Charge neutrality and ion conic distributions at the equatorward electron edge of the midaltitude cusp

S. Toplis, 1, 3 A. Johnstone, 1, 2 A. Coates, 1 W.K. Peterson, 3
C. A. Kletzing, 4 and C. T. Russell 5

Abstract. We have investigated the physical processes occurring in order to maintain charge neutrality at the equatorward edge of the cusp by examining their effect on the electron distributions across polar cusp crossings. The significant differences in magnetosheath ion and electron velocities could potentially create a region at the equatorward edge of the cusp where only solar wind ions and electrons are observed. Only six Polar cusp crossings were identified, however, where a clear interface between ions and electrons was observed. We then used state-of-the-art plasma instruments on Polar to examine particle features at the separatrix between ion and electron energies. We find evidence that electrons are observed at the lower boundary of the polar cusp, while H-like and He-like ions are observed at higher altitudes and have been observed in the central part of the equatorward edge of the cusp. In all cases, the only solar wind ions detected have energies below 200 eV. The electron and ion distributions observed at the equatorward edge of the cusp may play an important role in the generation of the background ion conic observed.

1. Introduction

In the open magnetosphere model [Dungey, 1961], solar wind plasma enters the magnetosphere through the reconnection. For southward interplanetary magnetic field (IMF) conditions, the combination of low-latitude reconnection, large-scale poleward convection, and MHD convection gives rise to the velocity filter effect [Rosenthal, 1975]. The significant differences in ions and electrons could potentially create a region at the equatorward edge of the cusp where only solar wind ions have access, as has been reported for the ISEE 2 crossing of the open-latitude boundary layer [Cuing et al., 1996]. A survey of 200 Polar cusp crossings reveals only six events where a separate electron only region is observed. The region is not generally observed for several reasons, including an unclear cusp boundary, nonsteady convection, and the use of state-of-the-art plasma instruments on Polar to examine in detail the equatorward edge of the cusp crossings where a clear "solar wind electron only" region is present. The particle data reveal evidence of parallel reacceleration of electrons above Polar and the perpendicular and parallel acceleration of ions below 200 km.

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1 Malvern Space Science Laboratory, University College London, London, England, United Kingdom.
2 Received May 28, 1999.
3 SwRI Research Laboratory, Palo Alto, California.
4 Department of Physics and Astronomy, University of Iowa, Iowa City.
5 Institute for Geophysics and Planetary Physics, University of California, Los Angeles.

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Plate 2. May 4, 1997, TIMAS particle and Magnetic Field Experiment (MFE) residual magnetic field data with the T96 model magnetic field removed. Panel 1 is total magnetic field, and panels 2-4 are x, y, and z components, respectively, in solar magnetic coordinates. Panels 5, 7, and 9 are H', He', and O' energy spectrograms integrated over all pitch angles. Panels 6, 8, and 10 are H', He', and O' pitch angle spectrograms, where O' pitch angle is parallel to the magnetic field.
Plate 3. Hydra field-aligned electron spectra on May 4, 1997, at 0849:12, 0851:44, 0857:01, 0901:09, 0910:08 UT. The black line is the one count level. Dotted and dashed black lines are modeled core and halo distributions, respectively.
Recent, high-altitude cupp crossings by Polar (Huddleston et al., 2000) have led to the observation of toroidal distributions. Our survey suggests that ions at Polar's altitude are not ion cocoons, as previously believed but at the equatorward edge of the cup, in agreement with earlier reports at lower altitudes. Transverse ion acceleration may be caused by wave-particle interactions (e.g., Chang et al., 1986; Andrén and Yau, 1997), and the presence of various waves at the equatorward edge of the cup has previously been reported (e.g., Klimas, 1986; Andrén et al., 1998). The timescales and spatial scales of some conic generation mechanisms, however, preclude their identification in all but the most favorable of circumstances (Angelopoulos et al., 2001).

Examination of high-resolution particle data reveals distinct differences in the conic distributions observed within the different regions at the equatorward edge of the cup. We find evidence of species-specific acceleration at Polar's altitude. H+ conics appear shortly after the first solar wind electrons appear at POLAR in the region before the first solar wind ions arrive. More energetic H+ conics, with a broader range of pitch angles, are seen soon after the first energetic solar wind ions arrive back at Polar from low altitudes. In contrast, O+ conics are only seen in one of the events presented and are present before the first solar wind electrons arrive. More energetic O+ conics are not seen until the first solar wind ions arrive from above Polar.

The two events that we present here show similar features in both the particle and wave data, and we therefore choose not to show the full data sets for each event. Instead, we concentrate on electron data and parallel electric fields in the first event, and then we focus on wave data in the second event. Although our observations come from two special noon sector events where clear separate electron and ion equatorward edges are observed, we believe the processes that we examine may be typical in the high-altitude cup during periods of southward IMF.

2. Results

2.1 May 4, 1997

On May 4, 1997, from 0830 to 1100 UT, Polar flew poleward across 7.5° to 8.6° Ry altitude, with a magnetic local time range of 1215-00 UT. Proton and electron spectrograms from Toroidal Imaging Mass-Angle Spectrograph (TIMAS) (Shelley et al., 1995) and Hydros (Scudder et al., 1995) instruments are shown in Plate 1. Before 0830 UT, high- and low-energy trapped magnetospheric protons are seen, along with similar electron populations. Open field lines are encountered by Polar from 0830:30 UT onward, as indicated by the disappearance of high-energy (>1 keV) magnetospheric electrons, and the appearance of lower-energy electrons presumably of magnetosheath origin. An enhanced flux of low-energy protons is observed shortly after the first magnetosheath electrons, with upper energies of 300 eV. After a brief initial encounter at 0834:00 UT, a higher-energy population of protons appears at 0850 UT, at an energy of 2-8 keV, which is at the top end of the solar wind thermal distribution. The low-energy population continues to be visible until 0950:00 UT, at which time there is quite an abrupt change in the magnetosheath ion distribution, as ions within a large energy range (40 eV to 5 keV) are then detected.

High resolution (8 samples/s) residual magnetic field data (with the 796 model magnetic field subtracted, Tsyganenko, 1996) from the Magnetic Fields Experiment (MFE) instrument on board Polar are also presented in Plate 1. The poleward edge of the cup from 0849 to 0904 UT is presented in panels 1-4 in Plate 2. Panels 5-10 show MFE H+, He+, and O+ energy and pitch angle spectrograms. The banding in H+ pitch angle spectra is an artifact of ground data processing which does not correctly model the pitch angle spectra in intervals with data from only one of two sets of interlaced energy bins. The TIMAS instrument acquires data in two interlaced sets of energy bins on alternate spins, and owing to limited telemetry bandwidth is sometimes unable to transmit both distributions. A slight enhancement in wave activity begins at 0853:40 UT as indicated by the spiked nature of the separate components of the magnetic field data, although no overall change in Ry is observed. These waves begin after the appearance of the low-energy H+ population already noted in the TIMAS data. Pitch angle data (panel 6) show this to be a transiently accelerated ion population. A second enhancement in wave activity begins in the MFE data around 0900 UT. Unlike the first enhancement, this is accompanied by a depression in the total magnetic field. At the same time, the lowest-energy H+ ions are no longer visible in the TIMAS data, but a broad band of H+ flux is observed with energies from 60 eV to 8 keV. He+ ions may be present during the same time interval as H+ ions are observed (see panels 7 and 8), although the low count rate is close to the instrument threshold. Panels 9 and 10 in Plate 2 reveal little evidence of any other activity. Data from the plasma wave instrument's Low-Frequency Wave Receiver (LPWF) (Green et al., 1995) (reference et al., 1995) at the event, so we have been unable to characterize the nature of the waves seen in the MFE data.

Field-aligned Hydros electron space charge density distributions for five intervals are plotted in Plate 3. Each distribution is averaged over 55 s. The electron distribution data have been fitted to the power-law distribution, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data. The open field lines are produced by the electron diffusion, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data. The open field lines are produced by the electron diffusion, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data. The open field lines are produced by the electron diffusion, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data. The open field lines are produced by the electron diffusion, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data. The open field lines are produced by the electron diffusion, as calculated by the Electric Field Instrument (EFI) on Polar (Harvey et al., 1995), and the black line is the one that best fits the data.
The last three spectra, obtained when magnetosheath ions are present at Polar, appear to consist of a lower-energy core Maxwellian population and a higher-energy halo Maxwellian component, with a shoulder between the two components appearing between 200 and 300 eV. The second phase space velocity in the "magnetosheath electron only" region, appears to consist of only the halo Maxwellian distribution.

2.2 April 21, 1996

On April 21, 1996, Polar encountered the cusp traveling outbound through the Earth's dayside magnetosphere, toward increasing latitudes. Proton and electron spectrometers from the TIMAS and Hydra instruments are shown in Plate 4. Before 01:30 UT, high- and low-energy trapped magnetospheric protons are seen, along with similar electron populations. Open field lines are encountered by Polar from 01:30-0UT, as indicated by the disappearance of high-energy magnetospheric electrons and the appearance of lower-energy < 1 keV) electrons presumably of magnetosheath origin. An enhanced flux of low-energy protons is also observed whose upper energy gradually increases from below 100 keV to 300 eV at 01:32:00 UT. At 01:32:30 UT, a higher-energy population of protons appears at an energy of 2-10 keV. The low-energy population continues to be visible until 01:33:30 UT, at which time there is an abrupt change from a narrow energy range of magnetosheath ions to a much broader distribution as noted in the first event. The magnetosheath ion population then displays a typical energy-biased dispersion, which is interpreted as the velocity filter effect [Reisenbichler, 1975].

Figure 4 shows the phase space density data from the MFE instrument at the equatorward edge of the cusp are presented in panels 1-4 of Plate 5, in the same format as displayed in Plate 4. Panels 5-10 show TIMAS H+, He+, and O+ energy and pitch angle spectrometers. An enhancement in wave activity is seen from 01:31 to 01:33 UT in the separate components of the magnetic field data, although no overall change in By is observed. These waves correspond to the appearance of the low-energy H+ population already noted in the TIMAS data. Pitch angle data again show this to be a transversely accelerated ion population. Close examination suggests that the peak of the enhanced wave activity occurs when the H+ ions have a pitch angle close to 90°, between 01:31:30 and 01:32:00 UT.

A second enhancement in wave activity begins in the MFE data at 01:35:10 UT. Unlike the first enhancement, this is accompanied by a large depression in the total magnetic field. At the same time the lowest-energy H+ ions are no longer visible in the TIMAS data, but a broad band of H+ flux is observed with energies from 60 eV to 10 keV. Data (not shown) from the Low-Frequency Waveform Recorder (LFWR) show similar enhancements in electric and magnetic waves at this time. Wavelet analysis of the LFWR time series data shows these enhancements to be of an irregularly pulsed nature at discrete frequencies similar to an event reported by Fladé et al. (2000), rather than broadband low-frequency waves which are generally associated with ion comas at low altitudes [André et al., 1998].

A transversely accelerated O+ population (panels 9 and 10) can be observed from 01:28 to 01:35 UT, decreasing in flux and increasing in energy during this period. A H+ conic distribution (panels 7 and 8) is also observed, at the same time as the H+ coma is observed. Lund et al. [1998] have suggested that H+ can be low-injected as energy in association with electromagnetic ion cyclotron (EMIC) waves, which may explain the high ratio of H+ to O+ observed by the TIMAS instrument. EMIC waves may, however, also preferentially accelerate O+ relative to H+ [Brinton et al., 1980]. In correspondence to the observations presented here. The presence of an O+ population during this event but not during the May 4, 1997 event, may be attributed to the lower magnetic field (over 2 Rp lower than the first event) or reduced O+ isotropic outflow. Ionospheric outflow is known to be affected by solar radio flux and geomagnetic disturbance [Yau et al., 1985], although the Kp index for both events is similar (Kp = 3 for May 4, 1997, and Kp = 3-4 for April 21, 1996, event).

The temporal evolution of the ions from 01:28:56 to 01:35:47 UT is shown in Plate 6. Four TIMAS proton energy against pitch angle plots are presented. Data are averaged over two spins (12 s), with O+ pitch angle corresponding to particles traveling field aligned, toward the earth. At 01:28:56 UT a low-energy population spread over all pitch angles is observed, indicating magnetospheric protons trapped on closed field lines. In panel 1, at 01:30:00 UT, a low-energy peak at pitch angles of 90° and 120° is observed. This corresponds to the low-energy enhanced flux population observed in Plate 4. There is also evidence of an ion beam traveling antiparallel to the magnetic field at energies of 0.2 to 1 keV. At 01:32:42 UT, in panel 3, a high-energy downstream proton population starts to appear, and the low-energy cones containing the high-energy protons are seen.

Finally, in panel 4, at 01:35:25 UT, downstream protons are seen over a broad energy range, along with two distinct populations of particles traveling upward, one with energies below 200 eV and the other with energies above 500 eV. In contrast to the inflowing population is interpreted as being magnetosheath particles which have mirror at the equator and are now traveling parallel to the lower magnetic field. This is confirmed on an examination of energy against pitch angle plots (not shown) at intermediate times between panels 3 and 4, where the magnetosheath particles broaden to 180° as particles with pitch angle close to 90° at Polar and particles which have already mirrored below Polar begin to arrive back at Polar's altitude from below the spacecraft. The low-energy upward traveling population is a conic distribution with a low-energy cutoff observable around 30 eV. It has reduced flux compared to the earlier low-energy cones seen in panels 2 and 3 and pitch angles extending to 180°. After 01:35:47 UT, it is impossible to distinguish between the upstream ionically H+ and the mirrored solar wind H+ populations as the flux minimum at intermediate energies separating the two populations diminishes.

A more detailed plot of the magnetic field data from 01:31:05 to 01:32:15 UT, before the solar wind ions arrive at Polar, together with the high-resolution (5 s) Hydra ion velocity distributions within this interval is shown in Plate 7. Plots of color vectors on lines in the magnetic field time series plots indicate when the ion velocity distributions were measured. Hydra ion and electron measurements are interfaced, which explains...
the gap between each ion distribution. The proton gyrofrequency at this time was 4.7 Hz. Plate 7 shows that the conic distributions are not a steady feature. The ion distribution in panels 1 and 5 show little evidence of a conic distribution, while a conic shape can be seen in the distributions of panels 2, 4, and is particularly evident in the distribution in panel 4 at 01:32:04 UT. This is typical of the whole period when conics are observed and suggests localized heating of the \( \beta_i \) ions. The conic distribution in Plate 7 may be associated with the increase in amplitude of the \( B_i \) component of the magnetic field between 01:24 and 01:32:06 UT. However, examination of the data from 01:32 to 01:33 UT reveals no clear correlation between peaks in the MFE \( B_i \) component and the appearance of conic distributions in the high-resolution Hydra data.

3. Discussion

A survey of 200 cup crossings from April 1996 to October 1998 when Polar is encountering the cup close to the noon-midnight meridian reveals only six events where a clear electron edge is observed ahead of magnetosheath ions. The width of the electron edge for these six events extends up to 5\( ^\circ \) in invariant latitude. For five of these events, time-tagged data from the magnetic field investigation on the Wind spacecraft [Zepf et al., 1995] report an IMF \( B_z \) component which is negative both before and during Polar's encounter with the equatorward edge of the cup. For the sixth event the IMF \( B_z \) component was positive, and on spectrometry for this event reveal a reversal (in latitude) energy dispersion interpreted as a signature of reconnection perpendicular to the IMF. For these six events, the measured electron edge was measured at the poleward edge of the cup. IMF \( B_i \) component for these six events vary, with the \( B_i \) component sometimes larger that the \( B_z \) component. Other solar wind values such as velocity and density vary between the six events but are not usually high or low. Statistical analysis of solar wind and geomagnetic data for these events reveals no parameter which can organize these events. Plate 7 shows the location of the IMF and IMF \( B_i \) component and the appearance of this event, yet only six of these events reveal a clear separation electron edge at the equatorward edge of the cup.

Ignoring charge neutrality constraints, we can use ionimagnetic field-aligned densities and magnetospheric convection to estimate the size of the region at the equatorward edge of the cup to which only electrons should have access. The high-velocity tail of magnetospheric ions to an electron density distribution extends to \( \sim 10^{-6} \) \( \text{cm}^{-3} \), corresponding to field-aligned velocities of \( \sim 1400 \) and \( \sim 1900 \) km/s respectively. The method of analyzing downstream and mirrored low-energy ions cutoff to obtain a reconnection site location [Doust et al., 1996] given a field-aligned distance of \( \sim 10 \) R\( _E \) from Polar to the reconnection site on the magnetopause for the April 21 cup crossing. The first electrons observed by Polar are believed to be behind the first electrons owing to their relative speeds, and assuming a poleward convection speed of \( \sim 10^{-6} \) km/s [Lockwood and South, 1994], this leads to a spatial separation of \( \sim 430-2150 \) km or \( \sim 0.7-3.3 \) \( R_E \) at Polar's altitude. This calculation assumes that Polar sees a steady spatial structure at the equatorward edge of the cup. An enhancement of reconnection rate [Smith and Lockwood, 1990] or motion of the reconnection site at the magnetic neutral line into the magnetospheric cup and any separation in electron and ion edges that Polar would observe. On April 21, 1996, Polar encounters the cup traveling in the noon-midnight meridian, with a poleward velocity perpendicular to the magnetic field of \( \sim 3 \) km/s, so for periods of steady convection, Polar should encounter magnetosheath electrons 3-12 min before magnetosheath ions. Poor eastern encounters the magnetosheath for 2 min before the ions, which compares reasonably with the simplified calculations. A similar calculation for the May 4, 1997, event suggests that magnetosheath electrons should be encountered 4-18 min before the ions, while data show a 3.5-4.5 min separation. The electron edge observed for all six events is generally narrower than that predicted by calculation.

3.1. Electrons Edges and Charge Neutrality

There are several possible physical explanations for why Polar does not encounter an electron edge as wide as our simple calculation suggests. They include slower magnetospheric convection speeds than used in our calculations, or a convection direction at an angle to the noon-midnight meridian (influenced by a \( B_i \) component of the IMF), and rearrangement or unexplored aspects of charge neutrality now accessible with the Polar high time resolution plasma and field data. Barck [1985] showed that suprathermal electron ion density measurements made by DE 1 in the cup were nearly the same, and he suggested that the difference was not an error in the ion mass. Other researchers [e.g., Singh et al., 1996] have suggested that a potential drop is measured between the magnetopause and the Earth. Electric fields will have a far greater impact on electron velocity than ion velocity, owing to the much larger ion mass; yet, the very fact that solar wind electrons have been observed ahead of solar wind ions proves that the electron flow is not directionally fixed to the solar wind ion motion. During Polar's pass of the equatorward edge of the cup on May 4, 1997, the EFI cannot track the low-energy tail of electrons (energies above an upper limit of \( \sim 2 \) \( \text{keV} \) [Olin Menyhr, private communication, 1999], which would be able to accelerate particles in energies of 4 \( \text{keV} \) over a distance of 4000 km. Large electric field spikes are often seen at the equatorward edge of the cup [Maynard, 1985], and these may be due to the plasma sheath to reestablish charge neutrality.

By suggesting Maxwellian distributions to low-altitude Defense Meteorological Satellite Program (DMSP) cup and low-latitude boundary layer (LLBL) electron spectra, [Singh et al., 1996] suggested a 20 \( \text{V} \) potential retarded electrons equatorward of the main cup. The large difference between the second electron spectrum measured by Hydra in Plate 3 compared to the spectra at later times suggests that a retarding potential may well be present in the initial solar wind electrons. Comparison of the second and third electron spectra in Plate 3 suggests that electrons at the earlier time are being retarded by a 100-300 \( \text{V} \) potential compared to electrons at the later time, assuming an identical source distribution in both cases.
There is, however, an inherent uncertainty in this method. When an electron distribution passes through a retarding potential, the low-energy part of that distribution is lost. If the original distribution can be compared with the final distribution, the retarding potential can be calculated. However, if only the final distribution is available, a potential can only be estimated by comparing this distribution to a typical source distribution obtained from a statistical average of spacecraft observations. This leads to large uncertainties due to the variability of the source distribution as illustrated by the differences in the final two spectra in Plate 3, both of which are from the cusp proper, where very low retarding potentials are believed to operate [e.g., Lemaire and Scherer, 1978]. For now we note the similarity of the second spectrum in Plate 3 to that of the model halo distribution, and we suggest that if the bulk of the lower-energy core electron distribution has been prevented from reaching Polar's altitude ahead of the solar wind ions, as postulated by Wing et al. [1996]. Further evidence of possible electron fields present at the equatorward edge of the cusp can be seen in the ion data. The presence of an upward-traveling ion beam in panel 2 of Plate 6 (also observed in high-resolution Hydra ion distribution, not shown) suggests that a parallel electric field may be briefly present below the spacecraft at the equatorward edge of the cusp. This field would be opposite in sign to that discussed earlier with regard to electron retardation above the spacecraft. Another feature is the abrupt change in peak energy of the solar wind ion distribution seen in both events (0000 UT on May 4, 1995 and 0335 UT on April 21, 1996) which the distribution finally arrives at Polar. This is a frequent observation in Polar cusp crossings. Fuselier et al. [1999] have suggested that this may be due to the magnetospheric source distribution exhibiting a break at 1.3 keV at this time. We believe it is made of two separate components. We suggest that acceleration due to auroral dipolarization as the ions and electrons travel away from the magnetopause reconnect area is responsible. This is in accord with the arrival of high-energy solar wind ion distribution at the equatorward cusp boundary before the bulk of the magnetospheric ion population as at Polar.

3.2. Perpendicularly Accelerated Ions

A survey of Polar cusp data from April 1996 to October 1998 reveals that H\textsuperscript{+} comets are a common high altitude feature in the cusp region. The average of the cusp can be seen in the two events presented in this paper, with the April 1996 event encompassing 0.4 keV and the May 1997 event at ~7.6 keV. Evidence of localized perpendicular heating over an extended range of altitudes up to 4.4 R\textsubscript{E} was reported by Panetta et al. [1992].

Our results suggest that localized heating can continue to altitudes as high as Polar's 4.6 R\textsubscript{E}.

Although H\textsuperscript{+} and O\textsuperscript{+} comets are frequently seen in the equatorward edge of the cusp by Polar, these two unusual events allow us to examine in more detail the separate regions in which they exist or are energized. The initial appearance of H\textsuperscript{+} comets is related to the arrival of the first solar wind electrons at Polar. A second, more energetic H\textsuperscript{+} comet population occurring at the edge of the cusp proper appears either to be related to the upcoming rimmed solar wind ions or to be related to the sudden increase in density as the bulk of the solar wind ion distribution arrives at Polar. It is unclear from single spacecraft measurements whether the more energetic ions seen deeper in the cusp originate from the earlier lower-energy ions or whether they are a separate ion population which may have been accelerated at lower altitudes. When O\textsuperscript{+} ions are present, they initially appear to be traversely heated on closed field lines at lower latitudes.

The presence of conic distributions together with low-frequency waves raises the unresolved question of which feature causes the other. The electromagnetic structure may be due to the downwelling solar wind electron ionization (Culter et al., 1998) or may be due to fouriers in the solar wind flow (e.g., Huddleston et al., 2000), which could explain the broad ion comets observed on closed field lines at lower latitudes. It may be that the same mechanism accelerates all three ion species but is inhibited at the higher H\textsuperscript{+} and O\textsuperscript{+} cyclotron frequencies until the arrival of a population of solar wind electrons.

Comparisons between peaks in the MFE wave data and the appearance of ion conic distributions in the high time resolution Hydra particle data do not show a clear correlation, although this may be limited by the temporal resolution of the particle instruments. If Polar is not on the source region where particles are being energized by wave-particle interactions, then a correlation would not necessarily be expected. However, as noted above, H\textsuperscript{+} comets are seen peaked at 50°-120° over a range of at least 2.2 R\textsubscript{E} altitude. This suggests that Polar is likely to frequently encounter regions of localized perpendicular heating as it crosses the cusp. TIMAS proton data and magnetic field data in panel 2 do suggest that the peak wave enhancement for the April 21, 1996 event occurs during the interval from 0313 to 0320 UT when H\textsuperscript{+} comets are centered close to 90°. The intermittency of ion conic distributions is also evidence of local acceleration.

Angelopoulos et al. [2001] have shown that the EMIC wave-particle mechanism is not always apparent in regions of perpendicular ion acceleration and that a detailed investigation of wave-particle interaction mechanisms in producing ion conic distributions would require a detailed analysis of high time-resolution wave data.

The presence or generation of ion comets at the equatorward edge of the cusp may be due to processes maintaining charge neutrality, as the solar wind electrons and ions occupy separate regions due to their different velocities and the convective electric field. Borovsky and Joyce [1986] have suggested that narrow electrostatic shocks are able to transversely accelerate ions into their respective regions by transferring energy. In this case, the electrostatic shocks are transversely accelerated, in disagreement with observations presented here. The presence of heavy ions in the "electron-only" region at this altitude may, however, be regulated by other processes occurring at low altitudes. Several studies have reported [e.g., Huddleston et al., 2001; Angelopoulos et al., 2001] that ion cyclotron heating does not appear to be responsible for the observed ion conic distributions. In these reports the appearance of comets appears to be related to small potential structures or pulses in the electromagnetic field. Huddleston et al. [1998] interpreted Viking observations of electron beams and elevated ion comets as the result of parallel electric fields.
Plate 4. TIMAS proton and Hydra electron energy spectrograms on April 21, 1996, integrated over all pitch angles.
Plate 5. April 21, 1996, TIMAS particle and MFE residual magnetic field data with the T6 model magnetic field removed. Panel 1 is total magnetic field, and panels 2-4 are x, y, and z components, respectively, in solar magnetic coordinates. Panels 5, 7, and 9 are H+ , He+ , and O+ energy spectrograms integrated over all pitch angles. Panels 6, 8, and 10 are H+ , He+ , and O+ pitch angle spectrograms, where O+ pitch angle is parallel to the magnetic field.
Plate 7. Hydro ion velocity distribution plots at 1.5 s resolution, for April 21, 1996, at 0131:57 ET, 0131:59 ET, 0132:02 ET, 0132:04 ET, 0132:06 ET. Measurements are reflected in the $v_{	ext{app}}$ axis to form a $360^\circ$ distribution. MFE residual magnetic field data with the T96 model magnetic field removed is shown for April 21, 1996. The bottom panels show total magnetic field, and $x$, $y$, and $z$ components in solar magnetic coordinates. The five pairs of colored vertical lines correspond to the time periods for the ion distributions plotted above, with distribution blue (0131:57 UT), green (0131:59 UT), yellow (0132:02 UT), orange (0132:04 UT), and red (0132:06 UT).
which are experienced as quasi-static by electrons but as wave fields by ions. It may be that processes occurring at or near the equatorward edge of the cusp can generate potential structures which may then play a role in the generation of the intertemporal ion conic distributions observed. An intermittent acceleration mechanism operating on sufficiently small temporal or spatial scales could explain the preferential acceleration of H+ over O+. Higher-time resolution field and particle data are required in order to understand the acceleration processes responsible for ion conic generation in this region.

4. SUMMARY

We have identified six Polar cup crossings outside of 200 km, which feature a separate electron region at the edge of the cusp up to 0.5 invariant latitude in size. No solar wind or geomagnetic parameter appears to organize the presence or lack of a separate electron edge. Our calculations suggest that separate electron edges should be larger and that these events should be more commonly observed. We have presented particle data from two events where the separate electron edge region is observed. Electron spectra within this region appear to show electron energies to be part of the solar wind halo distribution, suggesting that the core electron distribution has been prevented access by a parallel electric field. We have discussed the validity of identifying retarding electric fields from electron spectra. We have also found evidence of the presence of electric fields below the spacecraft in ion data in this region. We conclude that electric fields are present and are responsible for preventing the electrons from reaching the magnetosphere after they enter the magnetosphere in order to conserve charge neutrality.

In the unusual events where a separate magnetospheric electron edge is observed, we have found distinct differences in the ion conic distributions observed within the different regions at the equatorward edge of the cusp. More specifically, H+ and He+ ions with pitch angles between 90° and 120° are seen during the cusp only region at the equatorward edge of the cusp. Further into the cusp, when solar wind ions are present and the fastest of these ions have had enough time to rotate to lower altitudes and return to Polar, H+ and He+ ions with higher energies and a low-energy cutoff are observed, with pitch angles extending to 180°. O+ ions are sometimes also observed at low fluxes. These appear to have been initially energized at lower latitudes on closed field lines and are not correlated with the separation of H+ and He+ ions. The H+ and He+ ions are accompanied by irregular pulsations of waves at intermediate frequencies. The generation of these disturbances may be related to processes responsible for maximizing charge neutrality in this region.

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A. Coates and S. Toftland, Mullard Space Science Laboratory, University College London, Hallyburton St. Mary, Dorking, Surrey RH5 2NN, England, U.K. (acoates@mssl.ucl.ac.uk; stofland@mssl.ucl.ac.uk)

C. A. Kletzing, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 (kletzing@uiowa.edu)

W. K. Peterson, Lockheed-Martin Palo Alto Research Lab, 3251 Hanover Street, Palo Alto, CA 94304. (peterson@lapl.lmco.com)

C. T. Russell, Institute for Geophysics and Planetary Physics, University of California, Los Angeles, CA 90049 (cmrussel@igpp.ucla.edu)

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