Polar Observations of Cusp Electrodynamics: Evolution From 2- to 4-Cell Convection Patterns

N. C. Maynard  
Mission Research Corporation, Nashua, NH

W. J. Burke  
Phillips Laboratory, Hanscom Air Force Base, MA

D. R. Weimer  
Mission Research Corporation, Nashua, NH

F. S. Mozer  
University of California, Berkeley, CA

J. D. Scudder  
University of Iowa, Iowa City, IO

W. K. Peterson  
Lockheed Martin Space Sciences Laboratory, Palo Alto, CA

R. P. Lepping  
Goddard Space Flight Center, Greenbelt, MD

C. T. Russell  
University of California, Los Angeles, CA

1. Introduction

The dusk magnetopause quickly responds to changes in the polarities of IMF $B_Y$ and/or $B_Z$. Within a few minutes of the changes reaching the magnetopause, characteristic optical [1] and plasma convection signatures [2] appear in the ionospheric projection of the cusp. Global ionospheric convection patterns at high geomagnetic latitudes, however, represent a mixture of IMF conditions over the previous half hour. Maruwa [3] first reported observing magnetic perturbations during sustained periods of northward IMF whose explanation required sunward convection in the central polar cap. Electric and magnetic fields measured by the SI-2 [4], Atmospheric Explorer [5], and MAGSAT [6] satellites suggested that with IMF $B_Z > 0$

J. Moor et al. (eds.), Polar Cap Boundary Phenomena, 157-172.  
and $B_y \approx 0$, a four-cell convection patterns evolves. This convection pattern consists of two cells in the polar cap, whose polarity is opposite to the adjacent, standard negative potential (clockwise) afternoon and positive (counter-clockwise) morning cells. The polar cap convection cells are driven by magnetic merging at the poleward boundary of the cusp [7]. The residual, standard-polarity pair of cells at auroral latitudes are weak and probably are related to the low latitude boundary layer (LLBL) [8].

Hepper and Maynard [9] showed that during periods of northward IMF in which $B_y$ had large values, electric fields measured by the DE 2 satellite were consistent with the existence of two standard-polarity convection cells at high latitudes, distorted in shape. Flow (equipotential) lines had the same sense of rotation as those observed when $B_y < 0$. Further analysis for $B_y$ positive showed that the dayside portion of the afternoon cell rotated into the prenoon sector and consisted of two parts: (1) equipotentials whose associated magnetic flux is always open (lobe cells), and (2) equipotentials whose associated flux is both open and closed [10]. The lobe cell was embedded within the afternoon cell and had the same sense of rotation. Recent SuperDARN observations showed dayside convection patterns evolved from two distorted cells into four cells as IMF $B_y$ decreased in magnitude relative to $B_Z$ [11]. The observed evolution of dayside convection compared favorably with predictions of the empirical model of Weimer [12].

Satellite passes through the dayside high-latitude ionosphere encounter distinctive plasma characteristics. Nowell et al. [13] identified the spectral properties of electrons and ions in the dayside ionosphere whose magnetospheric sources are the central plasma sheet (CPS), the boundary plasma sheet (BPS), the LLBL, the cusp and the mantle. In energy-versus-time spectrograms the cusp is marked by intense fluxes of low-energy (<100 eV) electrons and energy-dispersed ions. The latter signatures is a time-of-flight, velocity-filter effect. During periods of northward (southward) IMF, the highest energy ions are detected near the poleward (equatorward) boundary of cusp precipitation [14]. Ionospheric plasma convection in the cusp has a sawtooth (poleward) component when the IMF has a northward (southward) component. The azimuthal component of convection is controlled by the polarity of $B_y$. Besides the large scale, Region 1/Region 2 systems, the dayside ionosphere is marked by cusp and mantle field-aligned current (FAC) systems, referred to as Region 0 [15].

This paper extends a study by Maynard et al. [16] based on particle and field measurements taken during three Polar orbits at dayside, high latitudes throughout which the $B_Z$ and $B_y$ were positive for extended periods of time. The observed energies/pitch angles of different ion species are used to improve identifications of the source regions for electrodynamic signatures detected by Polar. The T96 magnetic field model of Tsyganenko
[17] is employed to map from locations of Polar to the magnetosphere and the ionosphere. Results of Maynard et al. [16] are summarized in Figure 1 which shows three Polar orbits in the early afternoon to noon magnetic local time (MLT) sector. It also schematically represents the convection patterns they encountered. After leaving the region of plasma sheet precipitation, Polar detected quite different particle and field phenomena. During the April 3 orbit Polar skimmed along the projection of the LBL where it sporadically detected standard ion dispersions and He\(^+\) fluxes. The April 8 orbit crossed the ionospheric projection of the merging line at the poleward boundary of cusp precipitation within a small positive potential (counterclockwise rotating) cell in the afternoon sector. The orbit on May 11 moved along a zero equipotential line between two lobe cells where it encountered multiple reverse ion-dispersion events. The interpretation of Polar data was confirmed in observations of a four-cell convection pattern detected during a simultaneous high-latitude pass of the Defense Meteorological Satellite Program (DMSP) F13 satellite.

The following sections contain brief descriptions of the Polar sensors used in this study, particle and field measurements taken at middle altitudes (\(\approx 5R_E\)) by Polar on April 27, and 29, 1996, and their interpretation.
in terms of encounters with middle altitude projections of previously identified magnetotail phenomena. In both cases we were able to compare POLAR measurements with simultaneous particle and plasma drift observations of high-altitude convection by two DMSP satellites which confirm the interpretation that Polar made direct measurements of lobe-cell parts of four-cell convection patterns.

2. Instrumentation

Polar was launched into a 90° inclination orbit on February 24, 1996, with apogee above the northern polar cap at a geocentric distances of 9 R\textsubscript{E}. The spacecraft is spin stabilized at 10 rpm, with its spin axis perpendicular to the orbital plane.

The Electric Field Instrument (EFI) [18] consists of three dipoles to measure vector electric fields from potential differences between three pairs of spherical sensors. Two of the sensor pairs are held at separation distances of 100 m and 130 m by wire booms that rotate in the spacecraft’s spin plane. The third pair is held at a separation of 14 m by a pair of rigid booms, aligned with the spin axis. The two spin-plane components of the electric field are represented by the symbols \(E_{X,Y}\) and \(E_Z\). \(E_{X,Y}\) is approximately the projection of the spin-plane component of the electric field onto the geocentric solar ecliptic (GSE) XY plane. It is positive whenever the unit vector has a component in the \(-X_{GSE}\) direction. \(E_Z\) is positive toward the GSE north pole. The third component, called \(E_{6}\), points along the spin axis, positive in the sense that completes an orthogonal, right-hand coordinate system (see Figure 1 of Maynard et al. [16]). Thus, with POLAR orbitsing along the noon meridian, components of the vector \(E_{X,Y}, E_Z, E_{6}\) are positive in the \(\pm X_{GSE}, \pm Z_{GSE}, \pm Y_{GSE}\) directions. Spin-fit measurements are presented for \(E_{X,Y}\) and \(E_Z\) every 6 s and are used to calculate the potential along the orbit and \(V_{6}\), the velocity in the 5-6 direction. Measurements by the short booms of \(E_{6}\) are contaminated by differing levels of \(de\) offsets [16]. During the two passes, reduced-accuracy values of \(E_{6}\) could be determined and are used to estimate \(V_{X,Y}\).

The Magnetic Field Experiment (MFE) [19] consists of two orthogonal, triaxial fluxgate magnetometers that are mounted on a nonconducting boom at separation distances from the nearest satellite surface of 5.97 m and 4.75 m. Here, we are concerned with magnetic perturbations produced by field-aligned currents (FACs) that couple the high-latitude to the magnetosphere or the magnetopause. The positive-slope deflections in \(B_{6}\) with time (latitude) presented below are generated by FACs directed into the ionosphere.

The 3-dimensional electron and ion plasma instrument (HYDRA) [20]
consists of two pairs of electron and ion/electron spectrometers, which are each mounted 180° apart on the spacecraft body. In this paper we only use ion and electron measurements from the Duo Deca Electron Ion Spectrometer (DDEIS), which consists of six pairs of 127° electrostatic analyzers looking in different directions outward on a unit sphere. The electron spectrometer measures fluxes in the 2 eV to 35 eV range.

The Tooroidal Imaging Mass-Angle Spectrograph (TIMAS) [21] uses a first-order, double focusing system of ion optics that simultaneously measures the spectral characteristics of positively charged ions in the mass per charge range 1 - 32 AMU/q, and energy per charge from 15 eV/q to 32 keV/q. Here we are only concerned with fluxes of He++ ions which primarily come from the solar wind. They provide tracers for identifying direct (cusp/mantle) and indirect (LLBL) paths from the magnetosheath.

The DMSP F12 and F13 satellites are in sun-synchronous, circular polar orbits at an altitude of ~840 km near the 1000 - 2200 and 0600 - 1800 local time meridians. Both satellites carry up-looking spectrometers [22] to measure ion and electron fluxes in the energy range 30 eV to 30 keV, and drift meters [23] to monitor the vertical and cross-trajectory components of the ionospheric plasma's bulk motions.

3 Observations

In this section we present plasma and field measurements taken at dayside high latitudes by the Polar satellite between 1500 and 1800 UT on April 27, 1996, and between 1930 and 2130 UT on April 29, 1996. Subsidiary information about global conditions are provided from simultaneous, high-latitude passes of two DMSP satellites. In both cases the solar wind speed, measured by the Wind satellite, \( V_{\text{wind}} \approx 85 \text{ km/s} \), was constant at \( -350 \text{ km/s} \). Thus, signal propagation times to the magnetopause are \( \sim 25 \text{ minutes} \). Average values of IMF \( B_z \) were \( \sim -3.5 \text{ nT} \) in both cases. On April 27, IMF \( B_y \) was \( \sim 0 \) until 1527 UT, then oscillated between \( +1 \text{ and } -1 \text{ nT} \) with a period of \( \sim 38 \text{ minutes} \). On April 29, IMF \( B_y \) was varied between \( +1 \) and \( 3.5 \text{ nT} \) with a period of \( \sim 50 \text{ minutes} \). We regard the magnetosphere as responding to nearly constant northward IMF conditions in which exact propagation times from Wind to the magnetosphere are not critical.

3.1 APRIL 27, 1996

Figure 2a contains electron (top) and ion (bottom) spectra acquired by Hydra between 1500 and 1800 UT on April 27, 1996, in standard energy-time spectrogram formats. The color bars to the right of the spectrogram provide and the count-rate magnitudes. The DDEIS spectra give averages of 72 measurements at the given energy steps, accumulated over
13.8 s intervals. Data are presented as functions of universal time (UT), invariant latitude (ILT), magnetic local time (MLT) and geocentric distance in R_E. Values of the ILT and MLT were determined using IGRF '95 model. TIMAS measurements are not available for this orbit.

On a purely empirical basis, we divide the particle measurements from the April 27 pass into three time intervals. (1) Prior to 1525 UT the highest ion count rates were at energies in the 8 to 10 keV/nq range. The energy of peak counts was nearly constant with increasing ILT. Electron counts were ~100 at energies between 1 and 10 keV. After 1510 UT average electron energies decreased with increasing ILT. (2) A 1 hr period between 1525 and 1550 UT is marked by an intense, but fairly constant flux of electrons with average energies near 70 eV. The flux of ions reaching HYDRA also increased during this interval. The average energies of ions increased with increasing ILT, characteristic of an inverse energy dispersion structure. Smaller scale structures also appear during this interval in the ion spectrogram, with peak counts at 1532, 1540 and 1550 UT. They show both standard and inverse ion dispersion characteristics. (3) After 1600 UT, DDEIS detected electron fluxes whose intensities and energies were significantly reduced, and ion count rates near background levels. Based on experience with the spectral characteristics of ion and electron fluxes observed at low altitudes [13], we identify the source regions encountered by Polar during the three intervals as (1) the CPS, (2) the LLBL (1525 - 1531 UT) and cusp (1531 - 1550 UT), and (3) the polar cap.

From top to bottom, Figure 3a shows the spin-plane components of the electric field, the electric potential distribution along the trajectory, two components of the plasma-drift V_{x,y} and V_{z} and magnetic field B_{z}. The plasma velocity components are roughly in the sun-Earth and dawn-dusk directions. The B_{z} trace has the T96 model field subtracted. The reduced-accuracy V_{x,y} should only be used as a flow direction indicator. Potential values are given for the corotating (dashed line) and inertial (solid line) frames of reference for easy comparison with ionospheric patterns in the presentation below we describe convection patterns in the inertial frame of reference.

Attention is directed to the following seven points. (1) Prior to 1522 UT, the absolute values and variability of electric field was <1 mV/m. After this the amplitudes of variations grew. (2) From 1520 to 1555 UT the amplitude of electric field variations assumed values <3 mV/m. The periods of the variations ranged from a few ms of seconds to a few minutes (Pc 1 to Pc 4). (3) Average (quasi dc) values of the electric field along the spacecraft velocity vector reversed polarity near 1547 UT (see Figure 5). (4) The third panel shows that Polar crossed regions of positive (1525 – 1550 UT) and negative (after 1700 UT) potential. Viewed from above the north pole,
Figure 8. HYDRA measurements from (A) 1500 to 1800 UT on April 27, 1996, and (B) 1500 to 2230 UT on April 29, 1996, in energy-versus time spectrograms. The top panels show omnidirectional integrated counts from 12 detectors that is proportional to differential energy flux for electrons with energies between 1 eV and 20 keV. The bottom panels give count rates for ions with energies per charge between 10 eV/q and 20 keV/q. The dynamic ranges represented by color-bar scales are not the same for the two dates. The dashed lines on HYDRA spectrograms give mean energies derived from distributions, functions associated with observed count rates, assuming that the positive ions are H⁺.
Figure 3. Polar measurements from (A) April 27, 1996, and (B) April 29, 1996. From top to bottom the panels give the electric field spin plane components $E_{\phi}$ and $E_{\theta}$, the electric potential $\Phi$ derived from an integration along the Polar trajectory, the plasma drift components $V_{r}$ and $V_{\phi}$, and the magnetic field component $B_{z}$ transverse to the orbital plane. The particle regions described in the text are marked below the figures.
the sense of rotation for plasma convection is clockwise/counterclockwise in regions of negative/positive potential. In this case, the potential of the counterclockwise rotating cell is ~10 kV. (5) Negative values of \( V_{x,y} \) indicate that plasma convection had a supaward component in the regions of cusp and polar rain precipitation. (6) The dawn–dusk component \( V_{y} \) had low values prior to 1520 UT. From 1520 to 1550 UT Polar detected eastward flow (positive \( V_{y} \)), with an average value of ~15 km/s, and westward flow from 1550 to 1600 UT. (7) Variations in the trace of \( B_{y} \) mimic those of quasi-sinusoidal \( E_{y} = E_{x} \). This indicates that Polar crossed several large-scale FAC sheets which close via Pedersen currents in the ionosphere. (8) Positive (negative) slopes in the \( B_{y} \) trace indicate FACs into (out of) the ionosphere. Consistent with a postnoon MLT trajectory, the negative (1505 - 1512 UT) slope in \( B_{y} \) appears to result from Polar crossing the dusk-side Region 1 system [15]. It corresponds in time to Polar detecting LLBL fluxes. The afternoon Region 2 current system is either absent or very weak. The remaining FACs belong to the Region 0 system, associated with the cusp precipitation. The polarity of the main Region 0 current is opposite to that of the adjacent Region 1. A small region of upward current is located poleward of the main Region 0 current. At middle altitudes the Polar satellite moves rather slowly across the dusk-side high-latitude region while measuring local particles and fields. To understand their significance, it is useful to place these measurements in a wider context whenever DMSP satellites cross the auroral/polar latitudes at nearly the same time. On April 27, 1996, the DMSP F13 and F12 satellites crossed the region between 70° invariant latitude in the dusk/evening sectors to 70° in the dawn/day sectors from 1605 to 1615 UT and 1602 to 1614 UT, respectively. Figure 4a shows the trajectories of the three satellites and the particle precipitation regions [13] that they encountered. The dissections of plasma flow detected by DMSP F13 and convection cells observed by Polar are schematically indicated. Drift meter measurements from DMSP F12 were contaminated by sunlight and are not shown. A four-cell convection pattern is seen along the F13 trajectory. Flow is supaward in the auroral oval and in the central polar cap, and antisupaward along its flanks. This global flow pattern is consistent with Polar’s detection of a positive-potential lobe cell in the postnoon MLT sector. All three satellites detected CPS precipitation whose poleward boundary moved to higher geomagnetic latitudes on the day side. The latitudes for detecting cusp precipitation at the locations of Polar and F12 appear to be consistent. At this time BPS fluxes were detected near the dusk, evening and dawn MLT sectors, but not on the dusk-side. In their region of overlap, all of three satellites detected polar rain fluxes. The figure also indicates the polarities of FACs detected by Polar. The upward Region 1 current spans the latitudinally narrow strip
3.2. APRIL 29, 1996

Figure 2b contains electron (top) and ion (bottom) spectra acquired by HYDRA between 1930 and 2230 UT on April 29, 1996. Note that the dynamic range expressed by the color bars differ from Figure 2a. Again we divide the particle measurements empirically, this time into five intervals. (1) Prior to 2015 UT the highest ion count rates were again at energies in the 8 to 10 keV/q range and nearly constant with increasing IIT. Electron counts were ~100 at energies near 5 keV. Their average energies decreased slightly with increasing IIT. (2) From 2015 to 2040 UT electron fluxes became more irregular and their average energies decreased from 200 to 70 eV. The average energies of ions reaching Hydra also decreased with latitude. (3) Between 2040 and 2102 UT electron fluxes were most intense and varied smoothly. Average electron energies were ~70 eV. The spectrogram shows three ion injection structures, all with standard dispersion characteristics. Significant fluxes of He++ ions were detected by TIMAS only during this period. They were marked by three intensifications with standard energy-versus-latitude characteristics (4) During the interval 2102 to 2110 UT the flux of electrons and ions intensified and their average energies increased to values similar to those found in the second interval. (5) After 2110 UT, HYDRA detected electron fluxes whose intensities and energies were significantly reduced, and ion count rates near background levels. Applying the criteria of Newell et al. [13], we identify the source regions encountered by Polar during the intervals (1) and (3) as the central plasma sheet and the polar cap. We tentatively suggest that during intervals (2), (3) and (4) Polar cross field lines connected to the BFS, the LLBL, then returned to the BFS before entering the polar cap. We defer justification for these assertions to the discussion section.

Plasma and field measurements from the interval 1930 to 2130 UT are presented in Figure 3b. Attention is directed to four aspects of these data: (1) Prior to 2015 UT, the region of CPS precipitation, and after 2110 UT, the region of polar rain, measured electric fields were a few mV/m in magnitude and varied smoothly. Between these two intervals the magnitudes of electric field fluctuations more than doubled. (2) Prior to 2040 UT Polar crossed through ~2 kV of a positive potential cell. The potential turned negative (~1 kV), returned to ~0 kV near 2105 UT, then became increasingly negative. For later reference we note that the first and second negative potential excursions correspond to the second and fifth particle precipitation regions. The region in which the potential returned nearly to zero matches the particle flux intensification centered near 2004 UT. (3) Positive values
Figure 4. Schematic representation of high-altitude convection patterns and particle populations encountered by Polar on (A) April 27, 1996, and (B) April 29, 1996. Orbital traces for DMSP F12 and F13 along with particle populations are indicated. Arrows along the F13 trajectories show directions of plasma drift.
of \( V_x, y \) indicate that the plasma flow had an antisunward component of \( \Delta \) throughout the period of observations. (4) The east-west magnetic perturbation \( B_y \) has a strong positive slope from 2025 to 2030 UT, followed by three oscillations in a region of large-scale negative slope (2020 to 2102 UT). The oscillations in \( B_y \) after 2030 UT correspond to clear intensifications in the flux of precipitating electrons.

On April 29, 1996 the DMSP F13 and F12 satellites crossed the region between 70° invariant latitude in the dusk/evening sector to 70° in the dawn/day sectors from 2043 to 2054 UT and 2041 to 2052 UT, respectively. Figure 4b depicts the trajectories, velocities and convection cells. A four-cell convection pattern was traversed by DMSP F13. Its detection of sunward flow in the central polar cap is consistent with Polar entering a negative potential lobe cell in the presunrise UT sector. As indicated in the figure, the DMSP satellites observed CPS, BPS and polar rain fluxes as their latitudes increased. The regions of CPS and polar rain fluxes detected by Polar and DMSP are mutually consistent. A significant difference between this and the April 27 pass is the partial detection by Polar of the morning side auroral convection cell. Its structure is consistent with the convection characteristics detected by DMSP F13 near the dawn meridian.

The region tentatively identified as BPS near 80° and the LLBL occur in the antisunward part of the morning (positive potential) cell. The polarity of the FAC in the region of BPS fluxes is into the isosphere, consistent with the morning side Region 1 system.

4. Summary and Discussion

In the previous section we have presented responses of the duskside magnetosphere to prolonged periods of northward IMF from simultaneous viewpoints of DMSP satellites in the topside isosphere and Polar at middle latitudes. Through comparisons of observations from these viewpoints presented here and in Maynard et al. [16], we have come to recognize signatures of Polar encounters with different aspects of evolving four-cell convection patterns. In the rest of this section we first compare Polar observations on April 27 with those from the afternoon sector previously reported by Maynard et al. [16]. We then comment on the ion source location and temporal behavior. Lastly, we present a justification for our interpretation of measurements acquired during intervals (2), (3) and (4) on April 29 as encounters with BPS, LLBL and BPS particles and comment on its significance for understanding the structure of the magnetotail at this time.

Particle precipitation and convection patterns detected during the Polar orbits of April 8 and April 27 show repeatable elements. The universal times spanned by these two orbits are almost the same. Figures 1 and 4a
show that since the Polar orbit precessed slowly, the MLT-versus-invariant latitude trajectories are similar. In both instances Polar crossed a positive potential lobe cell in the early afternoon sector. Within these cells HYDRA detected cusp electron and ion spectra. The ions had inverse dispersion characteristics in which higher energies were detected at higher latitudes. There are two striking differences. First, on April 8, but not on April 27, Polar detected an auroral zone negative-potential convection cell extending into the noon region, presumably driven by the LLBL. Secondly, the highest voltages sampled within the lobe cells were ~3 kV on April 8, and ~16 kV on April 27. In both cases the solar wind speed was moderate, in the 300 – 350 km/s range. However, the relative strengths of IMF $B_Y$ to IMF $B_Z$ were quite different. On April 8 the IMF clock angle was near 80°. On April 27, the clock angle was nearer 20°. We know that on the May 11 event, which had a similar clock angle to April 8, a 4-cell pattern was observed [16]. The 4-cell nature of the pattern on April 27 was confirmed by DMSP.

Using these results and those of Burke et al. [10] we can piece together a scenario for positive $B_Y$ to evolve distorted 2-cell patterns into 4-cell patterns with decreasing clock angle. For IMF clock angles greater than 45° distorted 2-cell patterns dominate [9][10][12] with the large negative cell dominating into the noon sector. A negative lobe cell distorts the afternoon negative convection cell. As $B_Y$ weakens the negative lobe cell moves prenoon and negative potential boundary-layer-driven effects no longer extend into the prenoon region. A positive lobe cell develops postnoon (April 8) for clock angles between 30 and 40°. For smaller clock angles that positive cell becomes stronger (April 27) leading toward a more symmetric 4-cell pattern for pure $B_Z$ north. The afternoon negative cell no longer extends into the noon region as the positive cell strengthens.

The relation of particle signatures to convective bow waves combined with the location within the global context provided by the mapping of magnetic field lines passing through the Polar trajectory provide clues relative to the characteristics of the particle sources. In measurements from the slow moving Polar satellite, we consistently found that both large and small scale ion dispersions have standard and reverse structures in the antisunward flowing boundary layers and sunward moving cusp plasmas, respectively. We have also consistently detected fluxes of He+ ions only in regions where our analysis of HYDRA electron and ion data indicate that Polar was crossing the cusp or a boundary layer. It is through these two boundary regions where ions of solar wind origin have relatively direct access to middle altitudes and the ionosphere. The reverse dispersion is a signature of merging on the poleward side of the cusp. The structure observed as the ion energy decreased in Figure 2a as well as the multiple injections observed in the May 11 event [16] indicate that the lobe merging is both temporally and
spatially variable. Forward dispersion signatures with He\(^{++}\) ions on April 3, April 9, and May 11 which map to the boundary layers on the flanks indicate entry of magnetopause fluxes on the flanks. The exact nature of the process which creates the observed forward dispersion signature remains an open question.

In our presentation of Polar measurements from the April 29 orbit, we tentatively identified the particle fluxes detected in regions (2), (3), and (4) as originating in the BPS (2012 – 2040 UT), the LLBL (2040 – 2102 UT), and the BPS (2102 – 2110 UT), respectively. Our interpretation of the HYDRA measurements for regions (2) and (3) appears to be a simple application of criteria established by Newell et al. [13]. Region (2) appears just poleward of the CPS precipitation, is characterized by structured fluxes of electrons whose average energies exceed 100 eV, and straddles the convection reversal of the morning side convection cell. On the other hand, electron fluxes detected in Region (3) are less structured and have average energies below 100 eV. Ion fluxes have standard dispersion characteristics, contain a significant He\(^{++}\) component, and appear amid antisunward convecting plasma. The persistent presence of a high energy electron spectral component (Figure 2b) suggests Polar was crossing the middle altitude projection of a boundary layer to which plasma sheet electrons had access, the LLBL, rather than the cusp. The electrons with energies >100 eV and ions near 1 keV measured between 2102 and 2110 UT are spectrally similar to those observed at invariant latitudes equatorward of the LLBL. Data contained in the third panel of Figure 3b shows that Polar detected these enhanced fluxes at locations where the electric potential was similar to that measured prior to entering the LLBL. These particle and field measurements force us to conclude that after leaving the LLBL and before entering the polar cap, Polar again sampled field lines threading the BPS. Figure 4b shows that DMSP F13 and 13 detected BPS ion and electron fluxes up to magnetic latitudes of ~83° near the dawn meridian but only to ~80° near dusk. This asymmetric intrusion of BPS fluxes to high latitudes on the dawn side is consistent with our interpretation of Polar data.

To help understand our Polar measurements and the source regions they imply, we have mapped its locations between 2010 and 2130 UT to the magnetosphere using the T96 model. This mapping suggests that the field lines crossed by Polar mapped close to the dawnside magnetospheric boundary. After 2030 UT the mapping was to the night side of the dawn terminator. Figure 5 represents a cross section of the magnetotail with the source regions of BPS, the LLBL and polar rain particle fluxes indicated. A schematic magnetic mapping of the Polar trajectory (dashed line) onto this plane suggests that an intrusion of the BPS to high latitudes on the morning side could indeed provide the sequence of electron and ion fluxes observed
Figure 5. Schematic representation of a cross section for northern half of the magnetotail indicating sources of particles measured by HYDRA after 1530 UT on April 29, 1996. A qualitative magnetic mapping of the Polar trajectory onto this plane is indicated by the dashed line.

by HYDRA after 1530 UT on April 29, 1996. The IMF By in this case was varying. Chang et al. [25] recently developed a model for the generation of theta aurora arcs due to shifts in IMF By, while By remains northward. The Polar and DMSP results are suggestive of a polar cap arc or theta bar starting to break away from the dawn side of the oval as envisioned in the Chang et al. model.

References


