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Aeronomy and Space Physics in Polar Latitudes

This report describes my research progress as a Professional Research Associate and Adjunct Professor in the Institute, supported by the CSA under the CNSR Transition Award program.

My research is based on the large set of optical images of upper atmospheric emissions gathered by the Polar Camera system, which operated at the CNSR Polar Observatory at Eureka, NWT during the past three winters. Images of O(^{1}S) 557.7 nm and O(^{1}D) 630.0 nm, N_2^+ Meinel (2,0) 785 nm, and OH Meinel (6-2) P branch 829 nm and Q branch 835 nm emissions were acquired continuously during dark hours between October and March, with 24-hour operation for two months spanning the winter solstice.

The Polar Camera system consists of two highly sensitive all-sky cameras, each with bare CCD detector and five-position filter wheel, under computer control. The system was built at the University of Calgary with CNSR sponsorship, and was designed to operate virtually unattended in the harsh Arctic winter environment, acquiring long-exposure images simultaneously at two complementary wavelengths with high signal to noise ratio. These design goals were met, and the resulting images resolve emission brightnesses well below 50 rayleighs.

Three major lines of research have been initiated with the Polar Camera data: (1) study of ionospheric *F* region patches and high latitude ionospheric convection for southward interplanetary magnetic field (IMF); (2) study of polar auroras, particle precipitation and ionospheric convection for northward interplanetary magnetic field; and (3) study of airglow emission dynamics near the mesopause. Progress in each of these three areas is described below.

F Region Patches

Discrete "patches" of plasma at *F* region heights, separated by regions of much lower plasma density, are commonly observed throughout the polar cap during high geomagnetic activity. These patches convect antisunward across the polar cap in response to the dawn-to-dusk magnetospheric electric field. Despite increasingly intensive observations of patches in recent years questions remain as to the origins of patches, and the relations of their signatures in optical, radiowave, and plasma measurements, as well as the extent to which they can serve as tracers of the convection electric field.

A case study of patch dynamics was completed and submitted to *Radio Science* for publication in a special issue devoted to high latitude plasma structures. The study compared Polar Camera images and digital ionosonde observations (from the Canadian Advanced Digital Ionosonde (CADI) at Eureka) of an extended sequence of patches on December 8, 1993, observed during a period of strong southward IMF, and major

geomagnetic activity (Kp = 6 - 7). Patches were observed at the center of the polar cap almost continuously for over nine hours, and patch emissions were clearly imaged by the Polar Camera down to a threshold below 50 R at [OI] 630.0 nm (Figure 1), as well as at [OI] 557.7 nm for some of the brighter patches which stood out against the high E-region airglow background. Patch displacements between consecutive images were measured accurately, and from these displacements a record of the ionospheric convection velocity (both speed and direction) at the geomagnetic pole was developed. These velocities compared very favourably with simultaneous data from the CADI at Eureka (Figure 2). Grant *et al*. (1995) have shown that Resolute Bay CADI convection measurements are consistent with those from the SuperDARN radars. Cross-correlation of the drift azimuth at Eureka with the *y* component of the IMF indicated a delay of 20 min between IMF changes and drift direction changes at the center of the polar cap, consistent with earlier work by Greenwald *et al*. (1990) showing a delay of about 8 min between IMF changes and the corresponding convection changes in the cusp region. The changes observed at Eureka result from large-scale reorganization of the convection electric field, as the implied delay of 12 min between the cusp and the central polar cap is much shorter than the plasma transit time between these regions, which is of the order of an hour.

The virtual reflection heights during patch transits showed a clear anticorrelation with the 630.0 nm zenith brightness, which provides *prima facie* support for use of the column brightness as a proxy for the F-region plasma distribution, at least on a case-by-case basis. However, modelling work by Sojka *et al*. (1994) suggests that a simplistic interpretation of the optical data can be misleading, and a statistical study of correlations between Polar Camera and CADI patch observations is planned, to test the relationships identified in the modelling.

A by-product of the Dec. 8, 1993 event study was a montage view of the 630.0 nm emission distribution seen over Eureka for a period of 9 hours (Figure 3). This montage may be interpreted as a larger-scale view of the "tongue of ionization" that flows antisunward across the polar cap from its dayside point of entry. This type of presentation is novel, and may be useful in comparing patch observations at the pole with the time history of dayside processes from other observing platforms, both ground- and space-based.

During the past year I collaborated in a case study of patch formation and evolution led by Dr. Paul Prikryl of the Communications Research Centre, which examined a very wide range of observations and physical processes that took place on Dec. 2, 1993, just 6 days before the event described above. The study, which has been submitted to the *Journal of Geophysical Research*, identified a possible cause-effect relationship between, in turn, IMF B_y oscillations, Pc5 field line resonances on closed field lines equatorward of the cusp, pulsed magnetic reconnection on the magnetopause adjacent to the resonating L shells, flow channel events featuring strong horizontal electric fields that heated *E* region electrons and *F* region plasma, and subsequent detachment of patches into the polar cap. The study suggests that ionization associated with Pc5 bands drifting into the cusp contributed to the formation of polar patches.

Polar Auroras

During a review of the Polar Camera 630.0 nm images from the winter 1994-95, 15 - 20 instances of a previously unreported phenomenon were observed: diffusely emitting 'surfaces' drifting across the polar cap from either the dawn or the dusk sector (Figure 4). These emitting regions appeared to be associated with, and yet distinct from, polar auroral arcs. Examination of each case for which optical images were available, together with supporting data from the Eureka CADI, the Magnetic Fields Investigation and the Solar Wind Experiment on board the WIND satellite, and the SSJ/4 precipitating plasma sensor on board the DMSP satellites F10 - F12, established the following characteristics of the diffuse emission regions:

1. Emission was predominantly (if not exclusively) at 630.0 nm; no emission above background was detectable at 557.7 nm and 785 nm . Typical brightness at 630.0 nm was 50 - 200 R, well below the detection threshold of most all-sky cameras.

2. Emission occurred on one side of a roughly linear and sun-aligned leading-edge boundary, that drifted toward or past the geomagnetic pole in the direction (in the Northern hemisphere) of the y component of the IMF.

3. Emission was associated with polar arcs and occurred during northward Bz conditions.

4. Ionospheric drifts as measured by CADI had a component in the same direction as the motion of the emission boundary.

5. The polar cap as defined by DMSP particle precipitation was strongly contracted in the dusk and dawn sectors, with oval precipitation extending up to 80° GM latitude.

6. Particle precipitation above the diffuse emission regions was very weak but showed slightly enhanced electron and ion fluxes.

These findings were presented in preliminary form at a Polar Science Workshop, held at Windermere Manor, U.W.O., on May 25-27, 1995. A fuller presentation, with supporting evidence in the form of a video presentation of an image sequence, was given at the XXI General Assembly of the International Union of Geodesy and Geophysics (IUGG) held at Boulder, CO, on July 2-14, 1995. An application has been made to NSERC for funding to expand this preliminary work to include other years of observations and other ground- and space-based data sets.

A collaboration was undertaken with Dr. Israel Oznovich on a study of the altitudes of auroral arcs observed optically from the ground at multiple visible wavelengths including 630.0 nm. Using model height profiles (Meier *et al*., 1989) of 630.0 nm

emission for 0.25 keV and 2 keV electron spectra to synthesize meridian scans through red line arcs for various zenith distances, he showed that the zenith angle of peak slant column emission rate of the red line varies by less than 1.5° between arc widths of 5 and 50 km, and 0.25 and 2 keV characteristic electron energy. This behaviour makes the red line emission peak a useful benchmark from which to estimate the emission peak of a lower-altitude emission on the same magnetic field line, such as 557.7 nm, N_2^+ 1NG (0,1) 428 nm, or the related N_2^+ emission at 785 nm. It suggests that the peak emission height of the lower-altitude emission can be estimated from the "known" height of the red line emission, and the observed angular separation of the red and green arcs along the meridian perpendicular to the arcs. Such estimates are valuable, at minimum, for mapping imaged arcs to geographic or geomagnetic coordinates at the appropriate emission height, and can aid in inferring the characteristic energy of the precipitating particles.

We tested the algorithm using Polar Camera data from Eureka in the polar cap, since the field lines near the pole are essentially vertical and the arc geometry is therefore simpler. We examined a case from October 23, 1993 when two arcs traversed the sky at Eureka within 20 min of each other, and were both overflown within the Polar Camera field of view by the DMSP F8 satellite which measured the precipitating particle fluxes. Although the arcs drifted from one horizon to the other, we identified intervals when they were essentially stationary and inferred peak 557.7 nm emission heights of 180 - 190 km, which were unusually high for the green line although consistent with the predominantly red emission from the arc. DMSP F8 measured electron spectra peaking at 200 - 400 eV, consistent with the high emission altitude, and also gave a fix on the horizontal position of the arc where it overflew it. Comparing the zenith distance of the green arc as seen from Eureka with the arc coordinates yielded an emission height of 185 km, fully consistent with the altitude inferred from the angular distance between the red and green emissions. These results were presented at the 1995 Fall Meeting of the American Geophysical Union (AGU), held December 11-15, 1995 in San Francisco, CA.

Neutral Atmosphere Dynamics

Along with auroral emissions, the Polar Camera images two portions of the OH Meinel (6-2) band, which is emitted from the mesopause. The two portions of the band emission vary independently with the rotational temperature of the band, which reflects the ambient temperature at the mesopause. The two images, acquired simultaneously, should in principle allow the mesopause temperature to be inferred. This, together with the total band brightness inferred from the portions of the band sampled, should allow a measurement of Krassovsky's ratio, which has been shown by recent modelling to be a sensitive diagnostic of the particular mode of disturbance when waves are passing through the mesopause and perturbing both the ambient temperature and the column brightness of the OH emission layer.

Work has been undertaken, in collaboration with Prof. L. L. Cogger of the University of Calgary, to develop the technique sketched above for the particular data acquired by the Polar Camera, as a first step in applying the results to a measurement of

the wave spectrum at the mesopause above Eureka, both for particular cases and on a statistical basis.

Figure Captions

1. Images of 630.0 nm emission from antisunward-drifting patches at Eureka on December 8, 1993, from 0300 UT to 0330 UT. Geographic North is at the top of the images, and East is to the right. The field of view extends to 70º zenith angle in the upper corners, but is restricted to the South by a permanent moonshade. Full scale brightness is 300 R in these 60-s time exposures. The solar azimuth is to the upper left (geographic NW) at this time.

2. Comparison of ionospheric drift directions and magnitudes measured independently by two techniques. The thin lines in the second and third panels show the ionospheric drift direction (relative to geographic North) and the drift speed measured by a Canadian Advanced Digital Ionosonde CADI). The thicker lines show the direction and speed inferred from the Polar Camera patch images. The top panel shows the range-time characteristic of the CADI returns at 4.012 MHz, and the zenith 630.0 nm brightness at Eureka.

3. A montage of 630.0 nm patch emissions over Eureka from a nine-hour series of images. Sections of individual images, transformed to geographic coordinates, were pieced together using patch drift velocities as shown in Fig. 2. The sunward direction is to the top, and the spatial scale is as shown. Each panel spans approximately twice the nominal diameter of the polar cap.

4. A series of 630.0 nm images (350 R full scale) showing the poleward advance of polar diffuse aurora from the dawn sector of the polar cap between 2030 UT and 2100 UT on December 23, 1994. A polar arc forms at the poleward boundary of the diffuse emission after about 2048 UT.

Publications

1. Steele, D. P. and L. L. Cogger, Polar patches and the "tongue of ionization", *Radio Science*, in press.

2. Prikryl, P., I. F. Grant, J. W. MacDougall, C. W. S. Ziesolleck, D. P. Steele, G. J. Sofko, and R. A. Greenwald, Observations of polar patches generated by solar-wind-driven Pc5 field line resonances and pulsed magnetic reconnection at the dayside magnetopause, submitted to *Journal of Geophysical Research*, September 1995.

Conference Presentations

1. Steele, D. P., Observations of diffuse aurora at the geomagnetic pole, paper GAA51C-24 presented at XXI General Assembly, International Union of Geodesy and Geophysics, Boulder, CO, July 2 - 14, 1995.

2. Steele, D. P., and I. Oznovich, Single-point stereoscopy for ground based space research (abstract), *EOS Trans. AGU*, **76**, Fall Meeting Supplement, F483, 1995.

Other Presentations

1. Steele, D. P. and L. L. Cogger, Observations of diffuse aurora over geomagnetic pole, presented at CNSR Polar Science Workshop, Windermere Manor, University of Western Ontario, May 25-27, 1995.

2. Steele, D. P., The CNSR/University of Calgary Polar Camera, presentation to CANOPUS All-Sky Imager Science Team, University of Calgary, June 14, 1996.

3. Steele, D. P., High latitude magnetosphere-ionosphere interactions, presentation to I.S.A.S. Advisory Committee, November 26, 1995.

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4. Oznovich, I., D. J. McEwen, and G. G. Sivjee, Temperature and airglow brightness oscillations in the polar mesosphere and lower thermosphere, *Planet. Space Sci.*, **43**, 1121-1130, 1995.

5. Sojka, J. J., R. W. Schunk, M. D. Bowline, and D. J. Crain, Ambiguity in multi-instrument technique identification of polar cap F-region patches (abstract), *EOS Trans. AGU*, **75**, Fall Meeting Supplement, F???, 1994.