-layer features, with horizontal extents of hundreds of kilometres containing sub-structuring on a finer scale, and densities significantly above background, to be carried in a convective flow into the polar cap. The lifetimes of such structures will be dependent on the spectrum of the precipitation and the consequent height of the ionisation created. In the first case presented here, most of the plasma was to be found below 250 km in a region where recombination will result in degradation on a timescale of less than 10 min. Thus, while the structure might have been identified as a patch in the entry region it is unlikely that the form would have been preserved in the cross-polar convection. By contrast, in the other example, the spectrum of the precipitation resulted in the creation of ionisation above 250 km that may have been sufficiently long lived to survive transport across the polar cap while retaining the characteristics of a patch. The present study indicates that cusp/cleft particle precipitation alone may on occasion be capable of forming polar-cap patches. The solar wind density was unusually high on this particular day, and more cases have to be investigated before any decisive conclusion can be drawn on the relative importance of cusp particle precipitation compared to the other competing mechanisms.

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