Polar Patches and the ‘‘Tongue of Ionization’’

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Abstract

Optical images of 630.0 nm emission from drifting *F*-region polar patches, acquired with a sensitive bare-CCD all-sky imager, have been analyzed to infer the ionospheric convection velocity over a period of nine hours on December 8, 1993. The drift vectors agree well in both direction and magnitude with simultaneous measurements from a nearby digital ionosonde. The convection direction at the geomagnetic pole is shown to agree qualitatively with empirical models of *Heppner and Maynard* (1987), and the delay between an interplanetary magnetic field (IMF) B_y change at the magnetopause and the establishment of a new convection pattern is estimated. A montage of the optical emission from the patches observed over the period is presented to illustrate the range of optical patch shapes, sizes, and spacings observed, and evidence is provided for the action of a patch formation mechanism beyond that modeled by *Sojka et al.* (1994).

1. Introduction

The term ‘‘polar patch’’ denotes a discrete plasma density enhancement in the polar *F* region, of order 100 - 1000 km in horizontal extent, that convects through the polar cap under the influence of the magnetospheric electric field, and may be variously observed by means of scintillation of transionospheric radio signals (*Weber et al.*, 1984; *Basu et al.*, 1994), radiowave probing (*Buchau et al.*, 1985; *Valladares et al.*, 1994; *Rodger et al.*, 1994), in-situ plasma density measurements by satellite-borne sensors (*Coley and Heelis*, 1994), and optical emission at 630.0 nm and 557.7 nm (*Weber et al.*, 1984; 1986; *McEwen et al.*, 1994). Suggested sources of the enhanced plasma densities include the sunlit *F* region equatorward of the cusp (*Anderson et al.*, 1988; *Lockwood and Carlson*, 1992), and the precipitating particle impact-induced ionization in the cusp (*Rodger et al.*, 1994).

The existence of a ‘‘tongue’’ of relatively high density solar UV-ionized plasma convecting poleward through the dayside auroral region into the polar cap has long been recognized (*Sato and Rourke*, 1964), having first been identified using IGY monthly median values of peak *F2* electron densities (*Sato*, 1959). *Sojka et al.* (1979) have shown that the movement of the solar terminator in geomagnetic latitude throughout the UT day or, equivalently, the diurnal equatorward and poleward motion of the dayside auroral oval in geographic coordinates (*Foster*, 1993), produces a modulation of the strength of the subauroral ionosphere and a diurnal variation in the peak plasma density in the tongue of ionization (TOI), with the maximum plasma density occurring at about 1900 MLT. A ‘‘clear diurnal variation for the occurrence of patch-type ionization’’ above Thule, Greenland (86°CGL) has been observed by *Buchau et al.* (1985), agreeing closely in phase with *Sojka et al.*’s predictions.

Anderson et al. (1988) proposed a plasma-structuring mechanism involving the transient expansion of the high-latitude convection pattern across the terminator into the subauroral ionosphere, and the entrainment of higher-density solar-produced plasma into the antisunward convection through the polar cusp. The sizes and peak plasma densities of individual patches would depend on the duration and extent of the equatorward expansions of the convection pattern. The mechanism requires the solar terminator to lie just equatorward of the last quiet-time flow line. *Lockwood and Carlson* (1992) generalized this mechanism to one capable of converting any pre-existing plasma density gradients near the dayside oval into patches by means of ‘‘changes in the dayside flow pattern due to pulsed reconnection’’ (*Lockwood and Carlson*, 1994, and references therein).

Using the assumption that the plasma source for polar patches is the solar-produced ionosphere just equatorward of the cusp, *Sojka et al.* (1994) have modeled the seasonal and UT dependences of polar patches observed in the central polar cap. In their model, plasma structuring is caused by changes in high-latitude plasma convection that are controlled by the y component of the IMF. They deduce a seasonal/UT dependence of patch appearance at high latitudes that agrees well with the observations of *Buchau et al.* (1985). Of particular note is the predicted absence of patches, formed by changes in convection, between 0600 and 1200 UT within 20 days of winter solstice. *Sojka et al.* note that ‘‘observations made during this period would be able to deduce the extent to which other patch formation mechanisms operate.’’

Rodger et al. (1994) and *Pinnock et al.* (1993) have observed the formation of polar patches by separation of cusp plasma from the poleward edge of the southern-hemisphere cusp, apparently by a burst of enhanced plasma flow along a narrow zonally-aligned channel through the cusp. The increased ion velocity in the rest frame of the neutral atmosphere increased the plasma loss rate and created a plasma void at the equatorward edge of the patch. It is noteworthy that these observations took place at times when the terminator lay well poleward of the cusp, and changes in the convection pattern near the cusp would not produce significant modulation of the poleward-flowing plasma density. These observations suggest the existence of another patch formation mechanism beyond that of *Lockwood and Carlson* (1992).

Valladares et al. (1994) also observed the formation of polar patches in two cases, following the appearance of longitudinally-aligned high-speed plasma flows at Sondre Stromfjord. In one of the cases evidence was presented to indicate that the high-speed flow occurred at the poleward edge of the cusp. In both cases the cusp was in full sunlight. The flow channels drifted poleward with the patches, reaching Qaanaaq near the geomagnetic pole.

Polar patches can be used to delineate the local ionospheric convection for continuous ground-based monitoring. *Cannon et al.* (1991) compared daily averages of ionospheric drift directions measured by a digital ionospheric sounder (Digisonde; *Bibl and Reinisch,* 1978) at Qaanaaq during southward B_z conditions with expected drift directions from the *Heppner and Maynard* (1987) model convection patterns. For both signs of B_y, they found good agreement between the measured convection direction and that specified by the appropriate model convection pattern.

Optical observations of polar patches together with ionosondes and other radiowave diagnostics have revealed their characteristic sizes, structures, and drifts (*Weber et al.*, 1984, 1986; *Fukui et al.*, 1994). *Fukui et al.* (1994) followed patches through an all-sky intensified camera (ASIC) field of view at Qaanaaq to determine patch drift velocity (direction and speed), and compared these optically-derived velocities with those determined from Digisonde measurements on the same patches. They found good agreement between the two sets of drifts, in both direction and magnitude. The drift magnitude followed the IMF B_z, while the deviation of the drift direction from antisunward was controlled by the y component.

In this paper we report observations made with a sensitive dual- camera CCD-based all-sky imager located at Eureka, NWT (80.1 N, 273.6 E; 88.7 PACE GMLat (*Baker and Wing*, 1989). We observed the antisunward drift of F-region patches, by means of their optical emission at 630.0 nm, for a period of about 9 hours on December 8, 1993, near winter solstice. These patches were observed during a period of consistently southward IMF, when the cusp was several degrees poleward of the solar terminator. We use these observations to infer ionospheric convection velocities with 2-3 minute time resolution, to display a sequence of patches on a larger scale than that afforded by a single ground-based field of view, and to illustrate the variety of patch shapes, scales, orientations, and motions observed during this period. We show a close correspondence between the zenith 630.0 nm emission brightness and the 4.012 MHz virtual height measured by a nearby digital ionosonde. We discuss the relation between the IMF B_y and the ionospheric drift velocities, and estimate the time delay between changes in B_y and the the corresponding changes in the drift direction at the center of the polar cap. We show the appearance of patches at Eureka during a period when patches are expected to be absent from the central polar cap, and briefly discuss the implications of the observed patch scales for patch formation mechanisms.

2. Data and Analysis

Geophysical Conditions

The period of interest covered 0130 - 1100 UT on December 8, 1993. The IMP-8 satellite was in the solar wind during this period, at geocentric solar magnetospheric (GSM) coordinates X=16 R_e, Y=30 R_e, Z=-14 R_e, and returned IMF and solar wind data between 0100 and 0738 UT. The IMF is shown in GSM coordinates in Figure 1. During the period for which data are available, B_z was strongly southward (B_z < -9 nT), giving ideal conditions for the formation of *F* region patches in the polar cap. Before 0343 UT the y-component changed sign frequently (-2 to +5 nT), but after 0343 B_y was stably, albeit only slightly, negative (-1 to -4 nT). The solar wind speed was steady at 490 km/s and the number density varied slowly between 3 and 14 cm^{-3}.

Geomagnetic activity as indicated by the Kp index increased from quiescence to minor storm levels beginning at 12 UT on the previous day, and for the first 12 hours of December 8 the Kp indices were 6+, 6+, 5o and 5o. The DMSP F10 satellite observed the low-altitude particle cusp equatorward of 70° corrected geomagnetic latitude (CGMLat) during dayside oval crossings at 0134 UT (10.5 h MLT) and 0456 UT (11.7 h MLT), indicating significant expansion of the auroral oval. Despite this expansion, the solar terminator lay several degrees equatorward of the cusp at these times.

Optical Images

The all-sky images used in this work were acquired at the Polar Observatory established by the Canadian Network for Space Research at Eureka, NWT in December 1990 (*McEwen et al.*, 1994). The University of Calgary operated a sensitive CCD-based dual-camera all-sky imager throughout the period October 16, 1993 - March 20, 1994. Each of the two identical cameras had fisheye optics, a telecentric lens, a five-position filter wheel with narrow-band filters (1.0 - 5.2 nm passband), and a bare CCD detector cooled to -40° C to minimize dark current. A full description of the imager will be published elsewhere.

The two cameras acquired images simultaneously, typically with 60-s exposure times. The image acquisition program used on this date acquired two 60-s exposures at 630.0 nm ($O(^1D)$) in a period of about five minutes, with one of them accompanied by a simultaneous 60-s exposure at 557.7 nm ($O(^1S)$). Hourly dark frames were subtracted from all images, and flat-field corrections and measured sensitivities from on-site field calibrations were applied to convert them to measured slant column brightnesses. These brightness images are believed to be accurate to within 10%. Background subtraction of continuum emission and a uniform 25-R layer was applied to all 630.0-nm images to improve the patch contrast. A sample of the resulting images, showing the passage of a structured patch between 0340 and 0410 UT, is shown in Figure 2(a). Geographic north is toward the top of the images, and geographic east is to the right. The direction to the Sun is shown in the lower right of each frame. The peak brightness in the images shown is 300 R; the highest patch brightness seen on this data was just over 400 R.

Patch Drifts from Image Comparisons

Polar patches were observed from Eureka almost continuously between 0130 and 1100 UT, the longest interval between zenith passages being 45 min between 0220 and 0305 UT. In the photometrically corrected images of the convecting patches, the peak brightness and morphology of individual patches were quite stable during their transits across the field of view of the imager, after allowing for changes in perspective. On the basis of this observation, the images were rotated into constant alignment with respect to the solar azimuth and mapped to geographic coordinates at an assumed emission altitude of 250 km (Figure 2(b)).

We then estimated the patch displacement between successive images (in geographic coordinates) by shifting the second image relative to the first until the best match was obtained. This somewhat subjective procedure was found to yield displacements with an estimated uncertainty of not more than 10 km, if a patch was visible in a pair of successive images. Using this procedure, patch displacements between successive images were estimated over a period of 9.5 hours, from 0130 to 1100 UT. This record of patch displacement was converted to ionospheric drift velocities at 250 km altitude, using the known intervals between images. Figure 3 shows the magnitudes and directions (relative to the antisunward direction) of the resulting drift velocity vectors. Prior to 0448 UT the drift vectors were consistently rotated counterclockwise from the noon-midnight meridian into the evening sector; from this time until about 0900 UT the drift vectors fluctuated about the antisunward direction, and after 0900 UT the drift turned into the evening sector again.

The inferred ionospheric drifts during the period between 0130 and 0600 UT were compared with ionospheric drift measurements (I. F. Grant, private communication, 1994) made by a Canadian Advanced Digital Ionosonde (CADI; *MacDougall et al.*, 1994) operating simultaneously at Eureka. These drift measurements were obtained using a fixed frequency of 4.012 MHz. Antenna problems allowed only intermittent data collection on this date, but bottomside virtual heights for those patches observed by the CADI were in the range 260 - 290 km. The drift directions inferred from the images agree very closely with those measured by the ionosonde, as shown in Figure 4(b). The drift speeds estimated from the images are also in satisfactory agreement with the ionosonde speeds (Fig. 4(c)).

Full Correlation Analysis of Patch Drifts

The reproducibility of the patches from image to image afforded confidence in the reliability of the ionospheric drift velocities shown in Figure 3. However, as a check, the modified full correlation analysis (FCA) described by *Meek* (1980) was used to estimate patch drifts from the original Polar Camera images. Briefly, this analysis uses the autocorrelation and cross-correlation properties of time series of data measured in three separate directions in the sky to estimate pattern scales, orientations, and drift velocities, as well as characteristic times for pattern stability. These parameters were estimated from half-hour sequences of images. The robustness of the analysis was assessed by running the analysis for different sets of sky directions within the sequence of images.

While the drift velocities estimated from the FCA frequently showed poor internal consistency, the most consistent drifts agreed reasonably well with the half-hourly mean drift velocities inferred from the displacements of individual patches. In all cases where both the patch motion and full correlation analyses could be performed, the consistency in the individual patch drifts was comparable with or better than that of the results of the full correlation analyses. We conclude that the drift velocities inferred from the patch motions are corroborated by those from the FCA, and that the analysis of patch motions is a more robust technique of inferring drift velocities than the FCA.

Patch Montage

The apparent stability of the patch morphologies and peak brightnesses has already been mentioned. This characteristic suggested that a time series of images could be used to build up a meaningful picture of the optical emission from the convecting polar ionosphere on a larger spatial scale than that of the field of view of the imager. This larger picture was generated by extracting slices from each of the successive mapped images. From each successive image, a strip in the dawn-dusk direction was extracted, centered on the geomagnetic pole. The width of the strip was determined by the amount of shift in the noon-midnight direction required to match the image with the previous image. The strip was inserted into a montage, with the position of the pole in the strip shifted from that in the previous image by the noon-midnight and dawn-dusk shifts necessary to match the source image to the previous image. This procedure was carried out for all images acquired between 0132 UT and 1100 UT on December 8, 1993.

The resulting partial image of the patch sequence is shown in Figure 5. The direction to the Sun is toward the top of each panel of the figure (i.e., in the direction indicated by the long axis in the first panel of Figure 5.) Each of the panels in the figure shows approximately 1.5 hours of data, and covers a noon-midnight distance of about 3800 km, comparable to the nominal noon-midnight extent of the polar cap. Each panel may thus be regarded as depicting a segment of the TOI similar to that which was actually present in the polar cap at any time during the observing period. The crosses mark the location of the geomagnetic pole in each image. The full-scale brightness in the figure is 400 R, and individual patches are visible with peak brightnesses ranging from less than 100 R (0145 UT, panel a) to over 400 R (0350 UT, panel b). The shapes and sizes of individual patches vary widely, with noon-midnight extents ranging from a thickness of about 100 km for the patch passing the geomagnetic pole at 0409 UT, to over 800 km for the patch near the zenith at 0420 UT. Patch sizes in the dawn-dusk direction are typically greater than the 800 km diameter of the Polar Camera field of view at 250 km altitude. Many of the patches appear elongated in roughly the dawn-dusk direction. The dark gaps between the patches also vary widely in extent, from about 100 km at 0412 UT (panel b) to over 1100 km between 0230 and 0300 UT (panels a and b).

During the period shown here, Eureka was in the postnoon magnetic local time sector and had a somewhat fuller view of the dusk side of the noon-midnight meridian. The polar patches observed from Eureka passed the geomagnetic pole predominantly on the dusk side during most of the period, except for 0300 - 0510 UT (panels b and c) and 0940 - 1100 UT (panel f).

4. Discussion

Patch Images

We have presented the first well-calibrated images of 630.0 nm emission from polar patches, from a 9.5-hour period of patch observations on December 8, 1993. Patches were detected with peak emission brightnesses above background ranging from less than 100 R to more than 400 R. These patches were observed to drift through the imager field of view without significant change of shape. We used the motions of patches between successive images to infer the time history of the ionospheric convection velocity above the north geomagnetic pole. *Fukui et al.* (1994) used a similar technique but reduced the time resolution of their drifts by averaging the motion of each patch through the field of view.

Convection Velocities

Our optically-derived drift directions agree well with a limited set of simultaneous ionospheric drift measurements made by a digital ionosonde located some 15 km away. The optical drift directions are less variable than those measured by the ionosonde because of the 60-s exposure time and 2-3 min intervals of the images. Similar agreement between optical and ionosonde measurements of the ionospheric drift direction was also obtained by *Fukui et al.* (1994). The drift speeds in that study, derived assuming an emission height of 250 km, were on average 14% lower than the ionosonde speeds. Our optically-derived drift speeds tend to be somewhat higher than those measured by the ionosonde, but are overall in satisfactory agreement. Our assumed emission height of 250 km is consistent with the measured bottomside 4.012 MHz reflection virtual height of 260-290 km.

Patch Emission Montage

The inferred convection velocities allowed us to construct a montage of the large-scale optical emission from the ''tongue of ionization'' of which these patches are the visible manifestation. The montage shows that the width of the TOI is typically greater than the 800 km width of the imager field of view at 250 km altitude. At certain times (0315 UT, 0350 UT, 0505 UT, 1000 UT) the dawn-dusk brightness profile of the optical emission from the TOI gives the impression that it is much greater than this width. Previous measurements of patch sizes (*Weber et al.*, 1984, 1986; *McEwen et al.*, 1994) have given values in the same range, which is somewhat larger than the scale of the TOI modelled by *Sojka et al.* (1993, 1994). Observations of plasma flow through the dayside cleft into the polar cap (*Foster*, 1989, and references therein) indicate plasma entry over a range of up to 2-3 hours of MLT, which corresponds to a geographic distance at 70° latitude of 1100 km or more.

The montage shows a wide variety of optical patch shapes, ranging from very narrow (~100 km) forms with a roughly dawn-dusk alignment, to much larger ''blobs'' (~800 km or more in both noon-midnight and dawn-dusk directions). These optical patches are separated by gaps in the 630.0 nm emission field ranging from less than 100 km to over 1000 km wide. The question of the relation between the optical signature of patches and their ionization distributions is important if optical observations are to be used to map the *F* region plasma distribution. The rapid decrease of the molecular oxygen concentration with increasing altitude biases the OI 630.0 nm emission toward the bottomside of the *F* region, so that visible optical emission becomes a proxy for the presence of plasma below about 300 km. Thus, the 100 km-scale structure in the 630.0 nm brightness (e.g., 0315 UT, 0345 UT, 0415-0440 UT) could result from either actual small-scale ''breakoffs'' or density depletions in the TOI, or from short-wavelength (λ ~ 100-200 km) ripples in the bottomside of the F-region. While optical observations alone cannot distinguish between these possibilities, the CADI 4.012 MHz virtual heights shown in Fig. 4(a) show nearly a 1:1 correspondence

If the small-scale structure were caused by a travelling disturbance, i.e., a gravity wave, the motion of the ionization would be detectable as a vertical component of the drift velocity. Unfortunately the ionosonde data for this event are not extensive enough to allow us to evaluate this possibility. Higher resolution radiowave techniques (scintillation/TEC or incoherent scatter) would be required to ascertain the small-scale structure of the plasma distribution.

Inter-patch gaps of roughly 500 km extent are seen at about 0335 UT and 0810 UT. These gaps are larger than but reasonably consistent with the widths of the enhanced zonal flows observed in the cusp region by *Valladares et al.* (1994) and *Rodger et al.* (1994). These flows initiated density break-off events (in the terminology of *Valladares et al.*) and segmented the poleward-flowing tongue of ionization into a discrete patch. The present study cannot address the detailed causes of the observed morphology of the TOI but it is of interest to investigate the timing of TOI structuring in or near the cusp with respect to changes in the IMF. For the position of IMP-8 and the measured solar wind velocity and density, the method described by *Lester et al.* (1990) predicts a delay of 20-25 minutes between a magnetic field transition as measured by IMP-8 and the arrival of the transition at the dayside ionosphere. Plasma transit from the cleft region to the pole would require a further 60 minutes or so, assuming a mean drift speed of about 600 m/s (as inferred from the optical patch drifts) and a mean cusp latitude of 70° CGL. Thus, plasma that underwent structuring at the cleft as a result of IMF changes recorded at IMP-8 would be expected to pass the pole roughly 90 min after the IMP-8 observation. The present data do not show a clear relation between the IMF B_y changes that occurred between 0108 UT and 0343 UT, and the patches observed subsequently at Eureka; further study of this and other events, with fuller diagnostics from Eureka and other ground observatories as well as from space, may be expected to give a clearer picture of the effects of B_y changes on patch formation.

Large gaps between major emission features seen in the TOI montage are typically 750-1500 km wide (e.g., 0145-0220 UT, 0230-0300 UT, 0925-0950 UT, 1000-1030 UT).

It is notable that enhanced 630.0 nm emission was recorded at Eureka for a period of over 6 hours between the second and third of these major gaps. If they correspond to extended regions of low-density plasma, rather than elevations of the F-region base height or excursions of the high-density plasma outside the Polar Camera field of view, then they indicate that the process or processes responsible for the entry of high-density plasma into the polar cap throughout most of the 9-hour period on this day were inoperative during four intervals of 25-35 minutes.

At about 0440 UT the mean convection direction rotated counterclockwise out of the premidnight sector into close alignment with the noon-midnight meridian. This orientation persisted until 0830 UT (with perturbations between 0600 UT and 0730 UT), at which time the drift direction turned into the premidnight sector again. The mean drift direction prior to 0440 UT was toward an azimuth 20° clockwise from midnight. For comparison, the *Heppner and Maynard* (1987) convection model BC (appropriate to the $B_y > 0$ condition prior to 0343 UT) indicates a direction 46° clockwise from midnight. The general alignment of the mean drift with the noon-midnight meridian from 0440 UT to 0900 UT agrees well with the *Heppner and Maynard* (1987) model A, which applies to $B_y < 0$ conditions. The brief excursion of the drift direction to the postmidnight sector between 0615 and 0640 UT is (perhaps fortuitously) consistent with model DE of *Heppner and Maynard*, which also applies for $B_y < 0$. Although the B_y component became negative briefly between 0314 and 0328 UT, the durable transition to negative values occurred at 0343 UT. A delay of roughly 60 minutes elapsed between this sign change and the change in the convection direction at Eureka. This may indicate that roughly 35-40 minutes were required for a stable reconfiguration of the convection pattern after the sign change. IMF data from IMP-8 are not available after 0738 UT, so it is not possible to ascertain whether the clockwise rotation of the drift after 0900 UT resulted from B_y resuming positive values, but the trend between 0702 and 0738 is suggestive.

Our observation of polar patches between 0130 and 1100 UT on December 8 is in contrast with the predictions of *Sojka et al.* (1994) concerning the UT variation of patch occurrence at the geomagnetic pole near winter solstice. Using a model of plasma structuring by B_y-induced convection pattern changes, they predicted a deep minimum of patch occurrence between 09 and 11 h UT near day 345 of the year. On December 8 (day 342) we observed clear and well-defined patches (albeit with gaps as would be expected) between 0900 and 1059 UT. Unfortunately no IMF data were available during this period to support a tsronger test of *Sojka et al.*'s predictions, but from the *prima facie* evidence we can conclude that the patches observed during these two hours resulted from a mechanism other than that modeled by *Sojka et al.*

5. Summary and Conclusions

We have presented the first well-calibrated images of 630.0 nm emission from polar patches. The patches were observed for a period of over nine hours on December 8, 1993 at Eureka, NWT, near the north geomagnetic pole. The stability of the patches' appearances in successive images allowed a pattern-matching technique to be used to infer ionospheric convection velocities. These velocities agreed well in direction, and satisfactorily in magnitude, with simultaneous measurements from a digital ionosonde. The full correlation analysis (FCA) was applied to the image data and found to yield much poorer results than the pattern-matching technique. The derived convection velocities were used to piece together a montage of optical emission from the ''tongue of ionization'' (TOI) convecting antisunward from the dayside. The montage illustrates the ionospheric drift as well as the range of optical patch shapes, sizes, and spacings observed on this date, and gives some information on the overall scale of the TOI.

We conclude that, for the analysis of optical patch motion, pattern-matching techniques such as that employed in this work are more robust and effective than the full correlation analysis. This is likely due to our use of the full images rather than only small regions of the images in analyzing patch motions. The drifts inferred from the optical images agree well in direction with simultaneous ionosonde measurements, and are consistent with the *Heppner and Maynard* (1987) empirical convection models for southward B_z.

Optical patches manifest a wide range of sizes, shapes, and spacings. Small-scale patches with noon-midnight dimensions of the order of 100 km were observed, separated from neighbouring patches by similar distances. These small patches are likely caused by *F*-region bottomside irregularities, but higher-resolution radio diagnostics are required to confirm this conjecture. Several gaps of 500 km or so were observed between patches. These are roughly consistent in scale with previous radar observations of enhanced zonal plasma flows in the cleft (*Valladares et al.*, 1994; *Rodger et al.*, 1994), which were observed to segment the plasma flowing poleward into the polar cap. During four intervals of roughly 30 minutes each the TOI vanished or lay entirely outside the imager field of view. The processes responsible for turning off or significantly diverting the large-scale flow of dayside enhanced plasma remain to be identified.

A period of about one hour elapsed between a B_y transition from positive to negative values and the resulting change of the convection direction at the geomagnetic pole. A subsequent return to the original convection direction was later observed but IMF data are not available to establish whether this was in response to another B_y transition.

We observed patches during the period 0900-1100 UT when the modeling of *Sojka et al.* (1994) predicts an absence of patches created by B_y-induced convection transitions and consequent plasma structuring. We conclude that some other patch formation mechanism was responsible for the patches observed during this time.

6. References

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7. Figure Captions

Fig. 1. Interplanetary magnetic field data for December 8, 1993, 00-08 h UT from the IMP-8 satellite. Data are available from 0100-0738 UT. During this interval B_z was strongly southward, and B_y fluctuated between positive and negative values.

Fig. 2a. Calibrated images of 630.0 nm emission from antisunward-drifting patches at Eureka on December 8, 1993 from 0300UT to 0330 UT. The image format is down-looking, with geographic North at the top and East to the right. The field of view extends to 70° zenith angle in the upper corners of the images. A permanent moonshade restricts the view to the sOuth. The color bar on the right spans the brightness range 0-300 R. The solar azimuth is to the upper left (geographic N.W.) at this time.

Fig. 2b. 630.0 nm images from Fig. 2a, transformed to a geographic coordinate system. The coordinate system has been rotated to put the solar azimuth at the time of each image at the top of the image. The cross in the center of each panel marks the PACE geomagnetic pole (*Baker and Wing*, 1989).

Fig. 3. Ionospheric drift velocity vectors inferred from observed drifts of optical patches. A patch emission altitude of 250 km was assumed. The tail of each vector locates the time of the drift measurement. The antisunward direction is to

the bottom of each panel. Patch drifts were consistently toward the premidnight sector until 0448 UT, and again after 0900 UT. Between these times the drifts fluctuated about the antisunward direction.

Fig. 4. Comparison of ionospheric drift directions and magnitudes measured independently by two techniques. The thin lines in the second and third panels from the top show the ionospheric drift direction (relative to geographic north), and the drift speed measured by a Canadian Advanced Digital Ionosonde (CADI; *MacDougall et al.*, 1994). The thicker lines show the direction and speed inferred from patch images. The top panel shows the range-time characteristic fo the CADI returns at 4.012 MHz, and the bottom panel shows the vertical component of the drift velocity.

Fig. 5. Comparison of optical patch drifts derived by two methods. The upper three rows of panels show drift vector comparisons for half-hour averaged vectors from Figure 3. The small ellipse centered on their heads indicate the standard derivation in the averages. The broken-line arrows show the results of up to four independent full correlation analyses (FCA) of the optical data, as described in the text. The large ellipse indicates the standard derivation in the mean of the valid analyses. When the FCA results are consistent they generally agree well with the drifts inferred from individual patch displacements. The lower three rows of panels show the patch shapes and scales inferred from the FCA. Where they are consistent they agree well with the patch images in Figs. 2 and 6.

Fig. 6. Montage of the ‘‘tongue of ionization’’ in the polar cap as seen in 630.0 nm optical emission from Eureka, N.W.T., near the geomagnetic pole. Individual

630.0 nm images, transformed as in Fig. 2b, were pieced together using the patch drift velocities in Fig. 3 to create a large scale view of the optical emission from F-region plasma enhancements. The spatial scale is illustrated in panel (a). The Sun is at the top. Image times are shown approximately every 30 minutes. The brightest feature in the montage (at 0350 UT, panel (b)) is 400 R. The variety of patch sizes and shapes is evident.

panel (a) : 0130-0245 UT

panel (b) : 0240-0425 UT

panel (c) : 0420-0610 UT

panel (d) : 0600-0750 UT

panel (e) : 0740-0940 UT

panel (f) : 0930-1059 UT