Tomographic reconstruction of 630.0 nm emission structure for a polar cap arc

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Abstract. Monochromatic imagers located at two sites in the Canadian Arctic were operated in tandem during the poleward transit of a duskside sun-aligned polar cap arc on February 19, 1996. The morphologically stable arc was observed by both stations in 630.0 nm images over a 5-min period from 0232 to 0237 UT. Profiles of 630.0 nm brightness versus elevation angle were extracted from pairs of images along a great circle defined by the two ground stations. These data were supplied as inputs to a tomographic reconstruction for the arc-related 630.0 nm volume emission rate in a vertical (latitude versus altitude) plane: η_{630}(lat,z). The time evolution of η_{630}(lat,z) structure for this polar cap arc indicates that magnetospheric processes (such as modifications to the electron source energy distribution) and not thermospheric processes (such as neutral heating and plasma diffusion/decay) controlled the arc-related 630.0 nm emission.

1. Introduction

Our current understanding of polar cap aurora, typically observed during periods of northward IMF B_z (NBZ), is to describe such arcs as electrodynamic signatures for magnetospherically-imposed field-aligned currents (FACs) and as a direct sample of lobe, plasma sheet, or plasma sheet boundary layer regimes [*Weiss et al.*, 1993; *Carlson*, 1994, and references therein]. The magnetospheric regime responsible for polar cap arc precipitation and the specific topology of the arc-related field line is a question open to wide speculation [*Valladares et al.*, 1994]. Synoptic ground-based estimates for the characteristic energy (E_0) and energy flux associated with a polar cap arc therefore can help define the specific configuration of the NBZ magnetosphere by describing the energetic evolution for the source of the precipitating electrons.

The challenge for such ground-based aeronomical measurements is to isolate and observe soft ($E_0 < 100$ eV) *F*-region polar caps arcs which are free of significant ionospheric forcing. In contrast to soft polar cap arcs, intense polar cap arcs (with significant ionization below 200 km) [*Valladares and Carlson*, 1991] have been shown to be susceptible to modification by the ionospheric convection, chemical decay, and diffusion [*Crain et al.*, 1993; 1994].

Multistation optical imaging and subsequent atmospheric emission tomography (AET) can help gauge the relative dominance of magnetospheric and thermospheric control of polar cap arcs by reconstructing the vertical distribution of arc-related 630.0 nm emission from metastable $O(^1D)$. Auroral $O(^1D)$ is primarily created by energetic electron impact, and to a smaller extent by the chemical decay of ambient ionization [*Solomon et al.*, 1988]. Thus, the timescale for the evolution of η_{630}(lat,z) constrains the timescale for changes in the magnetospheric electron source and the timescale for thermospheric processes such as plasma and atomic oxygen transport. The goal of this study therefore is to measure 630.0 nm brightness from two stations and reconstruct η_{630}(lat,z) for a soft polar cap arc with sufficient time resolution to verify magnetospheric control and to estimate likely changes in the electron source energy distribution.

2. Campaign Overview

Imaging stations for this campaign were located at the NSF Resolute Bay Observatory (RBO, Resolute Bay, NWT, lat. 74.4° N, long. 265.4° E) and at the Canadian Arctic Stratospheric Ozone (ASTRO) Observatory (EUK, Eureka, NWT, lat. 80.2° N, long. 274.1° E). These two sites lie along a nearly common geomagnetic meridian with a baseline of approximately 550 km. The geomagnetic map shown in Figure 1 locates the imagers at 0220 UT. The optical fields of view for the RBO (large oval) and EUK (small patch) show the imaging coverage, at an assumed emission height of 250 km, for elevation angles down to 80° and 40°, respectively. The specific shape of the EUK coverage was due to the installation of a fixed moonshield. The approximate location of the polar cap arc at 0235 UT is overlain as well.

A stable sun-aligned polar cap arc was detected in RBO 630.0 nm images over a 55-min period from 0132 to 0237 UT. Nearly simultaneous image pairs were acquired at RBO and EUK stations from 0232 to 0237 UT. Magnetometer data from the WIND satellite, corrected for spacecraft position, indicates that B_z was northward (with the exception of a brief 8-min period) for 3.5 h prior to 0232 UT. Negative IMF B_y conditions prevailed for 1 h prior to joint imaging. Such an IMF orientation is consistant with the observed dusk-to-dawn drift of this polar cap arc [*Valladares et al.*, 1994].

3. Image Photometric Calibration

The allsky monochromatic imager installed at RBO is a bare-CCD telecentric design which yields 12-bit 329 by 258 PIXEL images at 4 by 4 binning [*Wu and Killeen*, 1996]. The 630.0 nm RBO images were integrated at either 30 or 60 s depending on arc brightness. Raw images were photometrically corrected as described by *Oznovich et al.* [1994] with subtraction of a dark noise image and normalization to a composite flat field/vignetting image. Due to the localized vertical nature of arc emissions, no correction was made for van Rhijn brightening. Geometric distortion and RBO imager orientation were determined by analysis of a star field image acquired through the wide-band OH filter.

The camera at EUK is composed of two telecentric imagers each using a thermoelectrically cooled bare CCD. The 128 by 128 PIXEL 16-bit images were integrated for 60 s and acquired approximately every other minute [*Steele and Cogger,* 1996]. In a manner similar to the RBO images, the EUK data were corrected for dark noise, flat field, vignetting effects, and lens spatial distortion.

Both RBO and EUK imagers were calibrated using low-brightness standard sources which had been previously cross-calibrated against U.S. National Institutes of Standards and Technology and Canadian National Research Council brightness standards, respectively. RBO images acquired within ± 30 s of EUK images were interpolated in time in order to define image pairs at 0232:44, 0235:11, and 0237:23 UT.

Profiles of 630.0 nm brightness (I_{630} in Rayleighs) versus zenith angle (ZA) were extracted from RBO/EUK image pairs along the great circle plane defined by the two stations. Figure 2 shows three pairs of I_{630}(ZA) profiles which indicate the slow poleward drift of the arc over a 5-min period. These profiles were supplied as inputs to the tomographic reconstruction of η_{630}(lat,z) described in the subsequent section.

4. Atmospheric Emission Tomography

AET techniques seek to reconstruct the spatial distribution of volume emission rates using line-of-sight photometric measurements from multiple sites. In this case, the tomographic measurement is I_{630} as a function of zenith angle extracted from two all-sky cameras; the reconstructed quantity is a 2-dimensional (latitude vs. altitude) slice of η_{630} within the polar cap arc.

The limited-angle viewing geometry in AET leads to an ill-posed inverse problem. In particular, the vertical dimension is not well supported by the data. To obtain a meaningful solution, the problem must be regularized in some way. An innovative AET technique which uses Chapman function regularization, subsequently followed by a multiplicative algebraic reconstruction technique (MART, *Censor* [1981]), has recently been developed for use by NSF's Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) Optical Tomographic Imaging Facility (COTIF). This method initially constrains the vertical dimension with Chapman functions with no horizontal constraint [*Semeter and Mendillo*, 1996]. Chapman functions provide an appropriate analytic form for the mean features of η_{630}(z) found in polar cap arcs. This regularization scheme embeds into the solution *a priori* the three physical quantities most relevant to aeronomical studies of the aurora: the maximum volume emission rate, the peak emission altitude, and the emission scale height.

Convergence of an initial Chapman solution, which minimizes errors between measured and modeled I_{630}, is accomplished by means of a Davidon-Fletcher-Powell algorithm. The Chapman constraint is then removed, and the η_{630}(lat,z) elements are iterated directly using the MART algorithm. The resultant arc reconstruction represents the best possible least-squares solution to the original set of I_{630}(ZA) measurements.

5. Discussion

Plate 1 shows the AET reconstruction for η_{630}(lat,z) associated with this drifting polar cap arc. Two sources of uncertainty dominate such a tomographic analysis: (1) contamination by distant auroral sources and (2) uncertainties in tropospheric scattering and extinction. Both are handled similarly by the AET algorithm. An increased brightness due to a distant source occurs only in observations at large zenith angles (such as in the RBO observations). Tropospheric effects on the photon flux also increase with increasing zenith angle. For this reason a weighting is applied during the reconstruction to favor fitting observations nearer the zenith [*Semeter and Mendillo,* 1996]. In this regard, the viewing geometry for this experiment is advantageous: the near zenith observations at EUK constrain the total photon inventory, while the off zenith observations at RBO guide the altitude profile.

The detailed study of auroral red line emission presented by *Solomon et al.* [1988] concludes that $O(^1D)$ creation results primarily from two classical mechanisms: (1) energetic (>1.96 eV) electron impact on O, and (2) charge exchange from O^+ to O_2 followed by rapid dissociative recombination of O_2^+. The auroral emission models presented by these authors indicate that process (1) is dominant and accounts for no less than 70% of the total auroral 630.0 nm emission. Both processes are modulated by the time evolution of the magnetospheric electron source, yet only process (2) is controlled by ionospheric plasma transport, diffusion, and decay. We now examine the evolution of η_{630}(z) for this case study arc to confirm that magnetospheric control of both processes was dominant.

Figure 3 presents three vertical profiles of η_{630} as sampled through the central core of the arc in each of the three panels in Plate 1. Note the similarity in η_{630}(z) shape over the 147-s period from 0232:44 to 0235:11 UT. For these two profiles, the height of the peak emission increases slightly and the topside emission scale height remain virtually unchanged. If one attributes the enhanced 630.0 nm emission at 0235:11 UT to an ionospheric process, then the apparent >40% increase in O^+ must have been due to plasma diffusion or due to horizontal or vertical plasma transport. Plasma diffusion can be ruled out as the *F*-region timescale required for a diffusive event is on the order of 1000 s [*Doe at al.,* 1993; *Crain et al.,* 1994] and not the 150 s observed. Horizontal transport, that is the zonal convection of a nearby plasma density enhancement, can be effectively ruled out by the longitudinal uniformity of the arc as observed in allsky images. Lastly, enhanced airglow due to bulk downward plasm transport can be ruled out as the bottomside shape of the emission profile remains virtually unchanged.

Subsequent evolution of $\eta_{630}(z)$ at 0237:23 UT shows a steepening of the topside scale height (above 315 km), a decrease in the height of peak emission, and a narrowing of the emission profile around the peak. The topside behavior is suggestive of an airglow signature resulting from the upward diffusion of ionospheric plasma. However such diffusion, as pointed out previously, cannot occur on 2-min timescales. An alternate explanation for the topside increase in 630.0 nm emission is that a neutral upwelling event increased the atomic oxygen abundance available for impact excitation. This hypothesis also fails as modifications to the O scale height require even longer timescales than required for plasma diffusion. We conclude then that the observed evolution of $\eta_{630}(z)$ from 0232:44 to 0237:23 UT was due to changes in the energy distribution of precipitating electrons from the magnetosphere. We will now consider the likely evolution of electron energy distribution in the magnetosphere.

Without appealing to a full auroral emission model, one can analyze the evolution of the arc-related $\eta_{630}(z)$ profiles by comparison with modeled altitude profiles of volume energy deposition $\epsilon(z)$ for a few candidate magnetospheric energy distributions. Such a comparison requires the reasonable assumption that 630.0 nm emission from auroral impact and from auroral secondaries (at a given altitude) should be proportional to the local rate of energy supply from the penetrating auroral electron beam. We therefore seek volume energy deposition profiles that are due to simple Maxwellian-like energy distributions and that mimic the time progression of $\eta_{630}(z)$ profiles as shown in Figure 3.

We first consider auroral energy deposition due to a monoenergetic beam of electrons as it degrades through the neutral atmosphere. For such a beam, the energy deposition rate is given by *Rees* [1989]:

$$\epsilon(z,E) \;=\; \left(\frac{\phi E \rho(z) \Lambda(z,E)}{R(E)}\right), \qquad (1)$$

where ϕ is the number flux of precipitating electrons at beam energy E, $\rho(z)$ is the MSIS-90 mass density function, $\Lambda(z,E)$ is the normalized energy deposition distribution function for a unidirectional beam [*Barrett and Hays*, 1976], and $R(E)$ is the effective stopping range. Candidate $\epsilon(z)$ profiles which match the $\eta_{630}(z)$ peak altitude and approximate shape can now be calculated by integrating equation (1) for Maxwellian-like energy distributions of ϕ versus E.

Figure 4 shows a family of three such energy deposition profiles which correspond to three Maxwellian-like magnetospheric sources. The source characteristic energy and number flux for the first two $\epsilon(z)$ profiles indicate that the shape-preserving increase in 630.0 nm emission observed from 0232:44 to 0235:11 UT is likely due to a simple fourfold increase in total number flux of a ~15 eV Maxwellian source. For the profile at 0237:23 UT, our modeled $\epsilon(z)$ matches the peak altitude and bottomside shape for the $\eta_{630}(z)$, yet fails to match the topside scale height. This result reflects the fact that our simple energy deposition model lacks sufficient low-energy terms to effect the 350 to 500 km regime. Overall, the progression of $\epsilon(z)$ profiles in Figure 4 is qualitatively similar to the progression of $\eta_{630}(z)$ profiles in Figure 3.

6. Conclusion

This study has used a novel tomographic reconstruction algorithm to synthesize the meridional 630.0 nm volume emission rate structure for a stable polar cap arc from pairs of allsky images. The AET technique expands traditional line-of-sight horizontal analysis into a third dimension by describing the time evolution of η_{630} in the vertical (latitude versus altitude) plane. The temporal resolution of the reconstructed polar cap arc emission structure is sufficiently fine to discriminate magnetospheric from thermospheric control. Specifically, the shape-preserving evolution of $\eta_{630}(z)$ from 0232:44 to 0235:11 UT, which could not be explained by invoking ionospheric plasma diffusion or transport, is shown to be consistant with a simple fourfold flux increase of a ~15 eV Maxwellian source. Likewise the subsequent evolution of $\eta_{630}(z)$ from 0235:11 to 0237:23 UT, which was unlikely to be caused by plasma diffusion or neutral upwelling, is shown to be consistant with a modification of the electron source from a 16 eV single Maxwellian to a 25/50 eV bi-Maxwellian (with an appended low-energy tail).

Future AET analysis of NBZ polar cap arcs will be augmented by radarwave estimates for N_e(lat,z). Such plasma density data can be used to "correct" the η_{630}(lat,z) structure for the contributions from recombination airglow. The resultant emission structure, presumably due only to auroral excitation, can be subsequently analyzed to reconstruct the a more precise shape for the magnetospheric source energy distribution.

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Figure 1. Polar geomagnetic map showing the location of RBO and EUK imagers and two stations in the MACCS array (GJO and IGK). The imaging fields of view from RBO and EUK are superposed as is the approximate location of the stable polar cap arc at 0235 UT.

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Figure 2. Pairs of 630.0 nm emission versus zenith angle profiles as extracted from photometrically corrected images. These profiles indicate that the arc was drifting slowly poleward during this period.

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Plate 1. Tomographic reconstruction for the time evolution of η_{630} structure in the RBO/EUK great-circle plane. The overlaping boundaries of the RBO and EUK fields of view are shown with dark lines.

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Figure 3. Three sequential vertical profiles of Log_{10} η_{630} as sampled through the central core of the arc in panels *a*, *b*, and *c* of Plate 1. This figure underscores the similarity in overall shape for profiles (1) and (2).

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Figure 4. Modeled volume energy deposition rate profiles constructed from soft Maxwellian-like profiles. The source characteristic energy (E_0) and number flux (Φ_N) for each of these three profiles were adjusted to best fit the shape of $\eta_{630}(\mathrm{z})$ profiles shown in Figure 3. Values for Φ_N are in units of $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

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