Electrodynamics of the poleward auroral border observed by Polar during a substorm on April 22, 1998

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Abstract

Observations from Polar during a substorm on April 22, 1998, are used to specify electrodynamic characteristics of the high-latitude auroral boundary on the nightside. Polar was moving equatorward near invariant latitude 72°, 2305 magnetic local time as it crossed the auroral boundary near the end of the substorm's expansion phase. This boundary was marked by severe east-west plasma flow shears, a reversal of the in-track electric field component, and multiple field-aligned currents. Harmonizing ground measurements with auroral images and in situ particle and field data from Polar reveals five electrodynamic features of the boundary. (1) A 20-min delay occurred between substorm onset and when the total magnetic flux in the polar cap began to decrease. This represents the time that elapsed before reconnection of open lobe flux began along a near-Earth X-line. (2) The reconnection electric field at the ionospheric projection of the X-line ranged between 20 and 70 mV m^{-1}. Reconnection was intermittent, turning on and off at different locations. (3) Electric and magnetic field structures observed by Polar suggest that Alfvén waves propagating along the auroral boundary carried a double-layer current. Downward Poynting flux was observed at the poleward auroral boundary associated with these currents. (4) Magnetic and electric field oscillations with periods of $\sim$90 s were detected on open field lines beginning $\sim$4 min before Polar entered the auroral oval. Oscillations with similar frequencies were observed both on the ground near Polar's magnetic footprint and at geosynchronous orbit. This indicates that the oscillations represent a large-scale phenomenon occurring over a large portion of the nightside magnetosphere. Coupling on open field lines derives from fringing fields associated with ionospheric closure of DP 1 currents. (5) Upward flowing hydrogen and oxygen ions were detected at and equatorward of the auroral boundary. Perpendicularly accelerated O^+ ions detected in the immediate vicinity of the boundary can be explained by direct acceleration by the ambient electric field perpendicular to the local magnetic field. Equatorward of the boundary, O^+ distributions were typical of ion conics.

1. Introduction

Understanding the global magnetosphere-ionosphere (M-I) interactions that occur during substorms has proven to be a scientifically complex and challenging enterprise. *Akasofu* [1964] was first to piece together auroral manifestations of substorm morphology in the ionosphere from all-sky film images. His synoptic model shows that substorm onset is marked by a brightening in the midnight sector of the equatorwardmost auroral arc. In the half hour following onset more poleward forms appear or brighten and then expand into the polar cap. Sequences of images from the Polar satellite [*Frank et al.,* 1998] confirm the general correctness of Akasofu's synthesis. These images also show that the area of the polar cap expands during the substorm growth phase and continue to expand for ten's of minutes after onset. Only after 30 min in that particular case did the polar cap area decrease. Since the interplanetary magnetic field (IMF) had a southward component throughout this substorm period, *Frank et al.* [1998] surmised that merging between the IMF and the Earth's magnetic field on the dayside proceeded at a faster rate than reconnection in the magnetotail. On the basis of simultaneous ground and Geotail measurements, *Maynard et al.* [1997] suggested that the delayed auroral expansion into the polar cap, and consequent decrease of its area, reflects the time required for the activated near-Earth X-line to begin reconnecting lobe magnetic flux. Only then can conjugate auroral forms expand rapidly into the polar cap. That delay time would be lengthened by continued reconnection at more distant locations.

Substorms are characterized by magnetic perturbations on the ground that appear as superposition effects of two large-scale, equivalent current systems called *DP* 1 and *DP* 2 [*Nishida*, 1968]. *DP* 2 currents are driven by the global convection electric field [*Heppner and Maynard*, 1987]. Data analyzed by *Clauer and Kamide* [1985] indicate that the *DP* 1 current system operates in the night sector and is roughly equivalent to the ionospheric part of the substorm wedge current [*McPherron et al.*, 1973]. That is, the eastward and westward edge of the main *DP* 1 current channel connect to filaments of field-aligned currents (FACs) directed into and out of the ionosphere, respectively.

Satellite measurements indicate that the electrodynamic characteristics of bright arcs observed along the poleward boundary of the expanded auroral oval are characterized by both sheet-like and filamentary FACS [*Fujii et al.*, 1994; *Hoffman et al.*, 1994]. A model of these arcs developed by *Inhester et al.* [1981] based on ground measurements predicted a FAC structure similar to that reported by *Hoffman et al.* [1994]. The model also predicts that the main westward electrojet flows along a Cowling channel within the arc.

Clearly, the poleward boundary of the arc must lie close to the open-close field line boundary. In which case it also lies near the ionospheric projection of the plasma sheet boundary layer within which intense electric field's have already been reported [*Pedersen et al.*, 1985; *Burke et al.*, 1994]. DE 2 measurements also showed spike-like electric field structures near and within the arc [*Fujii et al.*, 1994]. These spikes are probably Alfvén wave signatures of processes occurring at or near the reconnection line [*Hesse et al.,* 1999; *Yamade et al.,* 2000]. We also note that *Maynard* [1985] observed intense spike-like electric field structures at the equatorward boundary of the cusp. Comparing data acquired during a DE 1 crossing of the magnetopause with conjugate DE 2 measurements, *Maynard et al.* [1991] interpreted the electric field structures as signatures of magnetic merging on the dayside magnetopause.

Principles for calculating the electric field along a magnetic merging line were first derived by *Vasyliunas* [1984]. Ionospheric signatures of the nightside reconnection electric fields were first reported by *de la Beaujardiere et al.* [1991], who used incoherent scatter radar from Sondrestrom Fjord, Greenland, to obtain the velocities of both ionospheric plasma flow and the separatrix. The location of the separatrix was determined in the radar measurements from severe electron density gradients at E region altitudes at the auroral poleward boundary. Increased fluxes of precipitating energetic electrons enhance E region plasma densities in the auroral oval relative to the polar cap values. The motion of the separatrix was estimated from the apparent movements of the E region boundary between consecutive measurements taken at 3- to 5-min intervals. This technique led to estimates of 20 - 40 mV m^{-1} electric fields along the ionospheric projection of the reconnection line during a substorm expansion phase [*de la Beaujardiere et al.*, 1991].

Blanchard et al. [1996] made further measurements of the nightside reconnection electric field using the Sondrestrom incoherent scatter radar with all-sky images of 630.0-nm auroral emissions. Both the images and E region electron densities measured by the radar were then used to locate the poleward boundary of the auroral oval. Boundary locations determined by the two different methods were in excellent agreement. *Blanchard et al.* [1996, 1997] showed that the nightside reconnection electric field increased significantly during the expansion phase of substorms.

In this paper we interpret auroral particle measurements by Polar using the phenomenological description by *Winningham et al.* [1975]. That is, auroral electron fluxes are assigned to the boundary plasma sheet or the central plasma sheet. The boundary plasma sheet fluxes appear at higher latitudes. This useful nomenclature was assigned several years before the discovery of the plasma sheet boundary layer [*DeCoster and Frank,* 1979], which is characterized by field-aligned ion beams. At the ionosphere projection of the plasma sheet boundary layer, ions show an energy-versus-time dispersion. The highest-energy ions appear at the earliest times of detection [*Galperin and Feldstein,* 1991; *Lennartsson et al.,* this issue]. The transition to weak, low-energy electrons (polar rain) as observed by *Winningham and Heikkila* [1974] is indicative of open polar cap field lines.

To calculate the ionospheric projection of the tail reconnection electric field, we combined observations from multiple sensors on the Polar satellite to measure the plasma flow velocity and the motion of the separatrix surface. Plasma flow velocities across the separatrix line between open and closed magnetic flux are obtained directly from the velocity moments measured by the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) sensor [*Shelley et al.,* 1995] as Polar crossed the poleward auroral boundary. To validate the reliability of these TIMAS measurements, we compare ion moment calculations to the $E \times B$ drift velocity estimates from simultaneous electric and magnetic field observations. Uncertainties about the electric field component along the satellite spin axis restrict electric field measurements to the components in the spin plane for comparison with the TIMAS velocity data. The location of the separatrix boundary was determined from auroral images acquired by the Visible Imaging Syatem (VIS) Earth camera [*Frank et al.,* 1995]. In this paper we assume that the poleward boundary of the nightside auroral oval is either collocated with the separatrix line or, spatially close to the separatrix line and move's together with it.

2. Instrumentation

Polar was launched into a 86° inclination orbit with an apogee of 9 R_E over the northern polar cap, a perigee of 1.8 R_E, and an orbital period of 17.5 hours. Several of the different instruments on Polar are used in this study. Images from the VIS Earth Camera [*Frank et al.,* 1995] used here are of the O I 130.4-nm auroral emissions. The camera is mounted on the despun platform for continuous monitoring of the aurora and has a field of view of $20^\circ \times 20^\circ$. The Hydra instrument [*Scudder et al.,* 1995] Duo Deca Electron Ion Spectrometer (DDEIS) consist's of six pairs of electrostatic analyzers looking in different directions to provide high-resolution energy spectra and pitch angle information. Electron fluxes in the 1 eV to 10 keV range and ion fluxes with energy per charge ratios between 10 eV q^{-1} to 10 keV q^{-1} are measured. A full three-dimensional distribution is sampled every 0.5 s. The TIMAS instrument [*Shelley et al.,* 1995] uses a first-order, double-focusing system of ion optics that simultaneously measures the ion energy per charge between 15 eV q^{-1} and 32 keV q^{-1} and the mass per charge between 1 and 32 amu q^{-1}. A full three-dimensional distribution is sampled every 3 s. The electric field instrument (EFI) [*Harvey et al.,* 1995] uses the biased double-probe technique to measure vector electric fields from potential differences between three orthogonal pairs of spherical sensors. The Magnetic Field Experiment (MFE) [*Russell et al.,* 1995] consist's of two orthogonal triaxial fluxgate magnetometers mounted on nonconducting booms. Plasma observations from Wind [*Ogilvie et al.,* 1995] and magnetic field observations from Interball-Tail [*Klimov et al.,* 1997] are used to characterize the IMF and interplanetary conditions. We also use ground magnetometer data from Cape Dorset from the Magnetometer Array for Cusp and Cleft Studies (MACCS) data [*Hughes and Engebretson,* 1997].

3. Observations

Figure 1 shows the Interball-Tail observations of the interplanetary magnetic field (IMF) taken between 0200 and 0500 UT on April 22, 1998, near GSM coordinates (22, 14, 0) R_E upstream of the Earth. The panels from top to bottom show the IMF B_X, B_Y, and B_Z components in GSM coordinates. Throughout the interval the IMF was dominated by $B_Y \approx 6.5$ nT. IMF B_Z was negative until 0403 UT, when it began to oscillate between positive and negative values. IMF B_X was $\sim$+2 nT until 0315 UT, near zero from 0315 to 0400 UT, and $\sim$-2 nT thereafter. The solar wind flow velocity and density were observed by the Wind satellite at $X_{\mathrm{GSM}} = 220\ R_E$. Both quantities maintained steady levels near 390 km s^{-1} and 5 cm^{-3} across the period of interest. From the solar wind flow velocity and the separation distance between Interball-Tail and the Earth, we estimate the time delay between the Interball-Tail observations and the interaction of that solar wind with the magnetosphere to be $\sim$6 min.

At the time of interest, Polar was descending from apogee, traveling nearly along the 2305 magnetic local time (MLT) magnetic meridian. Selected images of 130.4-nm auroral emissions from the northern high-latitude ionosphere are given in Plate 1. The six images taken between 0339:19 and 0410:00 UT illustrate the evolution of the auroral oval during the substorm's expansion phase. The first image shows that the first brightening of the night side aurora that developed into a poleward expansion began at the equatorward edge of the oval near 2400 MLT close to 0339:19 UT. While there was an earlier brightening at 0334 UT near 2100 MLT, this diminished around onset and was not part of the substorm expansion. Onset was followed by a continuous intensification and poleward expansion of auroral forms into the polar cap. By 0350:09 UT the poleward auroral border in the midnight sector became very bright and had expanded northward of 72° invariant latitude (ILAT). At 0354:39 UT a second enhancement appeared near 2000 MLT at the poleward edge of the oval. This was followed by further poleward expansion of the auroral oval into the polar cap. Expansion of the nightside oval into the polar cap was completed by 0410:00 UT. Although emissions had dimmed near magnetic midnight, they remain fairly intense in the 1900-2000 MLT sector.

The U. S. Air Force (USAF) geosynchronous satellite 1990-095 observed an energetic electron injection at 0342 UT (0130 MLT) shortly after the onset of the auroral substorm (data not shown). Modulations of a 90-s period were observed in the 50-75 keV electron fluxes on the leading edge of the injection [G. Reeves, private communication, 1999].

We have constructed closed contours of the poleward edge of the northern auroral oval using all 47 VIS images acquired between 0329 and 0411 UT. Each contour was produced by selecting fiducial points along the poleward auroral boundary where the auroral emissions intensity dropped below $\sim$400 Rayleigh. A set of 100 equally spaced points along the contour path was obtained using a spline fit interpolation to the fiducial points. The spline fit contours were then used to calculate the enclosed area of the polar cap. Figure 2 shows these contours overlaid onto a map of Canada. Contours are shown at $\sim$5 min intervals. Using the Tsyganenko 96 magnetic field model [*Tsyganenko and Stern,* 1996], we mapped the Polar trajectory to an altitude of 200 km, where most 130.4-nm emissions originate. Dots show the magnetic footprints of Polar for the same times that the poleward edge of the aurora are shown. Expansion of the midnight sector was nearly complete when Polar crossed the poleward edge of the oval.

The first poleward expansion of the aurora appeared in the 2200 - 2400 MLT sector between 0345 and 0354 UT (dotted-A, dash-dot-dot-B, and dash-dot-C lines in Figure 2). This was followed by a more pronounced poleward expansion in the 2400-0130 MLT sector between 0354 and 0400 UT (dash-dot-C and solid-D lines). The last poleward motion occurred in the 1900 - 2200 MLT sector from 0400 to 0405 UT (solid-D, long-dash-E, and short-dash-F lines). The location of the ground magnetometer station at Cape Dorset (CD) is marked in Figure 2. It was very close to the magnetic foot point of Polar as the satellite crossed into the expanding auroral oval.

In an energy-versus-time spectrogram format, Plate 2 shows fluxes of ions and electrons observed by Hydra in the 0345-0445 UT interval. Plates 2a-2c show directional differential fluxes of ions detected with pitch angles antiparallel, perpendicular, and parallel to the local magnetic field, respectively. Plates 2d-2f show directional differential fluxes of electrons detected with pitch angles antiparallel, perpendicular, and parallel to the local magnetic field, respectively. The sampled energies for both species ranged from $\sim$30 eV to 30 keV. Measured energies of ions and electrons were shifted to E_{debye} by correcting for the spacecraft potential (Φ) using the relationship $E_{\mathrm{debye}} = E_{\mathrm{measured}} + q\Phi$. The spectra are also corrected using the Liouville theorem, so that plotted fluxes are normalized to those a hypothetically uncharged spacecraft would measure. The spacecraft potential is determined from the EFI observations when they are available.

The multicolored band that appears between the ion and electron fluxes in Plate 2 indicates the regions of space crossed by Polar. From 0345 to 0359 UT, as Polar moved from 75.65° to 72.8° ILAT, Hydra detected very low fluxes of electrons with energies <500 eV (Plates 2d-2f) and negligible ion fluxes (Plates 2a-2c), typical of polar rain in the polar cap (red) [*Winningham and Heikkila,* 1974]. From 0359 to 0406 UT (72.8° to 71.0° ILAT), Hydra observed variable fluxes of trapped energetic (>1 keV) electrons (Plate 2e) accompanied with variable fluxes of lower-energy (< 1 keV) field-aligned electrons (Plates 2d-2f). The observations show different electron anisotropies at high and low energies with low-energy electrons field-aligned and higher-energy electrons trapped. Beginning at 0401 UT, structured fluxes of energetic (>1 keV) ions appeared at the location of Polar. Energy-versus-time dispersion characteristics of fluxes observed from 0359 to 0406 UT are typical of the plasma sheet boundary layer (orange) [*Galperin and Feldstein,* 1991]. Close to the first observations of plasma sheet boundary layer particles at 0359 UT, the magnetic footprint of Polar crossed the northern boundary of the auroral oval (Figure 2) while auroral forms were still expanding poleward. After 0406 UT, Hydra observed more intense, steady fluxes of trapped energetic ions and electrons, typical of the boundary (yellow) and central plasma sheet (green) fluxes [see *Winningham et al.,* 1975, Figure 18]). For later reference we note that the trapped energetic ions penetrate to lower L shells than do the energetic electrons with fluxes extending to ~0442 UT (purple).

Significant fluxes of upward flowing ions were observed between 0359 and 0415 UT. Attention is directed to the fact that from 0359 to 0402 UT, Hydra detected perpendicular fluxes of ions with energies <1 keV (Plate 2b). Between 0402 and 0406 UT the fluxes of ions with energies <1 keV were directed upward (Plate 2a). The energy of these upflowing ions decreased as Polar moved toward lower latitudes. From 0406 to 0415 UT the energies of the upflowing ions increased to >1 keV (Plate 2a). Plate 3 shows TIMAS observations from the 0355 to 0425 UT interval. Plates 3a and 3b give energy-versus-time spectrograms of omnidirectional fluxes for H^+ and O^+ ions, respectively. Plates 3c and 3d give the ion pitch angle distributions for the same species, plotted at functions of UT. Pitch angles near 0° are along the magnetic field into the ionosphere. At 0400 UT the particle distributions were dominated by ion fluxes peaked perpendicular to the magnetic field at energies around 0.1 keV. A minute later the upflowing ions developed into conics that folded closer to the field line with increasing penetration into the plasma sheet boundary layer. The conics continue until 0406 UT, when Polar crossed into the plasma sheet. Then the energy of the upflowing ions increased to 1 keV, and their distributions became dominantly field-opposed.

Figure 3 shows the electric field observations from Polar using the sensors in the spin plane. The electric field measurements normal to the orbit plane were not usable. The two panels give the distribution of electric potential (Figure 3, top) and the electric field component along the Polar trajectory (Figure 3, bottom), which is nominally the component perpendicular to B in the orbit plane. The potential was obtained by integrating the electric field along the satellite trajectory and assuming that the potential approached zero as Polar passed equatorward of the auroral oval. The fact that the potential was generally increasing indicates that Polar was crossing part of the evening convection cell. At the poleward border of the aurora (~ 0359 UT) the electric field underwent a strong south to north reversal. This indicates that local plasma would experience a strong east to west shear. At 0438 UT, as Polar exited the auroral oval, it detected a large northward electric field spike that would drive a strong westward flow. This westward flow channel formed at the inner edge of the electron and ion plasma sheet (Plate 2) typical of a subauroral ion drift (SAID) event [*Galperin et al.,* 1974; *Spiro et al.*, 1979; *Anderson et al.,* 1993, 1991]. SAID's have also previously been observed in the inner magnetosphere by *Maynard et al.* [1980] using the ISEE 1 spacecraft.

Polar magnetic field measurements for the same interval are shown in Figure 4. Plotted are the three measured components of the magnetic field minus the International Geophysical Reference Field (IGRF) model values. A spacecraft coordinate system is used in the data display. The spacecraft coordinate system consist of three orthogonal axis labeled $X-Y$, Z, and 56. The $X-Y$ axis lies in the spin plane and is positive in a direction most away from the Sun, the 56 axis is along the spin axis and toward dusk, and the Z axis is generally northward completing a right handed coordinate system [see *Maynard et al.*, 1998, Figure 1]. The generally positive slope of the B_{56} trace beginning at 0355 UT indicates that Polar first crossed a net downward current. Conversely, the generally negative slope of the B_{56} trace after 0404 UT indicates a net upward current. However, considering all three components, the Polar data are not consistent with simple sheet current approximations, indicating that the structure is complex. This is addressed in Section 4.

During the intervals 0355-0359 UT and 0405-0409 UT, Polar detected a magnetic oscillation with a period of ~90 s in the B_{56} component. Similar variations also appear in the electric field measurements (Figure 3). Figure 5 presents electric and magnetic field perturbations in a field-aligned coordinate system. The perturbation fields were calculated by subtracting out the background values derived from 2-min sliding averages of the total fields. In this coordinate system the components U and V are perpendicular to each other and to the magnetic field. The U and V components are positive to the eastward and northward directions, respectively. The ~90-s period oscillations can be seen in both the electric and magnetic field perturbations between 0355 and 0415 UT. Polar crossed the poleward auroral border at 0359 UT. Thus these waves were detected 4 min prior to entering the auroral oval. The wave amplitude increased at the auroral boundary. Using these electric and magnetic perturbation fields, we estimated the field-aligned component of the Poynting vector shown as the bottom plot of Figure 5. In the polar cap (prior to 0359 UT) the associated Poynting flux was small and oscillating. At the poleward auroral boundary the Poynting flux increased dramatically and was generally toward the ionosphere. Equatorward of the auroral boundary the Poynting flux again became small and oscillatory.

The mapped Polar trajectory nearly passed overhead of the Cape Dorset ground magnetometer station. Figure 6 shows the three components of the magnetic field measured at Cape Dorset, where X is positive to the north, Y is positive to the east, and Z is positive downward. At 0400 UT the poleward edge of the aurora was directly over Cape Dorset. From 0355 to 0430 UT, negative deflections of the X component and positive deflections of the Z component indicate that there was a strong westward current south of Cape Dorset. Since the variation in the Z component was stronger than the X component, the centroid of the current lies significantly to the south and is from the main westward electrojet of the expanding auroral region. The negative Y variation can be interpreted in terms of Figure 3 of *Orr and Cramoysan* [1994] which shows a negative Y at the west end of a westward electrojet located to the south. Figure 7 shows the variations in the X component of the magnetic field. Note that the oscillations detected on the ground from 0354 to 0358, 0401 to 0405, and 0410 to 0415 UT had the same periods of ~90 s as those observed at Polar between 0355 and 0415 UT but start earlier.

4. Discussion

Having summarized Polar and Cape Dorset measurements acquired near the boundary of the poleward expanding auroral oval, we next consider the significance of the data for understanding high-latitude electrodynamics during substorms. On the basis of our observations, we treat four directly related topics: (1) we use boundary contours derived from VIS measurements to estimate the evolution of polar cap area (magnetic flux) during the substorm interval, (2) we combine TIMAS, VIS, and EFI measurements to estimate the electric field along the ionospheric projection of the magnetic reconnection line, (3) we compare magnetic field oscillations measured by the satellite and on the ground near the auroral boundary, and (4) we show that the perpendicular fluxes of O^+ ions observed by TIMAS as Polar entered the boundary region are consistent with direct acceleration by the ambient electric field.

4.1. Magnetic Flux in the Polar Cap

The total magnetic flux contained within the polar cap can be estimated if we know its approximate area [*Frank*, 1988; *Frank and Craven*, 1988]. We have done this using auroral boundary contours obtained from VIS observations. Figure 8 shows the resulting polar cap magnetic flux Φ_{PC} determined in this way. Prior to 0342 UT, Φ_{PC} was increasing. This is consistent with dayside merging proceeding at a faster rate than nightside reconnection during the substorm growth phase. No significant reduction in Φ_{PC} was observed at substorm onset (0339 UT). Between 0342 and 0359 UT, Φ_{PC} remained fairly constant, indicating a balance between dayside and nightside reconnection. It is not until 20 min after onset that Φ_{PC} began to significantly decrease. *Frank et al.* [1998] also reported a delay between substorm onset and when Φ_{PC} began to decrease. On the basis of simultaneous Geotail and ground-based measurements, *Maynard et al.* [1997] suggested that during the early part of substorm expansion both the near and distant reconnection lines operate simultaneously. The poleward boundary of the auroral oval in the midnight sector remains under the control of the distant X-line until the near-earth X-line begins reconnecting open lobe flux. During this time the poleward boundary may remain stable or move slowly in either direction depending on the balance of dayside and distant X-line reconnection. Only after the near-Earth X-line begins to reconnect previously open lobe field lines at a very fast rate does the auroral oval expand rapidly into the polar cap. The delay until this start of flux decrease may be ten's of minutes.

4.2. Reconnection Electric Fields

We assume that the poleward edge of the aurora either is or is very close to the ionospheric mapping of the magnetic reconnection line in the magnetotail. The correspondence of the Hydra and VIS observations from Polar clearly demonstrate that the poleward auroral border corresponds to a separatrix between open and closed magnetic field lines. Allowing for Alfvén transmission times, the poleward boundary of the aurora must correspond to the region in the magnetotail where the conversion from open to closed magnetic flux occurs. However, the measurements show that the poleward auroral boundary did not advance uniformly during the substorm. Rather, VIS imagery shows a sequence of small advances at different locations. This suggests that magnetic reconnection was temporally variable at different locations in the magnetotail.

The equation for calculating the electric field at the ionospheric projection of the reconnection line is given by $E_{\rm REC} = (V - U) \times B$, where $E_{\rm REC}$ is the projection of the X-line electric field in the ionosphere, U is the velocity of the open-closed separatrix, V is the plasma flow velocity across the separatrix, and B is the magnetic field strength. The following paragraphs describe how the quantities U and V, which must be normal to the boundary, were obtained.

Velocity moments were calculated from TIMAS observations starting at 0359 UT, when Polar entered the auroral oval. Prior to this time, ion fluxes in the polar cap were too low to measure their velocity components reliably. Using the measured north-south electric field component, we calculated the local east-west drift component ($V = E/B$). Plate 4a shows the comparison between the east-west component of the drift velocity from the EFI calculations with the drift velocity from the TIMAS O^+ ion velocity moments. Error bars for TIMAS velocity moments indicate the degree of uncertainty in the moment calculations. In the plots, velocities are positive to the east. During the largest excursions of the electric field the O^+ velocities measured by TIMAS tended to be a little smaller than those calculated from electric field observations. However, agreement between the two measurements appears to be good. This agreement provides confidence for using the north-south velocities measured by TIMAS to complete the velocity vector and for using it to determine the electric field along the reconnection line.

With poleward auroral boundary contours derived from VIS images we have determined the normal to the boundary at each time near the Polar trajectory and calculated the normal velocity of the boundary (U) at 2305 MLT, where Polar crossed into the auroral oval, using a two-point difference. The values of U that we obtain are plotted in Plte 4b (green line). Positive U is in the northerly sense. Error bars are based on the pixel size in the VIS images. Since auroral emissions used to identify the boundary location originate near 200 km, this plot represents the separatrix velocity at that altitude. Note from Figure 2 that the poleward edge is moving back and forth and the tilt is changing during that interval.

To compare the plasma flow velocity V with the boundary motion U, both must be referenced to the same altitude. Ephemeris data presented in Plate 2 show that plasma flow velocities were measured at Polar's altitude of 3.33 R_E and the separatrix velocity was measured at 200 km. The plasma flow velocity can be scaled to an altitude of 200 km in the following way. The drift velocity can be defined as $V_P = E_P/B_P$, where the subscript P references quantities to the altitude of Polar, and $V_I = E_I/B_I$, where the subscript I references quantities to 200 km. If we assume that the magnetic field lines are equipotentials, then $E_P/E_I \approx \sqrt{B_P/B_I}$. Thus $V_I \approx V_P\sqrt{B_P/B_I}$. Since $B_P \approx 650$ nT and $B_I \approx 57{,}000$ nT, then $V_I \approx 0.1V_P$. The magnetic field at Polar was measured with MFE, and the magnetic field strength at 200 km was taken from the IGRF model. The scaled components were used to determine the plasma flow velocity component in the direction of the normal determined by VIS. This is shown in Plate 4b, overplotted with the normal poleward edge velocity U. The difference $V_I - U$ represents the rate of plasma flow across the separatrix. Because U was measured at a lower time resolution than V, we have averaged V to the time resolution of the VIS images. Diamonds in Plate 4b represent averaged values of V_I.

We have calculated $E_{\rm REC}$ from 0359 to 0407 UT, along the 2305 MLT meridian, where Polar crossed the separatrix line, and we present it in Plate 4c. Values estimated at the sampling rates of TIMAS and VIS are represented by the solid line and the diamonds, respectively. During this interval the value of $E_{\rm REC}$ varied over a wide range of values. Some care must be taken in interpreting these results. Our calculation of the $E_{\rm REC}$ depends on knowing the plasma flow velocity at the separatrix surface. The Polar spacecraft was at the boundary location for only a brief moment (at 0359 UT); however, we may consider the ionosphere to be incompressible and interpret the flows in the local vicinity of the boundary to be representative of that at the boundary. No significant ion fluxes were observed poleward of the boundary. The first possible value of the reconnection electric field was determined to be 60 mV m^{-1} at 0359 UT. The most reliable measurements of the plasma flow velocity at the separatrix surface are probably from ~0359 to 0402 UT, at which time the reconnection electric field varied from 20 to 70 mV m^{-1}. The instance at 0403 UT where the reconnection electric field was negative could be due to uncertainties in the boundary location resulting from a reduction in the auroral emissions in the VIS images at that time. The reduced auroral emissions could be attributed to a temporal reduction in the merging rate to near or at zero. Given the many uncertainties connected with our calculation, we can not say whether the total variation is temporal. It is gratifying, however, to note that the estimates of E_{REC} given by *Blanchard et al.*, [1996, 1997] are in the same range of values and have similar variability.

The strong north-south component of the electric field in Figure 3 at the poleward boundary causes an initial eastward plasma flow. Strong eastward flows at the poleward boundary have been previously observed by *Burke et al.* [1994] using DE 2 and Defense Meteorlogical Satellite Program (DMSP) data. They found them to occur ~8% of the time. Considering that auroral expansions are typically 20 min, that substorms occur roughly every 3 hours during active times, and that IMF may be southward to increase the activity about half of the time, one could expect a 1 in 12 occurrence rate if we associate these strong eastward flows with active merging during expansion. As a point of comparison, *Maynard et al.* [1991] observed strong electric fields normal to the boundary at a rotational magnetopause discontinuity and in the ionosphere using DE 1 and DE 2 during a magnetic storm. They associated the strong normal electric fields often seen at the equatorward edge of the cusp [*Maynard*, 1985] with the merging process. The electric and magnetic field structure observed by Polar suggests an Alfvén wave at this boundary, carrying a two-layered current. Recent two-and-a-half-dimensional (2D) Hall MHD simulations of an active X-line in the magnetotail by *Hesse et al.* [1999] and Three-dimensional (3-D) simulations by *Yamade et al.* [2000] show a similar dual field-aligned current structure near the separatrix (e.g., Figure 9 of *Hesse et al.* [1999] and Figure 4 of *Yamade et al.* [2000]) with the downward current closest to the separatrix and an upward current just inside. *Yamade et al.* [2000] note a deflection of the flow initially toward dawn or eastward.

4.3. Magnetic Field Variations Near the Auroral Boundary

There are two aspects of the magnetic field measurements observed at Cape Dorset and at Polar that deserve comment. The first concerns plausible field-aligned currents and electrojet currents consistent with the data, and the second concerns the 90-s period wave activity observed at both locations.

Magnetic field data in Figure 6 showed that between 0355 and 0430 UT, Cape Dorset was under the influence of a westward electrojet (negative B_X) whose centroid was located to the south and east of the station (positive B_Z; negative B_Y). At first glance these data and the auroral data appear to be in conflict with Polar measurements shown in Figure 3. The spin plane components of the large-scale variation combine to give a perpendicular perturbation in B that is northward, which when added to the westward B_{56} component results in a perturbation field in the northwest direction. Remembering (1) that we are in the surge region of the *Hoffman et al.* [1994] generic substorm, (2) that the Harang Discontinuity is the location of the major upward current closing the substorm current wedge [*Erickson et al.*, 1991], and (3) that FAC pairs which close via Pederson currents have a magnetic field perturbation inside the loop that is perpendicular to the plane of the loop, we present a cartoon in Figure 9 showing a plausible nightside field-aligned current distribution for this pass, along with Polar's trajectory through the pattern. We have keyed the downward Region 0/Region 1 currents to the poleward boundary of the aurora at 0400 UT from Figure 2. The electrojet to the south and east of Cape Dorset is schematically noted. Note that it must be significantly south of the auroral border. While there may be currents at the border [*Inhester et al.,* 1981], the main electrojet must be farther south. It closes into the upward current at the Harang Discontinuity. The bold magnetic perturbation vector from the Polar trajectory represents the large-scale perturbation determined from the data in Figure 4. It is consistent with the Region 0/Region 1 downward current closing to the Harang Discontinuity. The intense smaller-scale variation at 0400 UT in Figure 4 has southward and westward components which place the direction approximately along the other arrow and approximately along the boundary of the aurora. This confirms that the small-scale feature is a pair of oppositely directed field-aligned current sheets in the plane of the boundary that are closed together. The intense downward Poynting flux shown in Figure 5 is associated with these currents.

Oscillating magnetic and electric fields were observed at the location of Polar both prior to and after the spacecraft crossing the auroral boundary at 0359 UT (Figure 5). Similar magnetic field oscillations were detected by the magnetometer at Cape Dorset (Figure 7). It is clear from the direction of the calculated Poynting vectors (Figure 5) that the waves observed between 0359 and 0405 UT originated in the magnetosphere. Downward Poynting flux at the poleward auroral boundary near midnight during a substorm has also been observed by *Wygant et al.* [2000]. However, the source of oscillations detected between 0355 and 0359 UT is not as obvious. Measurements taken at Cape Dorset show that intense oscillations with the same ~90-s period appeared in all three magnetic components beginning at ~0351:30 UT, roughly 3.5-min before they were detected at the altitude of Polar. Since the Cape Dorset magnetometer responded to perturbations produced by ionospheric currents, it is tempting to assume that the relatively low amplitude waves observed between 0355 and 0359 UT originated in the ionosphere and propagated to Polar in the Alfvén mode. This can only be a partial solution. The separation between Polar and the ionosphere was ~3.33 R_E. To take 3.5 min to propagate this distance requires an average Alfvén speed of ~10 km s^{-1}. This is much too slow. A more realistic scenario suggests that Polar crossed a spatial boundary at 0355 UT. Equatorward of this boundary, Alfvén waves propagated along magnetic field lines connected to source currents in the magnetosphere. Their closure in the ionosphere would require *DP* 1 fringing fields similar to those shown in Figure 10 of *Clauer and Kamide* [1985]. These fringing fields poleward of the open-closed boundary would have the same frequency of oscillation as that of the main electrojet. Note that the oscillations began at Polar when B_{56} showed the satellite entering a downward FAC. In addition to the oscillating magnetic and electric fields observed at Polar and on the ground, similar oscillations were also observed at geosynchronous orbit in the midnight region just prior to onset. This suggests that the 90-s period oscillation was a large-scale phenomenon occurring over a large portion of the nightside magnetosphere.

4.4. Accelerated Ions

During the interval 0359-0405 UT, as Polar crossed the auroral boundary, TIMAS detected an intense flux of O^+ ions with energies between 50 and 150 eV and pitch angle between 90° and 100° (Plate 3). Data plotted in the bottom panel of Figure 5 show that in this region the electric field had a southward component that rose abruptly from -5 to 10 mV m^{-1}, ramped to ~20 mV m^{-1}, spiked to 35 mV m^{-1}, then abruptly reversed polarity. An examination of EFI measurements at the highest time resolution (not shown) indicates that it is also a region of ELF wave activity. This offers two possible sources for the relatively energetic ions observed by TIMAS, heating by low-frequency waves [*André et al.*, 1990] and direct acceleration by the ambient electric field. Preliminary analysis of the broadband electric field fluctuations suggests that there may be sufficient wave energy available to produce the proton conic observed after ~0402 UT [*Chang et al.,* 1986]. Direct acceleration by the ambient electric field is analogous to the acceleration experienced by pickup ions [*Hardy et al.,* 1996]. The equations of motion of a positive ion of mass M and charge q in combined electric and magnetic fields $\mathbf{E} = E\hat{\mathbf{x}}$, and $\mathbf{B} = -B\hat{\mathbf{z}}$, where $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ are unit vectors in the X and Z directions, are

$$M\ddot{x} = q(E - B\dot{y}), \tag{1}$$

$$M\ddot{y} = qB\dot{x}. \tag{2}$$

A cold ion at an initial position (x_0, y_0) follows a cycloidal orbit

$$x(t) = x_0 + \frac{E}{\Omega B}[1 - \cos\Omega t], \tag{3}$$

$$y(t) = y_0 + \frac{E}{\Omega B}[\Omega t - \sin\Omega t], \tag{4}$$

where $\Omega = qB/M$ is the ion cyclotron frequency. We define the ion period $T = 2\pi/\Omega$ and "effective ion gyroradius" $\rho = E/B\Omega$. At t = T/2 the position of the ion is at a maximum $x(T/2) = x_0 + 2\rho$. It has moved across a potential drop $\delta\Phi = 2\rho E$. In electric and magnetic fields of 15 mV m^{-1} and 630 nT, $\rho \approx$ 6.3 km. The total energy gained by the ion would be ~190 eV. With the 35 mV m^{-1} electric field observed just before the field reversed, the energy gain would be ~450 eV. These values compare well to the observed energies of the oxygen ions. However, to reach definitive conclusions requires detailed comparisons of the relative contributions by waves and ambient electric fields to O^+ and H^+ ions. Such a study has been initiated and will be reported in a subsequent publication.

5. Summary

Observations from Polar have been used to determine the electrodynamics of the nightside auroral oval during the expansion phase of a substorm on April 22, 1998. The auroral substorm onset began at 0339 UT. At that time, Polar was descending from apogee along a nearly constant magnetic local time near 2300 MLT. Polar crossed the expanding poleward edge of the aurora at 0400 UT. On the basis of in situ measurements at Polar, ground-based data, and polar images, we concluded the following:

1. The total magnetic flux contained within the polar cap was estimated from auroral images obtained from the VIS camera. The polar cap flux varied depending on the balance of dayside and nightside reconnection. No significant decrease in the polar cap magnetic flux was detected until 20 min after the substorm onset. Similar results have been reported by *Frank et al.* [1998] and are consistent with a finite time interval required before reconnection of open lobe flux can begin at a near Earth X-line [*Maynard et al.,* 1997].

2. Using Polar observations we have estimated that the nightside reconnection electric field was between 20 to 70 mV m^{-1} near the end of the substorm's expansion phase of a substorm. Reconnection was intermittent, turning on and off at different locations as evidenced by motions of the poleward boundary observed by the VIS instrument. Our estimated nightside reconnection electric field is in the same range of values as those measured by *Blanchard et al.* [1996, 1997].

3. The electric and magnetic field structures observed by Polar suggest that an Alfvén wave propagated at the poleward boundary carrying a two-layered current. Similar field-aligned current structures have been predicted in recent Hall MHD simulations of an active X-line by *Hesse et al.* [1999] and *Yamade et al.* [2000]. A downward Poynting flux was observed associated with the pair of field-aligned currents. To harmonize the ground-based data, Polar images, and the in situ data, with the empirical model of *Hoffman et al.* [1994], we have constructed a large-scale context picture in which downward Region 0 currents close to the Harang Discontinuity. The smaller-scale pair of currents closes locally. The main electrojet was located significantly to the south of the auroral border.

4. Magnetic and electric field waves with ~90-s periods were observed by Polar on open field lines poleward of the auroral oval beginning ~4 min before the satellite entered the auroral oval. They continued as Polar crossed through the plasma sheet boundary layer. This placed some of the observed oscillations on open field lines. Similar waves were also observed on the ground near the magnetic footprint of Polar and at geosynchronous orbit. This suggests that the oscillations reflect a large-scale phenomenon effective over large portions of the nightside magnetosphere. The connection to open field lines was most likely effected through fringing fields associated with ionospheric closure of *DP* 1 currents.

5. Upflowing hydrogen and oxygen ions were detected at and equatorward of the auroral boundary. O^+ ions detected in the immediate vicinity of the boundary were accelerated perpendicular to the local magnetic field. A large east-west plasma flow shear and a reversal of the in-track electric field component marked the boundary. The ion acceleration occurred locally at Polar and may have been due to direct acceleration by the ambient electric field. Farther to the south, O^+ distributions were typical of ion conics.

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Figure 1. The GSM B_X, B_Y, and B_Z components of the interplanetary magnetic field (IMF) measured on April 22, 1998, by Interball-Tail near GSM coordinates (22, 14, 0) R_E upstream of the Earth.

Figure 2. Dots labeled with lowercase letters show the magnetic footprint of Polar in relationship to the poleward edge of the aurora labeled with capital letters at times (A,a) 0345, (B,b) 0350, (C,c) 0354, (D,d) 0400, (E,e) 0405, and (F,f) 0410 UT, with dotted, dash-dot-dot, dash-dot, solid, long dash, and short dash lines, respectively. A square marks the location of the ground magnetometer station at Cape Dorset. Lines of constant magnetic longitude and latitude are shown.

Figure 3. Electric field observations from Polar. (top) The integrated electric potential along the trajectory of Polar and (bottom) the component of the electric field along the velocity vector of Polar.

Figure 4. Polar magnetic field observations for 0330-0445 UT on April 22, 1998. Plotted are the three components of the magnetic field minus the International Geophysical Reference Field (IGRF) model in spacecraft coordinates. The $X - Y$ axis lies in the spin plane and is positive away from the Sun, the 56 axis is along the spin axis and is positive westward, and the Z axis is positive northward completing a right-handed coordinate system

Figure 5. The electric and magnetic field perturbations observed at Polar in a field aligned coordinate system and the parallel component of the Poynting flux (positive toward the ionosphere).

Figure 6. The X, Y, and Z components of the magnetic field measured at Cape Dorset.

Figure 7. The high-frequency X component of the magnetic field at Cape Dorset.

Figure 8. The total polar cap magnetic flux as a function of time measured from the VIS images of the northern auroral oval.

Figure 9. Cartoon showing a plausible nightside field-aligned current (FAC) distribution for this pass, along with Polar's trajectory through the pattern.

Plate 1. A time series of Visible Imaging System (VIS) images of 130.4-nm auroral emissions observed from 0339:19 to 0410:00 UT on April 22, 1998. Images have been mapped to a polar projection in corrected geomagnetic and local time coordinates with a grid overlaid. Lines of constant latitude are spaced at 10° intervals.

Plate 2. The ion and electron energy spectrograms from Hydra for April 22, 1998, from 0345 to 0445 UT. Shown are the (a) antiparallel ion flux, (b) perpendicular ion flux, (c) parallel ion flux, (d) antiparallel electron flux, (e) perpendicular electron flux, and (f) parallel electron flux. The color bar between Plates 2c and 2d indicates the regions of polar cap (red), plasma sheet boundary layer (orange), boundary plasma sheet (yellow), central plasma sheet (green), and the subauroral ion drift event (blue).

Plate 3. (a-d) Toroidal Imaging Mass-Angle Spectrograph (TIMAS) observations from 0355 to 0425 UT, on April 22, 1998. Shown are the energy time spectrograms for the omnidirectional fluxes and the pitch angle distributions for the H^+ and O^+ ions.

Plate 4. (a) A comparison of the eastward TIMAS particle velocity moment (red) with the electric field instrument (EFI) (blue) derived eastward velocity overlaid. (b) A line plot of the normal component of the TIMAS plasma flow velocity (red) and the average TIMAS flow velocity (red diamonds), with the normal velocity of the poleward edge (green) from the VIS data overlaid. (c) A line plot of the reconnection electric field with diamonds indicating the averaged field.