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PLASMA CHARACTERISTICS OF POLAR CAP F-LAYER ARCS

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Abstract. First results are reported of a comprehensive campaign to measure ionospheric structure and dynamics of nighttime polar cap F-layer or F-region arcs. Airborne optical and digital ionosonde data were collected simultaneously with ground based incoherent scatter radar data, continuously over many hours in time and 500 to 1000 km in space. Polar cap F-region sub-visual auroral arcs, which are commonly observed during quiet magnetic conditions, are found to represent boundaries (or shears) in the polar cap plasma circulation pattern. F-region electron concentration enhancements are found in these features and can be of significance to polar thermospheric circulation, composition, and thermal structure. The quiet polar ionosphere is so structured that high time resolution intensified optical images of thermospheric emmissions can make a major contribution to interpretation of incoherent scatter radar data.

Introduction

An entirely fresh view of the Polar Cap Ionosphere (Weber and Buchau, 1981) has resulted from the technology of image intensified optical systems, on highly mobile platforms. Buchau et al., (1983) have reviewed the structure and dynamics of the winter polar cap F-region, and shown that it has a bimodal character depending on the level of geomagnetic activity. Patches of enhanced ionization are observed to drift in the anti-sunward direction across the polar cap during disturbed magnetic conditions (Kp > 4) and when the north-south component of the interplanetary magnetic field, B_z, is southward. This is presumably due to a well ordered electric field imposed on the ionosphere by the solar wind-magnetospheric interaction under these conditions (Heelis and Hanson, 1980), resulting in a uniformly anti-sunward plasma convection pattern across the polar cap. Sun-aligned F-region arcs dominate the optical/ionospheric character under very quiet conditions. Precipitating electron morphology in the polar cap (Hardy, 1984) also supports the preferential occurrence of polar cap F-layer auroras during B_z northward conditions.

Weber et al., (1984) have reported coordinated observations directed at defining the properties of F-region ionization patches in the polar cap and some of the associated implications. Here we address the same for polar cap F-region arcs, by combining observations by the AFGL's Airborne Ionospheric Observatory (AIO) and the Sondrestromfjord incoherent scatter radar. Each diagnostic tool eliminates ambiguities of interpretation to which the other is subject.

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Experimental Design and Motivation

In designing an experimental campaign specifically to study the nature of polar cap F-region arcs, two primary issues at hand were: a) do the sub-visual F-region sun-aligned arcs identify boundaries between regions of differently directed polar plasma flow; and b) are there significant plasma density enhancements within these polar arcs.

The plasma flow boundary question was based on the properties of the arcs found in previous airborne campaigns (Weber and Buchau 1981, Buchau et al, 1983). The arcs are nominally sun aligned, tend to slowly drift at speeds of 100-250 m s^{-1} from dawn to dusk (perpendicular to their alignment), occur primarily during magnetically quiet or B_z northward conditions, and are produced by soft (100s eV average energy) particle precipitation. In view of previously reported velocity shears detected by in-situ ion velocity measurements during B_z northward conditions (Heelis and Hanson, 1980; Burke et al., 1979) and the fact that gradients in electric fields or conductivity lead to divergences of currents, it was speculated that under quiet conditions the F-region 6300Å auroras demarcate boundaries of velocity shear in the weakly ordered polar plasma flow, with the soft particle flux providing the required current continuity. The implications and value of confirmation are evident. Reiff et al. (1978) postulated a similar relation of polar cap auroras to velocity shears near midday.

The question of plasma density enhancements was raised by ionosonde measurements during previous campaigns using the AIO (Buchau et al., 1983). Drifting 6300Å arcs (with negligible 4278Å emission) were observed to yield F-region (with no E-region) ionosonde returns in excess of 10 MHz; severe spreading limited interpretation to a lower bound of 4 x 10^5 el cm^{-3} during passage of polar cap arcs in January 1982 AIO ionosonde data. This raised the question whether there were regions of sufficiently large ion concentration and velocity in the polar cap which could modify thermospheric thermal structure, composition and circulation.

The incoherent scatter radar (ISR) was required for unambiguous measurements of plasma concentrations and line of sight velocities (as well as temperatures). The instrumentation on board the AIO required for this experiment (and described in Weber et al., 1984), included: an

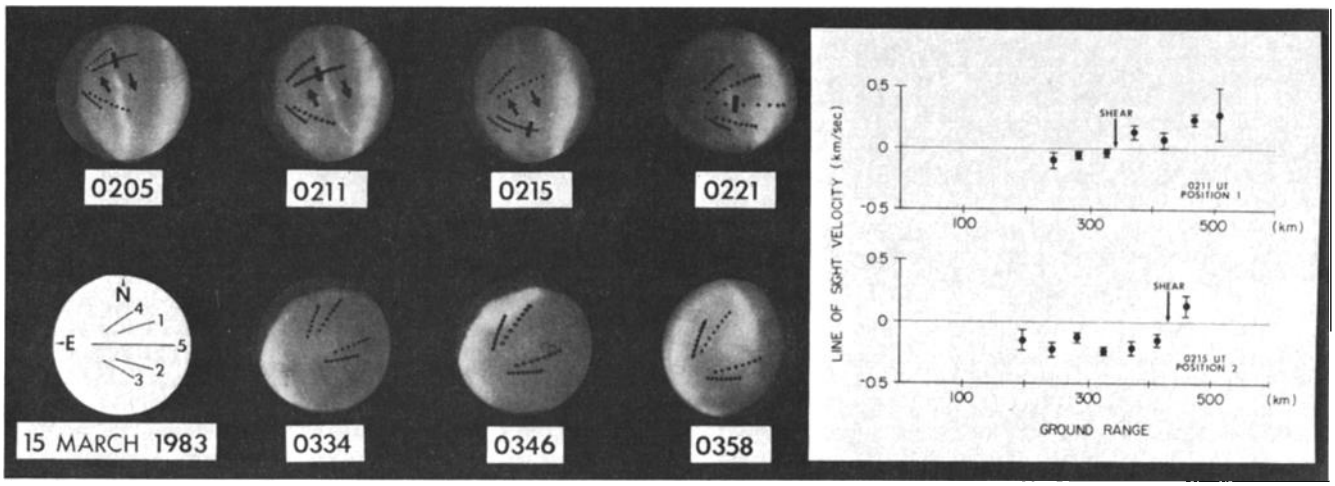

Fig. 1. a.) 6300Å All sky (intensified) photometer images for times coincident with incoherent scatter radar (ISR) velocity measurements during passage of two F-region arcs. Bar on ASIP locates velocity shear by coincident ISR. b.) ISR data defining velocity shears at 0211 and 0215.

all sky imaging (intensified) photometer (ASIP) to identify arcs and resolve ambiguities of interpretation of the ISR data due to rapid changes in space and time; and optics and ionosonde to test for soft vs hard electron precipitation and E-region ionization outside the E-region field of view of the ISR.

Observations

Although the AIO flew under aurora enroute to and from the ISR, the period discussed here is confined to the flight pattern over the ISR from 0200-0400 UT (00 to 0200 CGLT) on 15 March 1983. This confines the coincident data to moderate magnetic conditions with Kp = 3^- and 3^+ during this period.

Optical Observations

Optical images were obtained using a wide angle (155° field of view) all-sky imaging photometer (ASIP) with interference filters to measure 6300Å [OI] and 4278 Å [N_2^+] emissions at 30 second intervals. These images have a dynamic range of roughly 20-400R. For an assumed emission height of 250km, the useful image diameter (after reduction by lens vignetting) is almost 1200km. Coincident observations at 6300Å [OI] and 3914Å [N_2^+] by a zenith looking 1-m Ebert--Fastie spectrometer with a 4° x 5° field of view, (20 x 21 km at 250 km altitude) absolutely calibrated the images.

Two F-region arcs passed overhead during this experiment, one 0200-0230 UT and one 0330-0400 UT. Thirty-second time resolution ASIP images tracked their westward motion continuously. Figure 1 shows ASIP images selected to match the times of available ISR line of sight or vector velocity measurements during their passage. The all sky images in Figure 1 are oriented with geographic north toward the top and east to the left. During this time period the Corrected Geomagnetic (CG) noon-midnight meridian is aligned approximately in the geographic north-south direction. The thin arc overhead near 0215 and the western arc at 0358 are the F-region arcs.

The arc on the western horizon durnig 0200-0230 and that on the eastern horizon at 0358 are produced by strong fluxes of energetic particles, which also produce significant E-region ionization. The F-region arcs are distinguished from the latter by the absence of E-region ionization on the ionograms, and by optical measurements showing large (~ 30) 6300Å [OI]/4278Å [N_2^+] intensity ratios as well as low (~ 10R) 4278Å [N_2^+] intensities.

Velocity Measurements

The ISR scanned a spatial pattern designed to optimize measurement of gradients in plasma velocity and density across sun-aligned arcs. It cycled between an elevation scan from zenith to 30° elevation toward dusk in a plane perpendicular to the nominal sun-aligned direction, and two pairs of fixed profiles: 47° and 62° elevation symmetrically displaced from the elevation scan plane by ± 24° and ± 45° respectively. Eight 45 km resolution samples were taken per profile, with a 12-minute pattern cycle time dictated by 30-second integration times required per profile plus antenna motion. The locations of the 8 samples in each of the 4 fixed profiles are shown in each ASIP image (projected to 300 km altitude) in Figure 1a. Also shown are points in the ISR elevation scan plane, extending from the ISR zenith towards the west (toward dusk CGLT) at equal spacings of 100km for a 300km altitude. Note bending due to distortion introduced by the all-sky lens. The AIO maintained a flight pattern under the ISR elevation scan.

For the F-region arc almost stationary in the ISR field of view during 0205 to 0224 UT, each ISR line-of-sight velocity profile was examined. Sign reversals (toward vs away from the ISR) plasma flow velocity (see Figure 1b for 0211 and 0215 UT), and each reversal or shear point along that profile was marked on the 6300Å image from the nearest minute, as shown in Figure 1a. One-to-one collocation of velocity shear with 6300Å arcs was found.

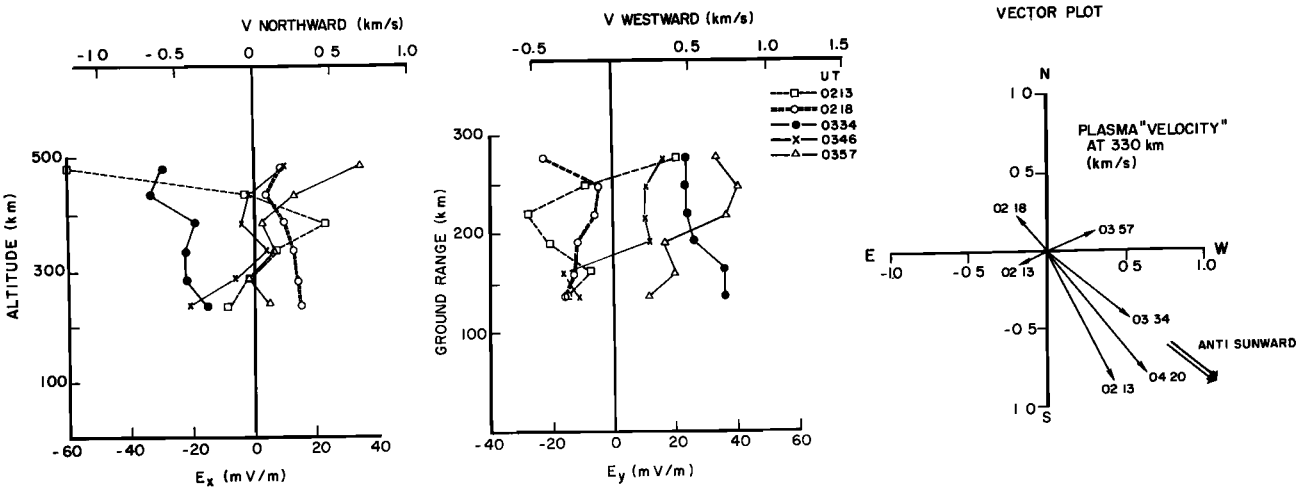

Fig. 2. a.) Profiles of ISR velocity components from convection analysis procedure. b.) Plasma velocity vectors derived by combining ISR and ASIP data, and showing change of anti-sunward flow from strong to stagnant in going from west to east side of ASIP F-region arc.

To compose a vector velocity, a mono-static ISR must combine differently directed line of sight velocities. Conventional ISR analysis assumes uniform plasma flow between symmetrically sampled different locations. Velocity components derived in this standard way for the 0210-0215 UT data are shown in Figure 2a. However, the ASIP arcs (and range displaced shears) demonstrate that this assumption is invalid for much of these data. Use of the ASIP frame of reference to combine line of sight velocities only on a common side of the arc leads to extraction of the pair of vectors shown for 0213 in Figure 2b, and rejection of the invalid intermediate velocity points. Thus we find the erratic profile simplifies to a strong anti-sunward plasma flow on the west side of the arc, and a stagnation of the flow on its eastward side. The next available velocity measurement, at 0218 in Figure 2B, exhibited no velocity shears and verified stagnation of the anti-sunward flow.

Three 62° elevation ISR velocity measurements, at 0334, 0346, and 0358 UT, bracketed passage of the second F-region arc. The ISR ground tracks for the velocity profiles are the outer pairs of lines in Figure 1A. The 0334 ISR data field has no ISR velocity shears or ASIP arcs, and shows a clear anti-sunward flow. The ASIPs show the westward moving F-region arc partially penetrates one of the 0346 ISR lines of sight, so fallacious velocities are expected from standard analysis. Further, the ASIPs show virtual motion of the arc so rapid as to discourage further use here of this profile. The 0358 ASIP shows no visual arc in the ISR field, possibly excepting the greatest ranges; the ISR velocity profile shows uniform stagnation of the anti-sunward flow, also possibly excepting the greatest range.

For both F-region midnight arcs, the plasma flow exhibited a strong shear, from strong anti-sunward to stagnation of the anti-sunward flow, in going from the west to the east side of the arc. The current divergence thus requires an upward current at the arc, or downcoming energetic electrons into the arc (the excitation source for the impact excited 6300Å [OI] emissions). This idea has already been postulated for midday polar cap auroras by Reiff et al. (1978). The return current for a reverse velocity shear would be upgoing thermal electrons, without visible signatures.

We find the F-region (sub-visual) arcs are simply the optical manifestation of (energetic) electrons, drawn in along magnetic field lines to satisfy the continuity of current, driven by shears of F-region plasma flow.

Plasma Density and Temperature Measurements

AIO ionosonde data during January 1982 have shown lower bounds on electron density enhancements near sun-aligned arcs of up to a factor of 4, from 3 to 6 MHz, or 1×10^5 to $4 \times 10^5 cm^{-3}$. The time constant for ion-neutral collisions to accelerate the F-region thermosphere is a few tens of minutes for ion concentrations of $10^6 cm^{-3}$, while several hours for 10^5 ions cm^{-3}. Using representative polar cap arc parameters, a 100km wide slab of plasma drifting 100 m s^{-1} transverse to its flow velocity (of up to 1000m sec^{-1}) has time to accelerate a significant fraction of the thermosphere to near the plasma velocity for $4 \times 10^5 cm^{-3}$. Thus, given the high polar plasma velocity differences across these arcs (order 1000m sec^{-1}), the slow lateral drift of the flow boundaries (order 100m s^{-1}), and large arc widths and separations (order 100km and 1000km respectively), this process could lead to significant modification of polar thermospheric temperature and composition structure, as well as circulation structure.

Searching this ISR data for such an effect, Figure 3 shows the electron concentration from the 0219UT ISR elevation scan. The arrow locates both the ISR line of sight velocity shear and the ASIP arc, to within available resolution of roughly 50km. Across this the maximum F-region ionization increases by a factor of 3 from 0.5 to 1.5×10^5 el cm^{-3}. During the March 1983 campaign the maximum electron densities in the arcs were only about 2×10^5 cm^{-3}, probably a solar cycle decrease from the larger values of 4×10^5 el

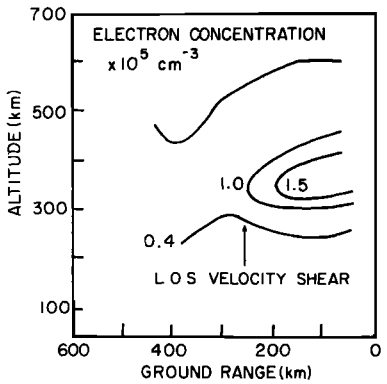

Fig. 3. Electron concentration enhancement measured by ISR across F-region arc at 0219 UT, 15 March 1983.

cm^{-3} observed during the January 1982 campaign. In the absence of simultaneous neutral wind measurements, conclusive changes in thermospheric circulation and temperature cannot be confirmed and we will not pursue this point further here.

However, the ISR ion temperature measurements during this 0205-0224UT 15 March 1983 period systematically show a 3 to 5 standard deviation enhancement at the range of the arc and velocity shear, being near 2000°K at that location and about 1200°K at other F-region ranges. Recall (Stubbe and Chandra, 1971) that frictional heating (due to relative ion-neutral drift) scales as the square of the velocity difference, being e.g., 8°K and 800°K for respectively a 60 and 600 m s^{-1} relative velocity. Combining the ISR line of sight velocities for this time assuming that the ASIP arc is a boundary between two regions of homogeneous flow on either side of the arc, a north-south plasma velocity shear across the arc of roughly 1000m s^{-1} is obtained. As the arc or flow reversal boundary slides sideways a given slab of neutral thermosphere, having for some time been subject to ion-neutral drag in one direction by plasma on one side of the arc, becomes subject to collisions with counter-flowing plasma on the other side of the arc. The high plasma temperatures confined to the region of the velocity shear are suggestive of this effect. The approximate doubling of the temperature in this vicinity (from 1200°K) is compatible with expectations for ion-neutral collisional heating.

Conclusions

- Line of sight velocity shears, measured by the ISR, co-located one-to-one with ASIP sun-aligned F-region arcs in the quiet polar cap. Further, strong anti-sunward plasma flow (~ 1000 m sec^{-1}) measured on one side of the arcs stagnated or reversed on the other side. This is presented as the first experimental verification that these sun-aligned F-region arcs are boundaries between regions of differing polar plasma flow in the quiet polar cap.
- Considering the sense of velocity gradients, the F-region arcs are viewed as produced by sheets of soft electron fluxes required for current continuity at the plasma flow discontinuity. This effect as observed here for midnight F-region arcs, is the same as postulated for midday polar cap auroras by Reiff et al. (1978).
- F-region arcs can involve sufficiently high electron concentrations and velocities to be of concern to polar thermospheric temperature, composition and circulation structure, due to ion-neutral collisional drag. Ion temperature enhancements seen near an arc as it slowly drifted transverse to its length are compatible with this effect.
- The ASIP data are found to provide an important frame of reference for future polar cap research. The quiet polar cap sun-aligned F-region arcs identify polar plasma flow boundaries. They help correct or recognize when vector velocities derived from mono-static ISR data, as at the Sondrestromfjord ISR, are subject to error due to rapid variation in time and space. Thus, ASIP data offers a valuable context within which to evaluate nighttime polar ISR plasma velocity data.

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