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

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Short title: TOMOGRAPHIC RECONSTRUCTION OF POLAR CAP ARC

Abstract. Monochromatic imagers located at two sites in the Canadian Arctic were operated concurrently during the poleward transit of a duskside sun-aligned polar cap arc on 19 February 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 vs. 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 of 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 cap arcs that 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) limits the time resolution with which the effects of changes in the magnetospheric electron source and thermospheric processes such as plasma and atomic oxygen transport may be observed. 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 qualitative changes in the shape and flux of 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 (EUR, Eureka, NWT, lat. 80.1° N, long. 273.6° 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 EUR (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 EUR coverage was due to the installation of a fixed moonshield. The approximate location of the polar cap arc at 0235 UT is overlaid 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 EUR stations from 0232 to 0237 UT. Magnetometer data from the WIND satellite, corrected for spacecraft position, indicate 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 consistent with the observed dusk-to-dawn drift of this polar cap arc [*Valladares et al.*, 1994].

3. Image Photometric Calibration

The all-sky monochromatic imager installed at RBO is a bare-CCD telecentric design that 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 wideband OH filter.

The camera at EUR is composed of two telecentric imagers each using a thermoelectrically cooled bare CCD. The 128 by 128 PIXEL 14-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 EUR data were corrected for dark noise, flat field, vignetting effects, and lens spatial distortion.

Both RBO and EUR imagers were calibrated using low-brightness standard sources that 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 ±60 s of EUR images were interpolated in time, by means of a weighted average, in order to define RBO-EUR image pairs at 0232:44, 0235:11, and 0237:23 UT, hereafter referred to as periods 1, 2, and 3.

Profiles of 630.0 nm brightness (I_{630} in Rayleighs) versus zenith angle (ZA) were extracted from RBO-EUR image pairs along the great circle plane defined by the two stations. Figure 2, which summarizes I_{630}(ZA) profiles for periods 1, 2, and 3, indicates the slow poleward drift of the arc. 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 two-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 that 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 $\eta_{630}(z)$ 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: contamination by distant auroral sources, and 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 EUR 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 $\eta_{630}(z)$ 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 shown in Plate 1. Note the similarity in $\eta_{630}(z)$ shape over the 147-s period from period 1 to period 2. For these two profiles, the height of the peak emission increases slightly and the topside emission scale height remains virtually unchanged. If one attributes the enhanced 630.0 nm emission during period 2 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 all-sky images. Lastly, enhanced airglow due to bulk downward plasma transport can be ruled out as the peak of the emission profile should move to a lower altitude and not to a higher altitude as observed.

Subsequent evolution of $\eta_{630}(z)$ from period 2 to period 3 shows a steepening of the topside scale height (above 300 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 are required for plasma diffusion. We conclude then that the observed evolution of $\eta_{630}(z)$ throughout this event 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 qualitatively 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 assumption that 630.0 nm emission from auroral electron 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]:

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

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. For our simple model, the lowest energy component is set to 30 eV which corresponds to an upper altitude limit of $\sim$350 km. Below this altitude, the model can produce candidate $\epsilon(z)$ profiles that match the $\eta_{630}(z)$ peak altitude by integrating equation (1) for candidate 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 period 1 to period 2 is likely due to a simple fourfold increase in total number flux of a bi-Maxwellian source. For the period 3 profile, 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 model the 350 to 500 km regime correctly. 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 uses 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 two-station all-sky 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 vs. 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 period 1 to period 2, which could not be explained by invoking ionospheric plasma diffusion or transport, is shown to be consistent with a simple fourfold flux increase of a bi-Maxwellian source. Likewise, the subsequent evolution of $\eta_{630}(z)$ from period 2 to period 3, which was unlikely to be caused by plasma diffusion or neutral upwelling, is shown to be consistent with a modification of the electron source from a 15/100 eV bi-Maxwellian to a 25/40 eV bi-Maxwellian electron source.

Future AET analysis of NBZ polar cap arcs will be augmented by radio-wave measurements of 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 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 EUR imagers and two stations in the MACCS array (GJO and IGK). The imaging fields of view from RBO and EUR are superposed as is the approximate location of the stable polar cap arc at 0235 UT.

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.

Figure 3. Three sequential vertical profiles of $\mathrm{Log}_{10}\ \eta_{630}$ 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).

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

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