Drifting *F*-Layer Patches over the Magnetic Pole

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Establishment of a polar observatory at Eureka, Canada in 1991 has permitted studies of *F*-layer ionization patches drifting over the north magnetic pole, using a multi-channel photometer and a digital ionosonde. Optical characteristics of two typical patches are shown. A case study of a sequence of several patches observed on February 17, 1993 is reported. Their optical intensities as determined from 630 and 558 nm meridian photometer scans averaged 200 R and 50 R respectively above airglow background. Their drift velocities through zenith, as measured by a digital ionosonde (CADI), averaged about 0.3 km/s while their bulk motion as seen optically was somewhat greater. The first 3 patches of the sequence, from 0945 to 1010 UT, moved generally in an antisunward direction while three immediately following, from 1015 to 1100 UT, had a velocity component in the dawn to dusk direction with a velocity vector rotated a full 90° from the earlier motions.

1. Introduction

One of the many dynamic features of the polar ionosphere is the appearance of large plasma patches of enhanced ionization which drift across the central polar cap in an antisunward direction from a source region near the dayside auroral oval. Such patches were first observed by Weber *et al.* (1984, 1986), predominantly when the interplanetary magnetic field (IMF) *B_z* was negative, using both optical and radio techniques. From a base at Thule, Greenland (86° corrected geomagnetic latitude (CGL)) they were observed as regions with plasma densities a few times higher than ambient, and with 630 nm emission significantly enhanced over background airglow levels.

While these patches have been more commonly observed during moderately disturbed (*K_p* > 4) geomagnetic conditions (Weber *et al.*, 1984), they have also been reported by Basu *et al.* (1990) to occur during very quiet periods. In general, there has been considered to be a UT dependence on appearance of polar cap patches, with an optimum time around 1700 UT (Anderson *et al.*, 1988; Carlson, 1994) due to the 10° offset between the geographic and geomagnetic poles. Lockwood and Carlson (1992) have suggested that the plasma patches are generated by magnetopause reconnection with flux transfer during IMF *B_z* southward conditions.

It has been shown that ionospheric drift across the central polar cap is antisunward in general and in good agreement with convection directions derived from satellite instrumentation when the IMF *B_z* is negative (Cannon *et al.*, 1991). A study of the convection of *F*-layer patches (Fukui *et al.*, 1994) showed excellent agreement of drift direction with ionospheric drift determined by the digital ionosonde technique. Both studies showed a deviation from the antisunward drift direction of up to –30° (anticlockwise) for the IMF *B_y* negative, demonstrating IMF *B_y* control of exact flow direction, in accord with model predictions (Heppner and Maynard, 1987).

There is evidence to suggest that the patches originate in the dayside sub-auroral ionosphere and are solar-produced plasma that are transported to the polar cap (Tsunoda, 1988). Simultaneous particle measurements over some observed patches (Weber *et al.*, 1984) have shown that the patches were not locally produced by structured electron precipitation. The fact that they convect across the polar cap, at speeds of up to 1 km/sec, also tends to suggest particle precipitation does not play a central role in

their production.

Until very recently no detailed dynamical study of *F*-layer patches has been undertaken. Fukui *et al.* (1994) has reported case studies of 43 individual patches and their motions from observations during the 1989–90 winter at Qaanaaq, Greenland (87° CGL). The establishment of a polar observatory at Eureka, North West Territories (80.0°N, 85.9°W, 89° CGL) in 1991 has permitted optical measurements of such *F*-layer patches during the 1991–92 and 1992–93 winters from that site. These have yielded both absolute (630 nm) intensities and other spectral information from which to draw conclusions regarding excitation of the emissions. In particular, the detection of 558 nm emission from the patches with no N₂⁺ emission points to O₂⁺ recombination as the source of the emissions. The addition of a digital ionosonde at the observatory in 1993 has provided a valuable additional tool for diagnostic studies of the patches and the polar winter *F*-region in general.

This paper shows illustrative optical cross-sections of two typical *F*-layer patches observed in 1991 as they drifted across the Eureka field of view. It then gives a comprehensive (optical-radio) analysis of a sequence of patches observed in February, 1993 shortly after the installation of the digital ionosonde. Its purpose is to compare in a quantitative way the optical information obtained on patch characteristics with what can be deduced from ionosonde returns.

2. Instrumentation

A 6-channel Meridian Scanning Photometer (MSP) operated at Eureka continuously during the dark hours of the 1991–92 and 1992–93 winters. The MSP had a one degree field of view and stepped through the meridian in one degree steps each 0.2 s. Meridian scans were repeated each 38 s. The emissions at 630, 589, 557.7, 486.1, 427.8 nm plus a background wavelength near 558 nm were monitored with a threshold sensitivity of 5–10 R.

The MSP scan during the 1991–92 winter began from the horizon 26°W of N. During the second (1992–93) winter it scanned the meridian from 24°E of N, this direction lying along the magnetic meridian and also on a line connecting with Resolute Bay (74.7°N) to allow bistatic chain measurements.

A Canadian Advanced Digital Ionosonde (CADI, MacDougall *et al.*, 1994) was installed at Eureka in February, 1993. An antenna array consisting of four dipoles arranged along the sides of a square enables the determination of the angle-of-arrival of the sounder echoes. This directional capability was not available to the previously published ionosonde studies of structure in the polar cap *F*-region. The line joining the north-south pair of antennas was oriented 14° east of north, and thus 10° west of the MSP scan. For the data described here, three CADI operating modes were interleaved. First, every 15 minutes an ionogram spanning 1–20 MHz was taken. Second, a Doppler drift measurement was taken at nominally 5 minute intervals, although every third one was lost due to a software error. The Doppler measurement consisted of 64 complex samples taken at a 10 Hz rate, on each antenna. These data may be analyzed to produce a “skymap” of echo locations coded by Doppler shift. A drift velocity vector can be fitted to the skymap by least squares, under the assumption that the velocity is uniform over the field of view. The Doppler drift technique is described in more detail by Cannon *et al.* (1991). Third, when not operating in ionogram or Doppler mode, CADI took a single sounding every 6 seconds on a frequency which was automatically selected from each ionogram and was held fixed for the following 15 minutes.

3. Data

Enhanced 630 nm emissions were frequently observed in the airglow data at Eureka, appearing as patches which drifted across the sky generally in an antisunward direction. Their appearance and characteristics are illustrated by two examples, from November 6 and December 11, 1991. Times were chosen when the antisunward direction was approximately along the MSP N-S meridian, so that a measure of the patch drift velocities could be determined.

A series of scans is shown of the measured brightnesses of both 630 and 558 nm emissions for the

whole period that each patch was in view. Each profile shown is an average of several scans recorded over a six minute period, in order to show in summary the full time history of each patch. The raw count rates were converted to absolute brightnesses using photometer sensitivities obtained from field calibrations and corrected for the Van Rhijn effect, ozone extinction and ground albedo. The brightnesses are plotted as a function of zenith distance, assuming an emission height of 300 km for both emissions. There was no detectable 427.8 nm emission during any of the periods shown, indicating that the emission enhancements were not particle induced.

3.1 November 6, 1991—0430–0520 UT

Figure 1 shows a 630 nm patch appearing poleward of Eureka, drifting through the zenith and exiting from the field of view, in the sequence of meridian scans from 0430 UT to 0520 UT. Each line plot is an average of scans recorded over a six minute interval. The patch leading edge appeared about 0430 UT north of Eureka at a zenith distance of about 500 km. It drifted antisunward and reached the southern extreme of the meridian scan at 0520 UT. The 630 nm emission intensity when the patch moved through the zenith at 0445 UT was 140 R above background. It is seen to have a length along the meridian (which is near the antisunward direction at this time) of about 1000 km. Its drift velocity along the meridian was 0.5 km/s. The green line emission at 558 nm can be seen about 50 R above airglow when the patch crosses the zenith.

This is but one patch of a series, and even it may be a double one or tending to bifurcate or lengthen

Fig. 1. A series of meridian scans of emission intensity vs time from 0430 to 0520 UT, November 6, 1991 for 630 nm (left) and 558 nm (right). Each profile is an average over 6 minutes. A patch of 630 nm enhancement can be seen to the north at a zenith distance of 500–1000 km at 0430 UT, assuming an emission height of 300 km. It broadens, and changes form, as it moves through zenith in an antisunward direction and begins exiting from the field of view at 0505 UT.

as it passed overhead at 0450 UT and beyond. There is a patch, visible in Fig. 1, moving out of the field of view at 0430 UT, and another moving into the field from the poleward edge of the field at 0520 UT.

3.2 December 11, 1991—0230–0330 UT

Figure 2 shows 11 scan averages, from 0230 to 0330 UT, with a 630 nm patch first appearing 700 km poleward of Eureka. It moves through the zenith at 0300 UT and fades from view about 700 km equatorward of Eureka by 0330 UT. This event was specially selected as the antisunward direction is approximately along the MSP meridian at 0400 UT (and we have assumed the direction of drift motion is antisunward). The 630 nm enhancement, above airglow background, is up to 150 R as measured when the patch is overhead (at 0300 UT, 80° geog N). The cross-section of the patch is best measured as it passes overhead. The leading edge (at 0250 UT) is quite steep; the trailing edge (at 0305 UT) is also fairly abrupt. The apparent length of the patch is only about 200 km and its velocity is 0.24 km/s along the MSP meridian. There is clear evidence that the vertical extent of this 630 nm emission patch is greater than its horizontal extent, or it is undergoing dynamical changes. This is apparent from the view in the zenith at 0305 UT compared with the scans before and after.

Emission can be seen at 558 nm, above airglow background, in the right side of Fig. 2. This shows about 70 R above the meridian profile during the period 0300–0315 UT when the patch is near the zenith. There was no detectable 428 nm N_2^+ emission during this whole 1 hour period, indicating that there was no significant electron precipitation (above a threshold estimated to be about 5 R at 427.8 nm, or 0.02

Fig. 2. A series of meridian scans recorded at Eureka from 0230 to 0330 UT on December 11, 1991 showing an *F*-region patch in 630 nm emission moving from 600 km poleward of zenith to 400 km equatorward at 0320 UT. Each scan is averaged over 6 minutes. Other drifting patches can be seen both leading and following this patch. A smaller enhancement is evident in the 558 nm emission when the patch is in zenith.

ergs/cm²s). Once again, drifting patches preceding and following the central one displayed in Fig. 2 plot can be seen.

3.3 February 17, 1993—0945–1115 UT

This was an active night with auroral sun-aligned arcs (Oznovich and McEwen, 1994) appearing through most of the early hours until 0830 UT and again beyond 1200 UT. In the interval between, from 0945 until 1115 UT, a whole series of *F*-layer patches appeared. Figure 3(a) shows echoes from these patches observed by the CADI as they drifted overhead. Figure 3(b) shows a plot of zenithal intensities of the 630, 558, and 428 nm emissions during this period from 0900 to 1200 UT. The 630 nm intensity shows enhancements of up to 500 R above airglow from 0945 to 1115 UT. The 428 nm N₂⁺ plot shows no signal above background continuum, until onset of twilight resonance emission beyond 1030 UT. This indicates there was no significant electron precipitation associated specifically with the patches. The 558 nm airglow has a mean level of about 70 R, with periodic, small, transient enhancements coincident with the 630 nm patches. A series of at least six identifiable *F*-layer patches are identified optically from the individual meridian scans. They are enumerated in Table 1, with their diameters, drift speed along the MSP meridian (which was oriented approximately antisunward during the times of the patch observations) and brightnesses. This was the first day of operation of the digital ionosonde (CADI). It too detected all of these ionization patches, and provided measures of their drift velocities with errors typically $\pm 20\%$. The drift azimuths are measured from geographic north. A summary plot of the MSP scans, averaged over 3 min to show the evolution of the patches is shown in Fig. 4. The MSP was oriented 24°E of geographic N (along the geomagnetic meridian) during the 1992–93 winter. This means that the direction of the meridian scan is antisunward at approximately 0800 UT. The data are plotted in time progression from 0945 to 1115 UT with intensities of 630 and 558 nm as functions of distance from the zenith over Eureka (89° CGM).

It can be noted from Fig. 4 that while the first three patches are drifting antisunward, the remaining three patches show little motion in that direction. They do appear to move across the meridian, taking about 20 minutes to cross the meridian (since their dawn-dusk size can not be determined, their drift velocity is also indeterminate from the optical measurements).

Figure 3(a) shows the virtual height versus time ($h'f$) for the CADI echoes for the interval during which the *F*-layer patches appeared in the MSP data. About 6 patches are visible between 0945 and 1110 UT as U-shaped $h'f$ features. The patches seen in the $h'f$ plot correspond almost exactly one-for-one with the main peaks in zenithal 630 nm intensity in Fig. 3(b). Patches 2 and 3 appear in the MSP scans as a single form which bifurcated before reaching the zenith. The f_oF_2 values measured from the ionograms during this interval indicate that the *F*-region maximum electron density varied from a maximum of about

Table 1. Patch characteristics.

Date	Time (UT)	Size (km)	Velocity (km/s)	Intensity (R)		Drift Vel km/s	Drift Azi degrees
				630 nm	558 nm		
Nov. 7/91	0430–0520	1000	0.5	140	50	-	-
Dec. 11/91	0230–0330	200	0.24	150	70	-	-
Feb. 17/93	0945–1115						
Patch 1	0945	200	0.8	160	40	-	-
Patch 2	0955	500	0.6	250	70	0.5	185
Patch 3	1010	300	0.4	200	70	0.3	171
Patch 4	1015	400	-	150	40	-	271
Patch 5	1040	700	-	300	100	0.3	270
Patch 6	1100	300	-	150	40	0.2	270

Fig. 3. (a) The CADI $h'f$ plot for the sequence of F -region patches on February 17, 1993. The axes are virtual height h' and time t . The soundings are every 6 seconds on a frequency which is fixed for 15 minutes at a time. Each patch has a U-shaped $h'f$ signature. (b) A plot of zenithal intensities of 630, 558, and 428 nm emissions from 0900 to 1200 UT, February 17, 1993. A series of enhancements appear in the 630 nm (dotted line) and 558 nm (solid line) plots between 0945 and 1100 UT. There is no detectable 428 nm emission above background in this time interval.

$8 \cdot 10^{11} \text{ m}^{-3}$ within the patches to about $4 \cdot 10^{11} \text{ m}^{-3}$ between the patches. The minimum F -layer virtual height on the ionograms during the patch sequence was between 270 and 310 km, so this is approximately the true height of the patches. The distance scale for the MSP scans in Fig. 4 assumes a height of 300 km.

The skymaps of echo location for this interval are shown in Fig. 5. The horizontal component of the

Fig. 4. A sequence of meridian scans from magnetic north (R) to south (L) of 630 and 558 nm emission intensities from 0950 to 1120 UT on February 17, 1993 showing a series of six *F*-layer patches, labelled 1 to 6. Patches 1, 2, and 3 show a steady motion southward (roughly antisunward), while patches 4, 5, and 6 have very little motion along the meridian indicating an abrupt change in drift direction.

drift velocity vector can be determined on each skymap which has enough echoes for an estimate. The vertical velocity components are much smaller than the horizontal components. The magnitude and direction of the horizontal Doppler drift vector for each patch are given in Table 1. The azimuthal direction of drift is measured clockwise from geographic north. For reference, the antisunward direction at 1040 UT is 250° azimuth at Eureka. For those patches associated with more than one skymap, the table entries are typical values. The drift direction is approximately south up until 1010 UT, and approximately west at 1025 UT and later. This is consistent with the MSP results showing that the three patches which appeared in the zenith before 1015 UT drifted southward, while the later patches did not. Another difference between these two intervals is that before 1015 UT the echoes are amorphous in their distribution, while after 1015 UT they are generally confined to a narrow band.

A well defined band of echo locations was observed in each of the three skymaps at 1035, 1040, and 1050 UT, oriented roughly NE-SW in each case. That these are three snapshots of a single moving structure is supported by the single U-shaped $h'f$ trace extending across these times (Fig. 3(a)). At 1040

Fig. 5. CADI skymaps for Doppler data collected during the sequence of F -region patches on February 17, 1993. Each skymap is labelled with the UT, sounding frequency in MHz, and virtual height in km. The skymap axes are the sines of the angles from the zenith in the nominally north and east directions aligned with the antenna array. Thus each map extends approximately 37° to each side of the zenith. Furthermore, each may be looked at as an undistorted map of a square section of a horizontal plane of the ionosphere, the scale of which is set by the height assumed for the plane. Each Doppler spectrum bin with significant amplitude is plotted at the location corresponding to the direction of arrival and with a symbol which codes the Doppler shift.

UT the band was approximately overhead and the echoes were very distinctly confined to a narrow structure. This patch has the highest echo amplitude of the sequence, and corresponds to the strongest peak in zenithal 630 nm. The structure is approximately sun-aligned. The horizontal Doppler drift vector is directed close to antisunward but with a duskward component. The component of the Doppler drift velocity that is perpendicular to the structure alignment is 300 m/s, which agrees reasonably well with the speed inferred from the North-west motion between skymaps. The structure appears to be associated with patch 5, and the echoes are possibly located at the near edge of the 630 nm feature as it appears on the MSP scans.

Another way of determining the velocity of a patch is to use the range, h' , and angles-of-arrival to determine the position of the patch at various times with respect to the station. From these the velocity can be calculated. Of course, this velocity estimation should be corrected for a number of effects: refraction, group retardation, and motion of the reflection point over the surface of the patch. Nevertheless, sometimes an uncorrected velocity estimation using just h' and angle-of-arrival gives good results. For patch number 5 (Table 1), the velocity calculated this way taking h' from the envelope of the patch and average angles-of-arrival, gave 300 m/s toward the west. This is in good agreement with the value shown in Table 1. None of the other patches had sufficiently well defined angles-of-arrival to permit use of this method for calculating their velocities.

4. Results

This is a first report of observations of drifting *F*-layer ionization patches viewed collectively by optical means and with a digital ionosonde from a location near the magnetic pole (89° CGM), at the Canadian Polar Observatory at Eureka, NWT. This location permits investigation of their characteristics as they move over the magnetic pole and across the central polar cap. Some statements can be made based on this initial joint survey of patches observed on a particularly active day (February 17, 1993) from 0900 to 1130 UT, plus more extended optical observations on earlier days:

1. Optically, the 630 nm enhancement within the patches generally ranges from 150 to 300 R. There is also 558 nm enhancement, about 25–35% of the 630 nm enhancement. Within the optical patches there is structure, or there are fluctuations with time, and the patch edges are very poorly defined.
2. The patches drift, in general, in an antisunward direction but there can be significant deviations from this (as seen from 1000 to 1015 UT on Feb. 17).
3. The patch diameters are a few hundred km and the patches tend to appear repetitively, sometimes overlapping. They are quite dynamic, with patches sometimes appearing to divide, or bifurcate.
4. Patches seem to appear throughout the 24-hour period; a UT dependence on generation was not evident from our rather limited sample. Statistics on occurrence will be presented later, when a sufficient data sample is acquired.
5. Echoes from patches are at times distributed over a broad area overhead, but in one case they were organized into a well confined sun-aligned band.
6. The Doppler drift velocities showed general agreement with the observed optical patch motions (as found also in a study by Fukui *et al.* (1994)). In one case, further confirmation of westward (duskward) motion came from the continuous variation of echo angle-of-arrival and range with time. The Doppler drift velocities changed direction by approximately 90° during the patch sequence.

5. Discussion

Further evidence is given here for identifying the ion component of the patches as O_2^+ , produced by charge exchange from O_2^+ . The dissociative recombination reaction

has been proposed as the likely source of the observed 630 nm emission. The coincident 558 nm emission observed from the patches shown here supports that mechanism, and gives a branching ratio of about 4:1 for production of O[¹D] vs. O[¹S] excited states in the above reaction. There may be some collisional deactivation of the O[¹D] state, dependent on the height of the patch. In that case the observed intensity ratio of the 630 and 558 nm emissions would give useful information on the height of the patch. This is a topic for further study with a larger data base.

The absence of detectable N₂⁺ emissions from the patches further suggests excitation of the O emissions by this reaction, however direct measurements of low energy particle influx and ion convection from satellite passes directly over observed patches would be useful for verification of the excitation mechanism.

The height of the peak emission (and electron density) has been arbitrarily assumed to be 300 km for purposes of plotting locations and drift speeds from the optical data (Figs. 1–4, Table 1). The long lifetimes of the O₂⁺ patches suggest that their height is of the order of 300 km or greater. The virtual height of the echoes received by the CADI ranged from 270 km to 310 km for the several patches identified. The true heights are less than or equal to these values suggesting the lower edges of the patches were somewhat below 300 km.

The drift velocities of 0.4–0.8 km/s inferred for patches 1–3 of the February 17 sequence from their motion along the MSP meridian (Fig. 4 and Table 1) were within experimental error of the velocities of those patches measured by the CADI.

There was general agreement in the observed drift directions of the patches as measured by both the optical and ionosonde means. From 0945 to 1010 UT this drift was, in general, southward but clearly varying during that time. By 1025 UT (patch 4 motion) the drift direction had changed by about 90° to 270° azimuth. If patch drift motion represents the instantaneous convection direction across the polar cap, as is likely, then the sudden change in direction is due to a change in the IMF By (as discussed by Cannon *et al.* (1991)). There are no IMF data for that time period, but our observations overall for that date (Oznovich and McEwen, 1994) suggest that the IMF Bz and By were highly variable during that period. There were sun-aligned arcs both before and after the 2-hour period from 0900 to 1100 UT when drifting patches were observed.

6. Summary

A preliminary report is presented of *F*-layer ionization patches drifting over the north magnetic pole, detected by both optical and radio (digital ionosonde) means. The two observing techniques are seen to be complementary for studying patch structure and dynamics.

The detection of 630 and 558 nm emission only, with an absence of N₂⁺ emission, from the patches strongly suggests that the emissions are due to ion recombination rather than particle excitation. An initial assessment of patch occurrences suggests there is mainly interplanetary magnetic field control, and perhaps little if any UT variation. Patches have been observed at all hours. A more extensive study of patch characteristics and occurrence patterns will be undertaken as a more extended data set is acquired.

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