The Polar Cap Environment of Outflowing O* 

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Ion composition measurements by Dynamics Explorer 1 often show upward O* beams at polar latitudes, with streaming energies of 1-20 eV or more. Here we utilize measurements of core (0-50 eV) and "energetic" (≥0.1 keV) ion composition, plasma waves, and auroral images from DE 1 and plasma ions and electrons from DE 2 to examine some of their properties in the context of the polar cap environment. It is found that two distinct populations of O* beams are observed: "high-speed" (10-30 eV or higher streaming energies) and "low-speed" (generally <10-eV streaming energies). The "high-speed" polar beams show an "auroral" connection; i.e., they are observed on or near field lines threading auroral arcs seen in DE 1 images. The "low-speed" streams are on or near field lines threading the dark polar cap and may be convected from the cleft ion fountain. The low-speed streams are generally much more stable in energy and flux, while the high-speed streams tend to be bursty. In general, the streams are convecting antiumward, with velocities of 5-15 km/s in the orbital plane. We sought to obtain plasma density estimates from plasma wave measurements, through analysis of features of auroral hiss as well as upper hybrid emissions. Densities in the range 1-5 el/cm3 were indicated for one segment of a DE 1 polar cap pass; however, the measurements generally indicate little auroral hiss or upper hybrid emissions in the polar cap for the other cases considered here. Estimates of electrostatic potential drops above the DE 2 satellite have been made using energy-angle spectrograms of photoelectron data, under the assumption that the field lines of observation are "effectively" open. Potential drops often are in the 20- to 40-V range. At other times the potential falls below the -5-V instrument threshold, or there are insufficient photoelectron fluxes for estimation. These limited data suggest that the largest potential drops are just poleward of the cleft or near its poleward edge and there is a decline of the drop in the antiumward direction. No obvious correlation between the potential estimates and "nearby" O* streaming energies is seen.

INTRODUCTION

Observations of low-energy, upwardgoing O* beams in the polar magnetosphere have been reported in several articles in recent years, particularly through measurements from Dynamics Explorer 1 (e.g., Shelley et al., 1982; Waite et al., 1985; Lockwood et al., 1985a,b,c; Moore et al., 1986; Chen et al., 1990). In the higher-altitude observations described by Waite et al. [1985], O* beams were characteristic of low streaming energy (E < 10 eV) and yet were "supersonic," with Mach numbers (ratios of O* streaming velocities to O* thermal velocities) of the order of 2-6. Convection mapping considerations indicated that these ions seemed to originate in the polar cleft topside ionosphere, a region found by Lockwood et al. [1985a], Moore et al. [1986], and Pollock et al. [1990] to be the site of fairly intense upgoing O* fluxes. The concept emerged [Lockwood et al., 1985b; Horwitt and Lockwood, 1985] of the "cleft ion fountain," which would be the major supplier of at least heavy ionospheric ions to the polar magnetosphere. Results of modeling the cleft ion fountain [Horwitt, 1984; Horwitt and Lockwood, 1985; Horwitt et al., 1985; Horwitt, 1987] are consistent with the basic observed features of the O* ions observed in the polar magnetosphere.

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It is not clear, however, that all of the O* ions observed in the polar cap magnetosphere necessarily arise from the cleft ion fountain. Observations of large outflows of O* over the polar cap made, for example, by Shelley et al. [1982] and Yau et al. [1984] were not interpreted in terms of a dayside source, leaving open the possibility that these ions may have originated in the topside ionosphere threading the polar cap itself. In any case, it is useful to utilize other complementary data to reveal further aspects of these O* beams and the polar cap environment in which they occur. Chen et al. [1990] have recently analyzed low-energy ion beams in the polar cap and deduced densities of about 0.1 cm-3 and temperatures in the range 0.1-5 eV. In this paper we will use data obtained with the multi-instrument complements of the DE 1 and 2 spacecraft. These data include, from the higher-altitude spacecraft DE 1, the low-energy ion measurements from the retarding ion mass spectrometer (RIMS), described by Chappell et al. [1981]; energetic ion mass composition from the energetic ion composition spectrometer (EICS), described by Shelley et al. [1981]; plasma wave observations from the plasma wave instrument (PWI) [Shawhan et al., 1981]; plasma ion and electron measurements from the high-altitude plasma instrument (HAPI) [Burch et al., 1981]; and auroral images from the scanning auroral imager (SAI), described by Frank et al. [1981]. Plasma ion and electron measurements at ionospheric altitudes are supplied by the low-altitude plasma instrument (LAPI) [Winningham et al., 1981] aboard DE 2.

OBSERVATIONS OF POLAR O* BEAMS

In this section we present data on upgoing low-energy O* at high latitudes as observed by DE 1 RIMS, together with complementary data by other DE instruments, for four DE 1 passes over the northern polar cap. In presenting these data, we note that we originally scanned data in summary fiche form for possible examination for the early part of the DE mission,
basically from October 19 to about November 28, 1981. Prior to October 19, 1981, O⁺ was not sampled by RIMS, whereas the HAPI instrument ceased operation around November 28, 1981. For approximately 30 segments of DE 1 passes over the northern polar cap, we examined low-resolution monochrome data format spectrograms of RIMS O⁺ data. Based in part on the availability of data supplied by other DE 1 experiments for these passes, RIMS O⁺ data for approximately 10 of these passes were processed in color spectrogram form. Four of these passes are presented with data from the other DE experiments in this section. As will be seen, the first two of these events presented contain what will be called "high-speed" O⁺ streams, while the latter two illustrate events which involve relatively stable, persistent, "low-speed" O⁺ streams. While we believe that these presented observations adequately span the range of characteristics typically seen in the mid-altitude polar cap, the present study is not statistical in nature, and no indication is made of the relative frequency of the various characteristics noted.

**Day 295 (October 22), 1981: 0945-1045 UT**

Plate 1 shows a composite of spectrograms of DE 1 RIMS, EICS, HAPI, and PWI data for the period generally between 0945 and 1045 UT on October 22 (day 295), 1981. In all the RIMS data (Plate 1a) only the O⁺ spectrograms are displayed, although other ions were sampled during these periods. The upper portion of Plate 1a is an energy versus time spectrogram in which the energy is the upper energy on the passband of the RIMS retarding potential analyzer (RPA), and count rates are displayed according to the indicated color bar. The lower portion is a spin-time spectrogram, in which the count rates in the full 0- to 50-eV passband are plotted as a function of instrument pointing spin angle, with the spacecraft ram direction in the center and the two dashed white lines indicative of the closest approaches to 0° and 180° pitch angle (α) relative to the local magnetic field direction; in this case, the ions are near α = 180° and correspond to O⁺ streaming out of the northern ionosphere. For the RIMS spin-time spectrograms the count rates (CR) may be interpreted as integral fluxes according to the relationship

\[ \text{flux [cm}^{-2} \text{s}^{-1}] = \text{CR [counts]/(0.8 \times 10^{-4} \text{cm}^{-2} \text{s}^{-1})} = 1506 \text{CR [counts]} \]

where count rates (CR) are in counts/sample. The HAPI data displayed in Plate 1c are differential energy fluxes versus energy and time for all upflowing ion species (lower panel) and precipitating electrons (upper panel), with the adjacent color bar in units of ergs/(cm² s sr eV). The energy scale on these data runs from about 5 eV to 30 keV. Plate 1b (the PWI data) consists of frequency-time spectrograms of electric field power. For the EICS data (Plate 1d) we display O⁺ fluxes in the 0- to 100-eV (lower panel) and 0.1- to 1-keV (upper panel) energy ranges as a function of pitch angle.

The RIMS data of Plate 1a indicate outflowing O⁺ with streaming energies of the order of 10 eV, except for the period 1014-1017 UT. During this period, O⁺ fluxes are seen at greater energies up to 30-50 eV, and there is a definite peak in the counts. Note that while RIMS is nominally an integral (RPA) instrument, for heavy ions such as O⁺ it behaves like a differential energy spectrometer, having a fixed-width energy band pass approximately 7 eV wide [see Moore et al., 1986]. Thus it begins to resolve O⁺ distributions with elevated mean energies as shown here. The shift in the peak in the O⁺ fluxes away from the magnetic field direction by 10°-20° opposite the ram direction in satellite spin angle is indicative of antisunward convection along the spacecraft trajectory of a few kilometers per second, as would be expected for this region (see also the sample O⁺ distribution functions in the next section). Generally similar peak flux offsets indicating antisunward convection along the satellite trajectory are observed in other polar O⁺ events that we examined. The HAPI data during this period (Plate 1c) show a steady drizzle of 200-eV precipitating electrons, with a flux enhancement throughout the energy range 5-500 eV during the 1014-1017 UT period when RIMS observed the 30- to 50-eV O⁺ beams. The upgoing ions shown in the bottom panel of Plate 1c display ion energy variations similar to the observations on RIMS. The EICS observations (Plate 1d) confirm the presence of an upgoing O⁺ beam with energies generally less than 100 eV, at least after 0955 UT. Other EICS data not shown indicate that this O⁺ stream was mixed with relatively isotropic H⁺ of a few hundred electron volts during the early part of the time range, presumably at the crossing of cleft field lines. The wave measurements from PWI (Plate 1b) display a distinct low-frequency (10-1000 Hz) broadband emission enhancement in the 1014-1017 UT period that could be associated with the more energetic O⁺ beam. PWI also observed auroral hiss with a clear plasma frequency cutoff near 20 kHz until about 1020 UT, and some narrow-band upper hybrid emissions (above the electron gyrofrequency) from about 1014 UT onward. The absence of significant auroral hiss after about 1020 UT may be related to the small reduction in precipitating electron flux which also occurs at this time.

Plate 2a displays an auroral image from SAI on DE 1, taken around 1014 UT, with a DE 1 foot point track overlaid for the period 0900-1100 UT. Electron measurements from the LAPI instrument on DE 2 are shown below in the form of energy-time spectrograms for precipitating (α ~ 10°) and upgoing (α ~ 163°) electrons in the range 5 eV to 30 keV. The SAI observations taken at 1014 UT suggest that DE 1 crossed the morning auroral oval by about 0930 UT, near 66° A (invariant latitude), and with no further auroral emission features at higher latitudes. HAPI observations (not shown) at about 0945 UT place the latitude of bright emissions closer to A = 70°. LAPI observations (Plates 2b and 2c) at ~0956 UT show a distinct electron flux spike at about 68° A, which is probably the same auroral feature, given the field line mapping uncertainties and the ~20-min universal time difference in the measurements. Based on the ~40-s transit time of DE 2, the latitudinal width of the aurora is ~230 km. The LAPI observations confirm the
absence of additional auroral features at higher latitudes in that local time sector.

If the polar O⁺ beam observed by RIMS at ~1015 UT near 76° A is to be plausibly associated with the auroral arc, we may postulate that 50-eV O⁺ ions left the ionosphere (say, 1.2 Rₑ geocentric distance) at about 66° A and arrived at the DE 1 satellite at about 4 Rₑ at 76° A. The transit time would have been about 725 s, with a convection speed of about 1.2 km/s at the ionospheric levels. This is consistent with observed polar cap convection speeds. Since the O⁺ stream intercepted by DE 1 might have originated at a different local time and perhaps invariant latitude, this estimate could change somewhat depending on the expected convection path.

**Day 312 (November 8), 1981: 1355-1430 UT**

Plate 3, using a data format similar to that of Plate 1, displays data from RIMS, EICS, HAPI, and PWI for the (RIMS) interval 1400-1430 UT on day 312 (November 8), 1981. As Plate 4a shows, the SAI observed a well-defined transpolar or theta auroral arc, crossed by DE 1, which was studied in detail by Frank et al. [1986] and Peterson and Shelley [1984]. Our focus is on the interval closer to the dayside which shows a persistent stream of low-energy O⁺ with a more energetic beam embedded within.

As seen from Plate 3a, throughout the interval 1400-1430 UT, RIMS indicates an upgoing stream of O⁺ ions in the polar magnetosphere. Between 1409 and 1413 UT the characteristic energy of the ions rises from just under 10 to tens of eV. During this period, EICS (Plate 3d) observes no detectable O⁺ fluxes in the 0.1- to 1-keV energy range, but high levels in the 0- to 0.1-keV channel, indicating that the energy of the beam is confined to less than 100 eV. HAPI (Plate 3c) observes a burst of <100-eV precipitating electrons during the period of the "high-speed" O⁺ stream. Wave emissions in the 100- to 1,000-Hz range fluctuate throughout the full interval, with several bursts of broadband 10- to 100-Hz noise, and these show some correlative enhancement with the presence of the beam. For example, there is a series of intensifications of such broadband low-frequency noise, particularly in the 100- to 300-Hz range, in the 1409-1415 UT range where the energy enhancement of the O⁺ beam seen by RIMS and EICS and the burst of precipitating electrons seen by HAPI are observed. There is also some evidence for upper hybrid emissions during parts of this interval.

From Plate 4 we see that DE 1 was within the dayside polar cap at the time of the nominal crossing of the energetic O⁺ beam, but there are indications of Sun-aligned arcs near the auroral oval in the morning sector that may have extended into the DE 1 track up to about 80° A. Signatures of these arcs are also seen in HAPI electron spectrograms for earlier times shown in Plate 3c. From the LAPI measurements at DE 2 altitudes (Plates 4b and 4c), electron flux spikes are evident at 77°-78° A as well as the surrounding vicinity. These could be associated with the Sun-aligned arcs, or possibly the lower latitude features, and these auroral features could plausibly be the origin of the upgoing "energetic" O⁺ beams seen at 84° A with convective transport effects included.

**Day 311 (November 7), 1981: 1000-1030 UT**

A more typical polar crossing, associated with low-energy polar O⁺ beam characteristics, was observed in the period 1000-1030 UT on day 311 (November 7), 1981. As shown in Plate 5a, RIMS detected a fairly constant upgoing stream of O⁺ ions with energies of 5-8 eV, although a sizable reduction in flux is observed between about 1005 and 1010 UT. During this time, HAPI indicated a featureless drizzle of precipitating electrons, with virtually no upgoing energetic ions. Wave emissions observed with the electric field antenna also show nothing distinguished during this interval, with significant emissions observed only below about 100 Hz, although some weak upper hybrid emissions may be present. It may be noted, however, that strong upper hybrid emissions were present prior to 1000 UT, and these indicated plasma densities of 5 e/cm³ or higher.

As seen from Plate 6a, the SAI observations at 1005 UT show that, assuming a stable auroral configuration, the DE 1 satellite was on field lines threading the dark polar cap during at least the period 0900-1000 UT. HAPI observations (not shown) indicate that DE 1 crossed into the polar cap by ~0920 UT. The LAPI data shown in Plates 6b and 6c are unfortunately only for the southern hemisphere, but these data indicate only low-energy electrons, probably photoelectrons of energies of <20 eV, for latitudes above 70° A. The approximate symmetry between upgoing and downgoing fluxes probably results from the fact that DE 2 was at relatively low altitudes (<400 km) and thus in the photoelectron production region.

**Day 316 (November 12), 1981: 1315-1350 UT**

In Plate 7 we see a somewhat different type of interval in which RIMS observes relatively low energy O⁺ in a burst at about 1329-1338 UT but little flux before or after this interval. EICS data basically corroborate this observation and show no detectable O⁺ fluxes at energies above 100 eV. Starting at the time of this O⁺ burst and continuing after, HAPI detected enhanced fluxes of precipitating electrons, with energies below 1 keV. However, there is no obvious change in these precipitating electrons correlated with the end of the low-energy O⁺ burst at about 1337 UT.

The SAI image in Plate 8a suggests that the DE 1 spacecraft was on dark polar cap field lines before 1315 UT, which is consistent with the HAPI data of Plate 7c for times after 1315 UT. Hence the O⁺ burst seen is evidently not on auroral field lines at DE 1 altitudes. However, the LAPI data of Plates 8b and 8c indicate precipitating auroral electrons at around 76° A. The O⁺ fluxes might have been associated with this auroral region at ionospheric altitudes and then convected longitudinally from higher latitudes and later local time, say more toward noon, where the SAI image indicates the presence of more intense auroral emissions. In any case, the burst nature of the O⁺ fluxes indicates that an auroral association is most plausible.

**SAMPLE LOW-ENERGY POLAR CAP O⁺ VELOCITY DISTRIBUTION FUNCTIONS**

Both RIMS and EICS data can be used to construct O⁺ velocity distribution functions (see Moore et al. [1986] for a description of the special methods employed with RIMS data to construct such distribution functions). Figure 1 displays selected RIMS O⁺ distribution functions for some of the periods discussed in the previous section. Each of the five panels displays a contoured O⁺ distribution function in the RIMS radial head spin plane, with the spacecraft ram direction on the right middle of each panel, and the magnetic field line direction indicated as a slanted line passing through the origin of each
Plate 2. (a) DE 1 SAI auroral image at ultraviolet wavelengths 123-155 nm obtained in a 12-min time interval beginning at 1014 UT on October 22, 1981. The position of the DE 1 spacecraft is mapped magnetically and overlaid on the image. (b and c) LAPI data in the form of energy-time spectrograms of differential energy flux for precipitating and upgoing electrons, respectively.
Plate 3. Similar to Plate 1 but for 1400-1430 UT on November 8, 1981, and with no HAPI ion spectrogram.
Plate 4. Similar to Plate 2 but for a pass on November 8, 1981.
plot. The origin of each distribution is referenced to the spacecraft frame, which is moving at about 2.5 km/s.

Figures 1a and 1b are for two 2-min intervals during the October 22, 1981, pass seen in Plate 1. The plot for the 1014-1016 UT period in Figure 1a is for the interval in Plate 1 when the RIMS energy-time spectrogram shows energetic (30-50 eV) O⁺ fluxes and the distribution contours confirm the existence of an O⁺ stream with field-aligned bulk velocity of about 16 km/s. By 1023-1025 UT (Figure 1b) the stream’s bulk velocity has declined to 6-8 km/s. Note that in both cases the core of the distribution suggests an ion convection velocity of 4-6 km/s in the direction of the spacecraft motion, which would involve an antisunward component at this time.

Similarly, Figures 1c and 1d display contrasting O⁺ distribution functions for November 8, 1981. The distribution for 1413-1415 UT indicates a broad, relatively intense O⁺ beam with a field-aligned velocity of about 12 km/s, while the 1423-1426 UT period distribution is colder with a field-aligned velocity of about 5 km/s. Neither deviates significantly from the magnetic field direction, suggesting that the antisunward convection velocity component in the direction of spacecraft motion is near the spacecraft orbital velocity. There is an indication that the distributions are wider in the perpendicular direction than in the parallel direction, which would suggest recent perpendicular heating, and, for Figure 1c, a rough estimate of the parallel and perpendicular thermal energies gives about 1 and 2 eV, respectively. However, the resolution of these distributions is probably insufficient to establish this trend conclusively. The distribution in Figure 1e, in which the field line direction merges with the vertical axis, also indicates a field-aligned streaming velocity of about 10 km/s. The leftward shift opposite to the spacecraft ram direction is presumably due to spacecraft motion through the plasma at a velocity greater than the convection velocity. There is little indication of a convection component in the spin plane for this case. The estimated thermal energy for this case is about 0.6 eV.

EICS O⁺ distribution functions on November 8, 1981, are displayed in Figure 2. Since the distribution function values for energies below 100 eV are determined from a single channel, these low-energy distributions for these periods are not resolved by the EICS instrument. However, these data do confirm that there is very little contribution to the distribution functions for these beams for energies above about 60 eV (V = 26.8 km/s).

**POLAR CAP ELECTRON DENSITIES DETERMINED FROM WAVE EMISSIONS**

In the polar magnetosphere, inference of electron densities is normally based on the cutoffs of auroral hiss at the plasma frequency [e.g., Persoon et al., 1983]. At other times, narrow-band upper hybrid resonance emissions may be used for such density estimates. In Plates 1, 3, and 5, such auroral hiss and the associated cutoffs as well as upper hybrid resonances were only observed with sufficient clarity during the pass on October 22 (Plate 1). Figure 3 indicates the estimated electron densities for the period 0950-1030 UT of this pass. As is indicated, the densities from 0950 to 1013 UT were determined from hiss measurements, while those in the period 1013-1030 UT were determined from upper hybrid resonance. During most
Plate 6. Similar to Plates 2 and 4 but for a pass on November 7, 1981. Ultraviolet wavelengths for the auroral image are 136-160 nm.
Plate 7. Similar to Plates 1, 3, and 5 but for November 12, 1981, with no PWI data available.
Plate 8. Similar to Plates 2 and 4 but for November 12, 1981.
of the period 0950-1004 UT the density was determined from the electron plasma frequency cutoffs of the hiss, whereas during the period 1004-1013 UT the more poorly defined (due to Landau damping [see Persoon et al., 1988]) upper-frequency cutoffs were used; for this latter period, density estimates shown are lower limits.

A particularly interesting feature is the brief period of elevated densities (~5 el/cm³) which occurred in the interval 1014-1017 UT. This coincides with the period of the high-speed O⁺ beam and enhanced precipitating electrons (Plate 1). Overall, the densities for this pass are in the range 1-5 el/cm³. This is consistent with the observations of Persoon et al. [1983]
SELECTED \( O^+ \) VELOCITY DISTRIBUTION FUNCTIONS
FROM DE-1/EICS ON NOVEMBER 8, 1981

![Velocity distribution functions](image)

Fig. 2. Various \( O^+ \) distribution functions (in units of \( s^3/bn^6 \)) observed by DE 1 EICS on November 8, 1981. Velocity units are kilometers per second.

for this geocentric distance range (3.8-4.1 \( R_E \)), which indicate densities of 1-5 \( \text{el/cm}^3 \) (see their Figure 10). However, Gallagher et al. [1986] reported one case in which the electron density was unusually high in the polar cap, of the order of 50 \( \text{el/cm}^3 \).

**ESTIMATED \( O^+ \) BEAM ENERGIES AND FIELD-ALIGNED ELECTROSTATIC POTENTIAL DROPS**

Winningham and Gurgiolo [1982] have reported observations by DE 2 LAPI of simultaneous electron flux spectra for electrons traveling up and down along the magnetic field lines. They found that often in spectra observed over the polar cap the electron fluxes were equal up to some energy, at which point the upgoing fluxes began to exceed the downcoming fluxes. Their interpretation was that there was an outwardly directed electric field and associated electrostatic potential drop which was reflecting back downward those upgoing photoelectrons which had energies below the magnitude of the potential drop. Hence the transition energy could be used as a measure of the potential drop above the DE 2 satellite. If this is the case, it is of further interest to obtain these estimates during DE 1 measurements of polar \( O^+ \) beams to compare the energies of these beams with the potential drops above the ionosphere (see also Pollock et al. [1991]).

Plate 9 shows three sample energy-pitch angle spectrograms for electrons observed in the polar cap or its vicinity by LAPI. In Plate 9a the quantity plotted is the distribution function (only for energies up to 200 eV), while Plates 9b and 9c display energy fluxes. We found that examining these quantities in the displayed energy-pitch angle format provides a more consistent
and more reliable method of obtaining determinations of potential drops than the approach of comparing line plots of spectra for a pair of particular upgoing and downgoing electron pitch angles.

Plate 9a shows an example for which we estimate a potential drop above DE 2 of about 20 V as follows. It can be seen that there are upgoing photoelectrons extending to about 80 eV in the $\alpha = 90^\circ-180^\circ$ range. There are significant distribution function contributions in the $\alpha = 0^\circ-90^\circ$ range as well, but these decline significantly above about 20 V. For the time being, we will assume that the field lines for these and subsequent very high-latitude observations are effectively open so that downward coming electrons neither originate nor are magnetically reflected from a conjugate location; we will return to this point later. We therefore conclude that there was a potential drop of about 20 V (involving an upward directed electric field) above the satellite which was reflecting a major portion of the electron distribution below 20 eV and allowing the electrons above this level to escape on these presumably open magnetic field lines.

Plates 9b and 9c exhibit data consistent with a potential drop of less than 5 V and insufficient photoelectrons for potential drop estimation, respectively. In Plate 9b, upgoing photoelectron energy fluxes are clearly observed up to about 60 eV, but almost no fluxes are observed in the downgoing pitch angles, at least above the 5-eV LAPI threshold. Therefore these data appear to be sufficient to determine that the potential drop above DE 2 was no greater than 5 V (of course, these data alone would not exclude potentials with downward electric fields that would accelerate the upward going electrons above the satellite). In Plate 9c, the spacecraft is in the dark polar cap and observes virtually no fluxes of either upgoing or downgoing electrons, so this case is indeterminate.

We were interested in examining the behavior of both the $O^+$ streaming energies and the potential drops and also, if possible, in determining whether there was any relationship between the flow energies of the $O^+$ streams observed by DE 1 RIMS in some of the cases we examined and estimates of electrostatic potential drops on "nearby" magnetic field lines from DE 2 LAPI. Figures 4 and 5 show such quantities plotted versus invariant latitude (IL) in which the left side of the plot is for the sunward segment (morning) of the satellite (DE 1 or 2) pass over the northern pole and the right side is for the antisunward (or evening) segment. The $O^+$ streaming energies were estimated from the upper energy cutoff of the fluxes in the RPA spectrograms (e.g., the upper panels of the RIMS data presentations in Plates 1a, 3a, 5a, and 7a).

Considering first the $O^+$ streaming energies, we see that in most cases the streams persist at energies of 1-5 eV over substantial ranges of invariant latitudes of $10^\circ$ or greater. These are the more typical "low-speed" streams. Besides these, there are the bursts of "high-speed" streams (e.g., in Figures 4a and 4b and Figure 5a) which have energies of 20-40 eV and last for only a few minutes, corresponding to $\sim1^\circ$ invariant latitude.
DE–2/LAPI Polar Cap Electrons

Plate 9. Sample energy-pitch angle spectrograms for polar cap electrons observed by DE 2 LAPI. (a) A distribution function for October 22 (day 295), 1981, in which there are upgoing photoelectrons (α = 90°-180°) up to about 80 eV but the downgoing electrons terminate above about 20 eV, indicating a potential drop (electric field directed upward) of about 20 V somewhere above DE 2. (b and c) Sample energy flux plots for November 12 (day 316), 1981, indicating potential drops of less than 5 V and insufficient photoelectrons for such potential drop estimation, respectively.
Fig. 4. Estimates of O\(^+\) field-aligned streaming energies at DE 1 and field-aligned potential drops above DE 2 for four relatively close passes of the polar cap by the two satellites.

With the caveats indicated below, the electrostatic potential drops above DE 2 appear to be identified in the range 5-40 V for several of these passes. In Figures 4a-4d and Figure 5a there is a suggestion of a declining trend for the potential drop magnitudes in the antisunward direction. In these cases the potentials are in the range 25-40 V around 75\(^\circ\) A (just poleward of the cleft position or toward its poleward edge) and decrease to 0-10 V by -85\(^\circ\) A. Toward the antisunward side of the northern polar cap on some of these passes are indicated regions where there were insufficient photoelectrons (the atmosphere below was in darkness) for potential drop estimation. We should note that we have examined the LAPI data on day 295 (Figure 4a) at higher time resolution than the 1-min estimations indicated and find that the downgoing electron fluxes show rapid fluctuations, perhaps indicating more rapid fluctuations in the electrostatic potential than shown in Figure 4.

As noted earlier, the analysis of the LAPI photoelectron data in terms of potential drops depends on the assumption that the field lines of observation be open or at least "effectively" open to the extent that the possibility of the downward coming electrons being mirrored or originating from a conjugate hemisphere may be excluded. Examination of DE 1 HAPI plasma data (for times not shown here) indicates that at least on the passes for October 22 and November 12, 1981, the field lines may be connected to the low-latitude boundary layer (LLBL) to about 80\(^\circ\) A during the DE 2 LAPI pass on October 22 and about 83\(^\circ\) A during the DE 2 pass during 1200-1220 UT on November 12. At these magnetic latitudes and local times it is possible [e.g., Tsyganenko and Usmanov, 1982] that these field lines do map to the LLBL and furthermore are closed. If this is the case, we must consider alternative possibilities for how the upper energies of the downcoming electron spectrum would be less than those of the upcoming spectrum. It may be that the downcoming electrons originate in the conjugate southern hemisphere and pass through a potential drop on their way to the northern hemisphere; however, why this would not reflect the upcoming electrons and therefore provide the same reliable signature is not clear. Another possibility is that there is no potential drop and the downcoming electrons represent the spectrum from the conjugate hemisphere, which could be different owing to different atmospheric and solar zenith angles. However, it would still be difficult to understand why there would then not be corresponding signatures of the mirrored electrons from the opposite hemisphere of origin. Since these alternatives appear to be contrived, the simplest and most straightforward conclusion still seems to us that these are in fact
Fig. 5. Similar to Figure 4 for additional passes of the DE 1 and 2 satellites. Figure 5d shows O⁺ streaming energies for two passes, with no potential drop estimates.

real potential drop signatures as indicated, although we hope that it will be possible to use more conclusive tests in the future.

In three of the passes there was some overlap in the general locations (invariant latitude and local time) of the DE 1 beam energy measurements and the DE 2 potential drop estimates. These correspond to Figures 4a and 4b and Figure 5a. For the most part, the streaming energies are considerably smaller than the potential drop estimates and show more fluctuation. Hence, at this juncture, we do not observe any obvious correlation between these two quantities.

**DISCUSSION**

The data of Plates 1-8 as well as Figures 4 and 5 suggest a separation of the polar O⁺ beams into two major categories: "high-speed" (10- to 30-eV streaming energies) O⁺ beams such as during 1014-1017 UT on October 22, 1981 (Plate 1), and "low-speed" (generally <10-eV streaming energies) O⁺ beams, such as were observed throughout the pass on November 7, 1981 (Plate 5). For the "energetic" beams, it was possible to infer a plausible auroral connection with some reasonable intervening convection. Such auroral connection may be less direct in the case of the low-speed beams. For example, the DE 1 track on the November 7 (Plate 5) pass was completely in the dark polar cap. These low-speed streams could have been convected long distances from auroral regions in their transport up to the DE 1 altitudes or from the cleft ion fountain [e.g., Lockwood et al., 1985b; Horwitz and Lockwood, 1985].

As compared to the "high-speed" streams, the low-speed streams are significantly steadier with regard to time scales for changes in streaming energy and flux intensity. For example, again for the November 7 (Plate 5) pass, the stream energy was varying only between about 5 and 10 eV throughout the 30-min period shown, while the energetic beam of October 22 (Plate 1) persisted only about 3 min. The energetic beams also seem to be correlated with bursts of 0.1- to 1-keV electron precipitation at the DE 1 altitudes at or near the time of the O⁺ beam. This is seen by HAPI in the 1013-1015 UT interval of October 22 (Plate 1), during 1328-1330 UT on November 12 (Plate 7), and during 1408-1415 UT on November 8 (Plate 3). The steady, low-speed streams seem to occur in association with a steady drizzle of 100- to 300-eV precipitating electrons, as seen for example on November 7 (Plate 5).

With regard to electric field wave emissions, little significant wave activity could be observed in association with the low-speed stream of Plate 5 throughout the 1000-1030 UT
The Polar Cap Environment of Outflowing \( O^+ \)

![Diagram of the Polar Cap Environment of Outflowing \( O^+ \)](image)

**Fig. 6.** A schematic view of certain aspects of the polar cap environment of outflowing \( O^+ \).

period (at the lowest frequencies (<30 Hz) near the ion gyrofrequency, it is possible that spacecraft-generated noise obscures real magnetospheric emissions). On the other hand, periods in which the "high-speed" \( O^+ \) beams are observed seem to be associated with bursts of relatively broadband electrostatic noise, especially in the frequency range 100-1000 Hz. The periods 1011-1016 UT on October 22 and 1409-1415 UT on November 8 are illustrative examples.

Although the PWI-based electron densities could be obtained only for the 0950-1030 UT period on October 22, these densities were in the range 1-5 e/cm\(^3\) which, as noted earlier, is consistent with the observations of Persoon et al. [1983] for this geocentric distance range (3.8-4.1 \( R_E \)). We also saw evidence on this pass of a density enhancement associated with the passage of a high-speed \( O^+ \) stream. This might indicate that the energization process for the high-speed stream enhanced the localized outflux from the topside ionosphere, as this energization would mitigate both the charge exchange conversion to \( H^+ \) and the gravitational restraints on the outflow, thereby enhancing the density. Also, the density would be expected to be enhanced in these high-speed regions owing simply to proximity to the field line of the source region, so that lesser dilution due to spreading by convection across a span of field lines occurs.

We have presented evidence of large-scale parallel drops at very high latitudes above the topside ionosphere, with some indication of a trend of the largest potential drops of 20-40 V observed just poleward of the cleft or near its poleward edge and a decline antisunward. Often, however, potentials of greater than 5 V are not established. The altitudinal location of these potential drops is unknown; the apparent lack of correlation, in three relatively collocated situations, with the energies of streaming \( O^+ \) could be taken to suggest that the potential drops lie generally above the DE 1 spacecraft. The processes leading to the formation of these polar cap potential drops are not established. Winningham and Gurgiolo [1982] suggested that the Earth and its ionosphere be viewed as a photoemissive "probe" which must become positively charged in order to inhibit electron currents away from the ionosphere/Earth to maintain current balance.

A summary view of some of our indications, from this report and others, about the mid-altitude polar cap magnetosphere in the context of outflowing \( O^+ \) is presented in Figure 6. There are many aspects which should be established and clarified. A definitive statistical study of \( O^+ \) bulk parameters (density, temperature, and parallel flow velocity) is greatly needed for the mid-altitude polar cap, to complement, for example, the lower-altitude study recently presented by Chandler et al. [1991]. Further conclusive information on the existence and location of field-aligned electrostatic potentials in the polar cap is needed, as is their possible dependence on likely influences such as interplanetary magnetic field and polar rain. The relationship of electrostatic waves, energetic electrons, and the properties of the high-speed streams is a further area where new investigations may reveal interesting plasma physics phenomena. Clearly, the polar cap magnetosphere is an interesting region for further observational, as well as theoretical, study in the years to come.

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