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Reconnection at the high-latitude magnetopause during northward interplanetary magnetic field conditions

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Abstract. The Polar spacecraft had a prolonged encounter with the high-latitude dayside magnetopause on May 29, 1996. This encounter with the magnetopause occurred when the interplanetary magnetic field was directed northward. From the three-dimensional electron and ion distribution functions measured by the Hydra instrument, it has been possible to identify nearly all of the distinct boundary layer regions associated with high-latitude reconnection. The regions that have been identified are (1) the cusp; (2) the magnetopause current layer; (3) magnetosheath field lines that have interconnected in only the Northern Hemisphere; (4) magnetosheath field lines that have interconnected in only the Southern Hemisphere; (5) magnetosheath field lines that have interconnected in both the Northern and Southern Hemispheres; (6) magnetosheath that is disconnected from the terrestrial magnetic field; and (7) high-latitude plasma sheet field lines that are participating in magnetosheath reconnection. Reconnection over this time period was occurring at high latitudes over a broad local-time extent, interconnecting the magnetosheath and lobe and/or plasma sheet field lines in both the Northern and Southern Hemispheres. Newly closed boundary layer field lines were observed as reconnection occurred first at high latitudes in one hemisphere and then later in the other. These observations establish the location of magnetopause reconnection during these northward interplanetary magnetic field conditions as being at high latitudes, poleward of the cusp, and further reinforce the general interpretation of electron and ion phase space density signatures as indicators of magnetic reconnection and boundary layer formation.

1. Introduction

The interconnection of the interplanetary magnetic field with the terrestrial magnetic field has a dominant effect on Earth's magnetosphere and ionosphere, as a mechanism both for plasma entry and for energy input from the solar wind. When reconnection occurs on Earth's magnetopause, the intermixing magnetosheath and magnetospheric plasmas form a number of distinctive regions, including the magnetosheath boundary layer (MSBL) that lies outside the magnetopause current sheet, the low-latitude boundary layer (LLBL) that lies at low latitudes just inside the magnetopause, the cusps that extend from the magnetopause down to the northern and southern polar ionospheres, and the mantle and polar rain at higher latitudes [e.g., *Cowley*, 1982; *Newell et al.*, 1991a; *Fuselier et al.*, 1995].

The ability to resolve the electron and ion signatures of reconnection has provided confirmation that reconnection is a dominant process in Earth's magnetosphere; and it is a valuable tool for investigating the details of reconnection and the evolution of the open magnetosphere. The measured ion distributions in the cusp have been shown to be consistent with the direct transport of magnetosheath plasma across the open magnetopause [e.g., *Newell et al.*, 1991b; *Onsager et al.*, 1993], and they have been used to estimate the plasma properties in the vicinity of the remote reconnection site [*Lockwood et al.*, 1994]. The cusp ion measurements also have been used to estimate the rate of reconnection and its variability [*Lockwood and Smith*, 1992; *Lockwood*, 1997a, 1997b]. At the magnetopause, ion and electron measurements have been used to estimate the location of reconnection and to identify the MSBL and the location of the magnetopause itself under low magnetic shear conditions [*Paschmann et al.*, 1993]. These identifications are based on features in the particle distribution functions that form both inside and outside the magnetopause as the plasma evolves following reconnection and as it interacts with the magnetopause current sheet. A detailed, multi-instrument study of the subsolar magnetopause under northward interplanetary magnetic field (IMF) conditions indicated a number of different boundary layers surrounding the magnetopause, and it was suggested that an outer boundary layer could form as high-latitude reconnection creates new closed field lines [*Song et al.*, 1993].

An important issue regarding reconnection is understanding what determines the location where it occurs on the magnetopause. For any given orientation of the magnetosheath magnetic field, it is not known how reconnection is distributed over the magnetopause. One possibility, referred to as "antiparallel merging," is that reconnection is favored to occur where the magnetosheath and magnetosphere fields are most nearly antiparallel [*Crooker*, 1979]. Another possibility,

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referred to as "component merging," is that shear in any component of the vector magnetic fields is sufficient for reconnection to occur. In the case of a southward directed magnetosheath field, the subsolar magnetopause has been shown at times to be the preferred location for reconnection [*Gosling et al.*, 1990]; however, other studies have suggested that antiparallel merging may occur, resulting in reconnection occurring at higher latitudes, removed from the subsolar region [e.g., *White et al.*, 1998].

When the magnetosheath magnetic field is directed northward, both antiparallel and component merging have been identified, with significant differences in the magnetospheric interconnection that results. When antiparallel merging occurs, reconnection will take place poleward of the cusps, interconnecting the magnetosheath field with either open lobe field lines or closed magnetospheric field lines [*Maezawa*, 1976; *Cowley*, 1981]. There is considerable observational evidence for this reconnection configuration in low-altitude cusp measurements that exhibit a distinctive "reverse-dispersion" signature [e.g., *Burch et al.*, 1980; *Woch and Lundin*, 1992; *Matsuoka et al.*, 1996], as well as from in situ measurements at the high-latitude magnetopause [*Gosling et al.*, 1991; *Kessel et al.*, 1996].

There is also evidence that under northward magnetosheath field conditions, reconnection may occur on the dayside magnetopause, equatorward of the cusp [*Nishida*, 1989; *Onsager and Fuselier*, 1994; *Fuselier et al.*, 1995]. The interconnection would then be between the magnetosheath field and the closed dayside magnetospheric field lines. In these cases, reconnection may occur where there is relatively little magnetic shear.

One important consequence of high-latitude reconnection, i.e., that occurring poleward of the cusp, is the formation of an LLBL on closed field lines when the IMF is northward [*Song and Russell*, 1992; *Le and Russell*, 1996; *Lockwood and Moen*, 1999]. In this scenario, new closed magnetospheric field lines are formed by reconnection occurring in both the Northern and Southern Hemispheres. The new closed field lines that form in this way contain a mixture of magnetosheath and magnetospheric plasma and may be transported downtail to contribute to populating the plasma sheet.

In this paper we describe observations obtained by the Polar spacecraft during a prolonged encounter with the high-latitude dayside magnetopause. This encounter with the magnetopause occurred when the IMF was directed northward. From the three-dimensional electron and ion distribution functions measured by the Hydra instrument, it has been possible to identify nearly all of the distinct boundary layer regions associated with high-latitude reconnection. Reconnection over this time period was occurring at high latitudes, interconnecting the magnetosheath with the plasma sheet and lobe field lines in both the Northern and Southern Hemispheres. Newly closed boundary layer field lines were observed, as reconnection occurred first at high latitudes in one hemisphere and then later in the other hemisphere. The regions that have been identified from the particle and magnetic field measurements are (1) the cusp; (2) the magnetopause current layer; (3) magnetosheath field lines that have interconnected in only the Northern Hemisphere; (4) magnetosheath field lines that have interconnected in only the Southern Hemisphere; (5) magnetosheath field lines that have interconnected in both the Northern and Southern Hemispheres; (6) magnetosheath that is not magnetically connected with the terrestrial magnetic field; and (7) high-latitude plasma sheet field lines that are participating in magnetosheath reconnection.

The identification of magnetosheath field lines that have interconnected with the magnetospheric field in either the Northern or Southern Hemisphere or in both hemispheres is further evidence that new closed magnetospheric field lines are formed from high-latitude reconnection, as suggested by *Song and Russell* [1992]. The reconnection does not simultaneously occur in both hemispheres, but can occur in either hemisphere prior to the other. This situation has been observed in 630-nm emissions in the northward IMF cusp, produced by magnetosheath electron precipitation along recently reconnected field lines [*Lockwood and Moen*, 1999]. These authors deduced that the reconnection rates at the two high-latitude sites could vary, such that the order in which a given field line is reconnected in the two hemispheres would reverse. In addition, they deduced that the reconnection at high latitudes was both reconfiguring already open lobe flux (produced by a prior period of southward IMF) and generating some new open flux by merging sheath field lines with closed plasma sheet field lines.

The key measurements that allow the various regions to be differentiated are the phase space densities of the ions and electrons at velocities parallel and antiparallel to the background magnetic field. Because some plasma heating occurs at the magnetopause current layer, the location of the current layer and the locations where the spacecraft is magnetically connected to the current layer can be detected. In addition, D-shaped distributions [*Cowley*, 1982], which are characteristic of plasma that has either been transmitted across or reflected at the open magnetopause, are observed, further supporting the determination of spacecraft location relative to the different reconnection layers. These measurements and the spacecraft location derived from them support the framework within which the measured fluid and field parameters, such as the divergence of the pressure tensor and parallel electric fields and currents, can be analyzed to investigate the sources for nonideal transport in collisionless plasma and the dynamics of the magnetopause (J. D. Scudder et al., Fingerprints of collisionless reconnection at the separator: Ambipolar Hall signatures, submitted to *Journal of Geophysical Research*, 2001).

2. Topological Regions Associated With High-Latitude Reconnection

The different topological regions that result from high-latitude reconnection are illustrated in Plate 1a. All of the numbered regions were detected as Polar moved through the high-latitude cusp, magnetopause, plasma sheet, and lobe. These regions are all characterized by distinctive signatures in the electron and ion distribution functions, as described in detail below.

These different regions form through reconnection occurring at high latitudes in both the Northern and Southern Hemispheres. The diagram is drawn from the perspective of reconnection occurring first in the Northern Hemisphere and then in the Southern Hemisphere, but as shown below, reconnection may occur first in either hemisphere. In both cases, the topological evolution of the field lines is determined by two different and vastly separated reconnection sites.

The following regions have been identified: (1) the lobe (region 0) and high-latitude plasma sheet (region 1) that are convecting toward the reconnection site; (2) magnetosheath field lines that are disconnected from the magnetospheric field (region 1'); (3) the magnetosheath boundary layer (MSBL), located outside the magnetopause current on magnetosheath fields lines that have interconnected with the magnetospheric field in either the Northern or Southern Hemisphere (region 2'); (4) a layer of new closed boundary layer field lines outside the magnetopause current that forms due to reconnection of the magnetosheath field on the high-latitude magnetopause in both the Northern and Southern Hemispheres (region 3'); (5) the high-latitude cusp, located inside the magnetopause current on field lines that have interconnected with the magnetosheath field (regions 2 and 3); and (6) closed dayside magnetospheric field lines consisting of ring current and dayside plasma sheet plasma (region 4). Note that region 3 has been drawn both inside and outside the magnetopause. Although part of the region 3 field lines will initially be located outside the magnetopause (region 3'), eventually the field and plasma will evolve to lie within the magnetopause as new closed flux continues to be added to the outer magnetosphere [e.g., *Song and Russell*, 1992].

For the illustration shown in Plate 1a, reconnection first occurs in the Northern Hemisphere between magnetospheric (region 1) and magnetosheath (region 1') field lines. Equatorward of the reconnection site and within the magnetopause, the cusp (region 2) forms as the magnetosheath plasma enters across the magnetopause (dashed line) and as the magnetospheric plasma escapes. Outside the magnetopause current layer, the MSBL forms (region 2') as plasma that either was reflected at the magnetopause or has escaped across it from within the magnetosphere streams away from the magnetopause toward the magnetosheath.

Tailward of the reconnection site, analogous boundary layer regions also form inside and outside the magnetopause. The plasma in these boundary layers will be quite different, however, from the boundary layers equatorward of the reconnection site due to the properties of the magnetosheath at high latitudes. In particular, the high-latitude magnetosheath flow is directed primarily downtail. Whereas this bulk flow carries the plasma toward the magnetopause on field lines equatorward of the reconnection site, it carries the plasma away from the magnetopause on field lines tailward of the reconnection site. Therefore relatively few particles will have access to the magnetopause from the magnetosheath to populate the boundary layers poleward of the reconnection site.

Subsequent to the initial reconnection in one hemisphere, reconnection may also occur in the other hemisphere. Outside the magnetopause current, the MSBL field lines that reconnect in the other hemisphere become new closed magnetospheric field lines (region 3'). These new closed field lines cross the magnetopause at two locations and contain a mixture of magnetosheath and magnetospheric plasma. Part of the field lines lies outside the magnetopause current (region 3') and part lies inside the magnetopause (region 3). This Southern Hemisphere reconnection may or may not involve the same magnetotail field lines that previously participated in the Northern Hemisphere reconnection. If it does involve field lines that previously reconnected in the other hemisphere, it will create field lines that thread the magnetotail and have both ends connected to the solar wind.

The particle signatures that characterize these different regions are illustrated schematically in Plate 1b, which contains an expanded view of the Northern Hemisphere reconnection site. The arrows in each of the regions are used to illustrate the magnitude of the parallel and antiparallel temperature of the electrons. In the magnetosheath (region 1') the parallel temperature is typically less than or nearly equal to the perpendicular temperature (not illustrated), and the parallel and antiparallel fluxes are relatively balanced.

Upon reconnecting in one hemisphere, the MSBL (region 2') is distinguished by a parallel-antiparallel anisotropy in the electron fluxes, usually most notable at energies of a few hundred eV. Because reconnection has not yet occurred in the Southern Hemisphere, the plasma that is continuously flowing parallel to the magnetic field from below toward the Northern Hemisphere reconnection site still has the characteristics of the magnetosheath plasma (region 1'). On the other hand, the plasma that is flowing equatorward from the reconnection site (antiparallel to the magnetic field) is coming from the magnetopause where some heating of the plasma occurs. Therefore, in the MSBL (region 2'), the antiparallel temperature is greater than the parallel temperature.

The cusp (region 2) is characterized by the entering magnetosheath plasma. The parallel electrons in the cusp are those that crossed and were heated at the open magnetopause, and the antiparallel particles are those that mirrored at low altitudes and are returning to the magnetopause, also of magnetosheath origin. The parallel and antiparallel electron fluxes in the cusp are well balanced and are comparable to the antiparallel fluxes found streaming away from the magnetopause in the MSBL (region 2').

It is important to note when describing these regions that the formation of the cusp (region 2) and the MSBL (region 2') on the recently reconnected field lines is an evolutionary process, with the plasma flowing into these regions as it convects with the magnetic field away from the reconnection site. This evolution forms the well-known energy-latitude dispersion in the cusp and the electron and ion edges in the LLBL, the cusp, and the MSBL [e.g., *Gosling et al.*, 1990]. The electrons with their high speeds will quickly spread along the recently opened field lines, whereas the ions will travel much less far along the field in a given amount of time since the field lines reconnected.

The transition from the MSBL (region 2') to the new closed field lines outside the magnetopause (region 3') is then observed through a change from unidirectionally heated electrons to bidirectionally heated electrons. From an observation point in the Northern Hemisphere, the first indication that the Southern Hemisphere reconnection has occurred is seen in the parallel electrons that are streaming up the field lines from the Southern Hemisphere magnetopause. These electrons exhibit heating similar to that observed in the antiparallel electrons in the MSBL (region 2'). On the new closed boundary layer field lines (region 3') the parallel and antiparallel electron fluxes are well balanced, and the parallel temperature is higher than the perpendicular temperature.

Within the magnetopause the cusp is divided into two topological regions, region 2, which connects magnetically to the solar wind, and region 3, which connects to the ionosphere in the other hemisphere. Because all of the magnetosheath particles in the cusp have crossed the magnetopause current layer at least once, there are no parallel-antiparallel anisotropies in the electrons, provided there has been sufficient time for the entering magnetosheath electrons to mirror at low altitudes and return to the observation location. The distinction between region 2 and region 3 when viewed from within the magnetopause is only in the number of times that the particles have crossed the magnetopause. This difference may result in the cusp plasma in region 3 being somewhat hotter than in region 2, and evidence that supports this suggestion is given below.

3. Overview of Regions Encountered on May 29, 1996

The Hydra instrument measures the three-dimensional electron and ion velocity-space distribution functions using 12 narrow field-of-view detectors spread over the unit sphere [*Scudder et al.*, 1995]. The distribution functions described here cover the energy range from 5 eV/q to 20 keV/q with a temporal resolution of 13.8 s. These 13.8-s distributions are averages of the ion and electron energy sweeps made over the entire energy range in 1.15 s. It has been assumed in the analysis that all ions are protons. The magnetic field measurements were obtained from the Polar Magnetic Fields Investigation [*Russell et al*, 1995] that measures the vector magnetic field at 8-Hz resolution.

The solar wind conditions on May 29, 1996 are shown in Figure 1. The bulk plasma measurements were obtained from the Solar Wind Experiment [*Ogilvie et al.*, 1995], and the magnetic field measurements were obtained from the Magnetic Field Investigation [*Lepping et al.*, 1995] on board the Wind spacecraft. At this time, Wind was located approximately 150 R_E upstream from Earth and within about 15 R_E of the Earth-Sun line. Note that the data have not been shifted in time to

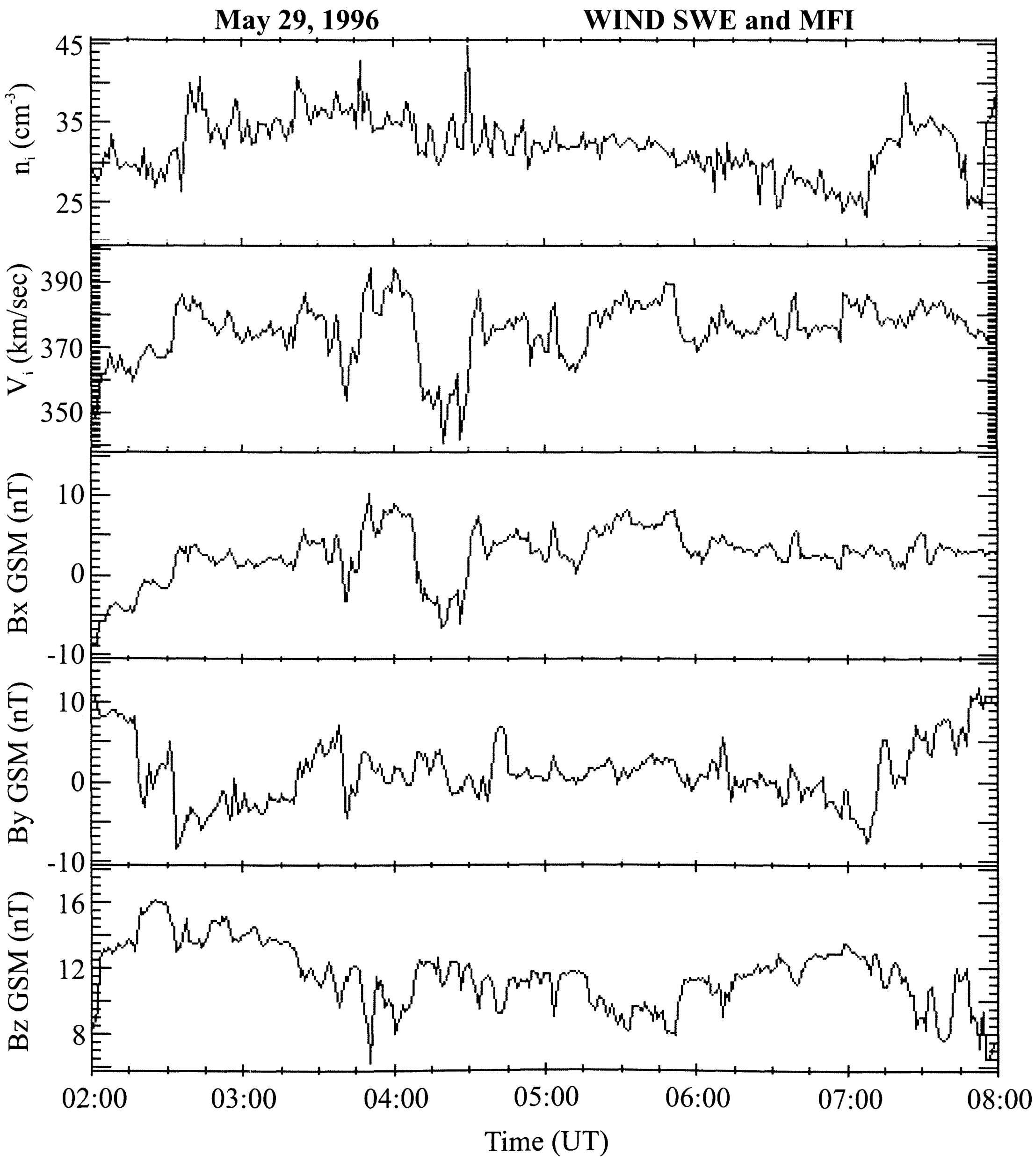

Figure 1. Solar wind density, bulk flow speed, and three components of the interplanetary magnetic field (IMF) measured by the Wind spacecraft in the solar wind upstream from Earth.

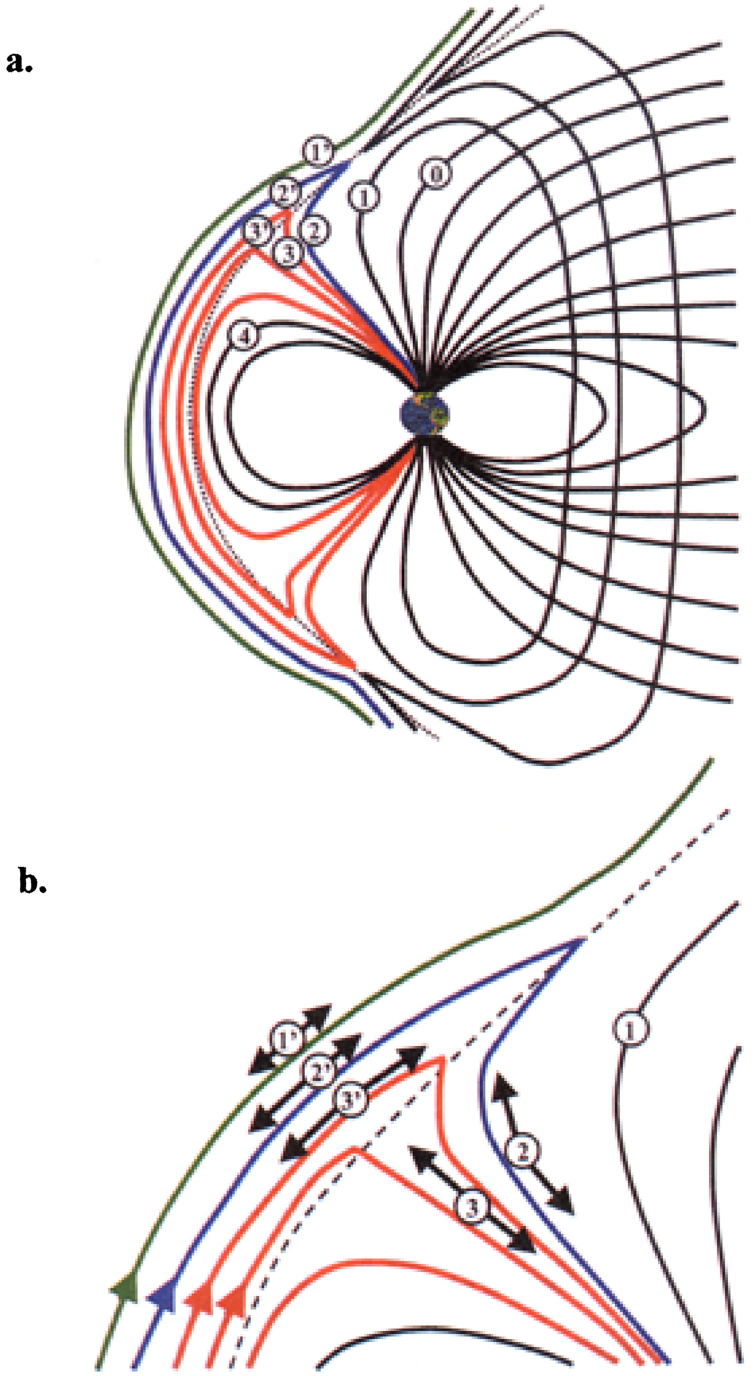

Plate 1. (a) Schematic representation of the different regions encountered by Polar on May 29, 1996: 1, the high-latitude plasma sheet (region 1) and lobe (region 0) that are convecting toward the high-latitude reconnection site; 2, magnetosheath field lines that are disconnected from the magnetospheric field (region 1'); 3, the magnetosheath boundary layer (MSBL), located outside the magnetopause current on magnetosheath fields lines that have interconnected with the magnetospheric field in either the Northern or Southern Hemisphere (region 2'); 4, a layer of new closed boundary layer field lines outside the magnetopause current that forms due to reconnection of the magnetosheath field on the high-latitude magnetopause in both the Northern and Southern Hemispheres (region 3'); 5, the high-latitude cusp, located inside the magnetopause current on field lines that have interconnected with the magnetosheath field (regions 2 and 3); and 6, closed dayside magnetospheric field lines (region 4). (b) Illustration of the parallel and antiparallel electron heating that is used to identify the different boundary layer regions shown in Plate 1a. The black arrows schematically indicate the electron temperature parallel and antiparallel to the magnetic field.

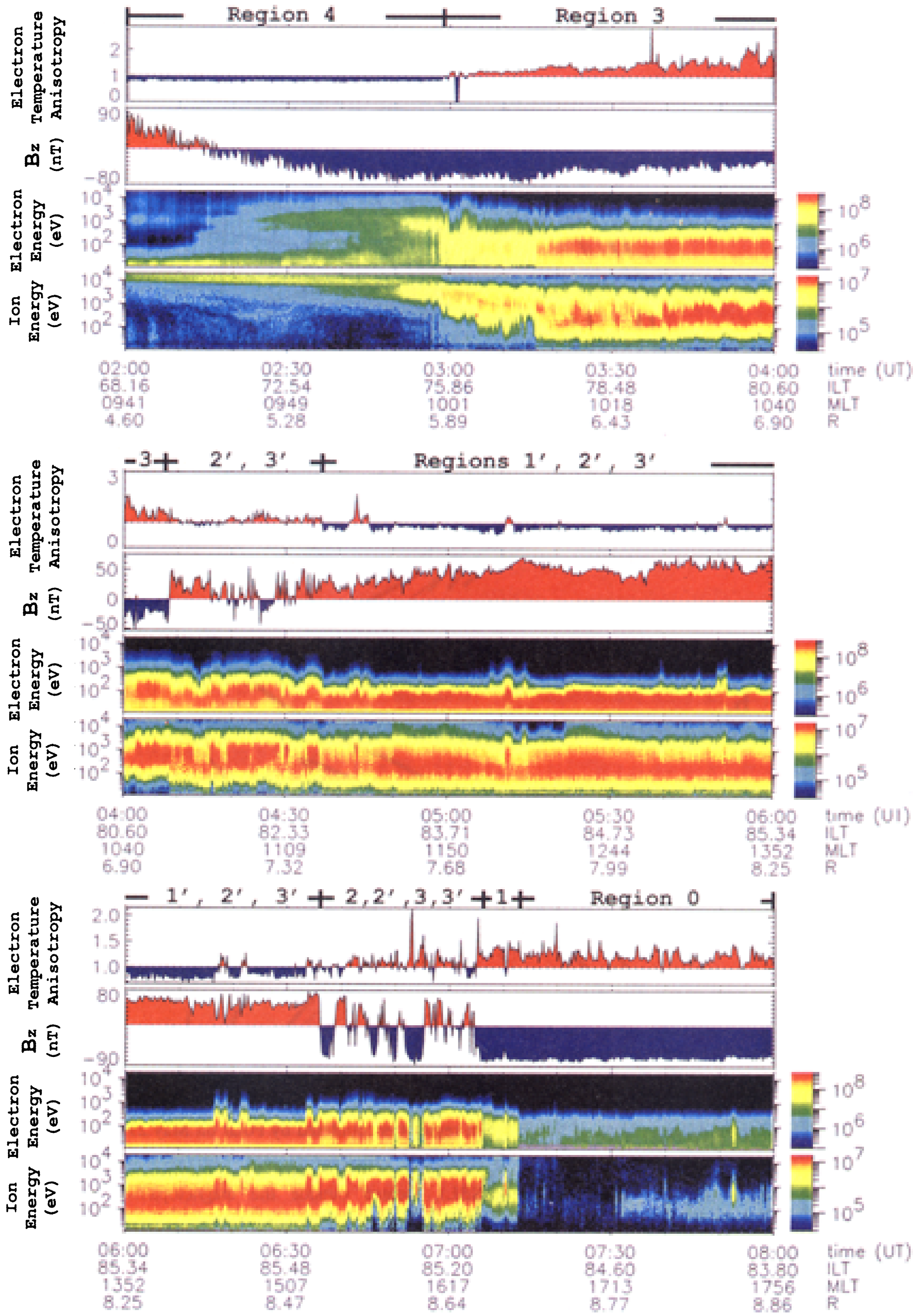

Plate 2. Three panels, each showing, from top to bottom, electron temperature anisotropy ($T_{\parallel}/T_{\perp}$); z component of the magnetic field in GSM coordinates; electron flux averaged over all angles; and ion flux averaged over all angles. Electron and ion flux is in units of cm^{-2} s^{-1} sr^{-1} ΔE^{-1} E. The approximate regions illustrated in Plate 1a are indicated above each panel. Note that these measurements of electron and ion flux are plotted in the spacecraft rest frame.

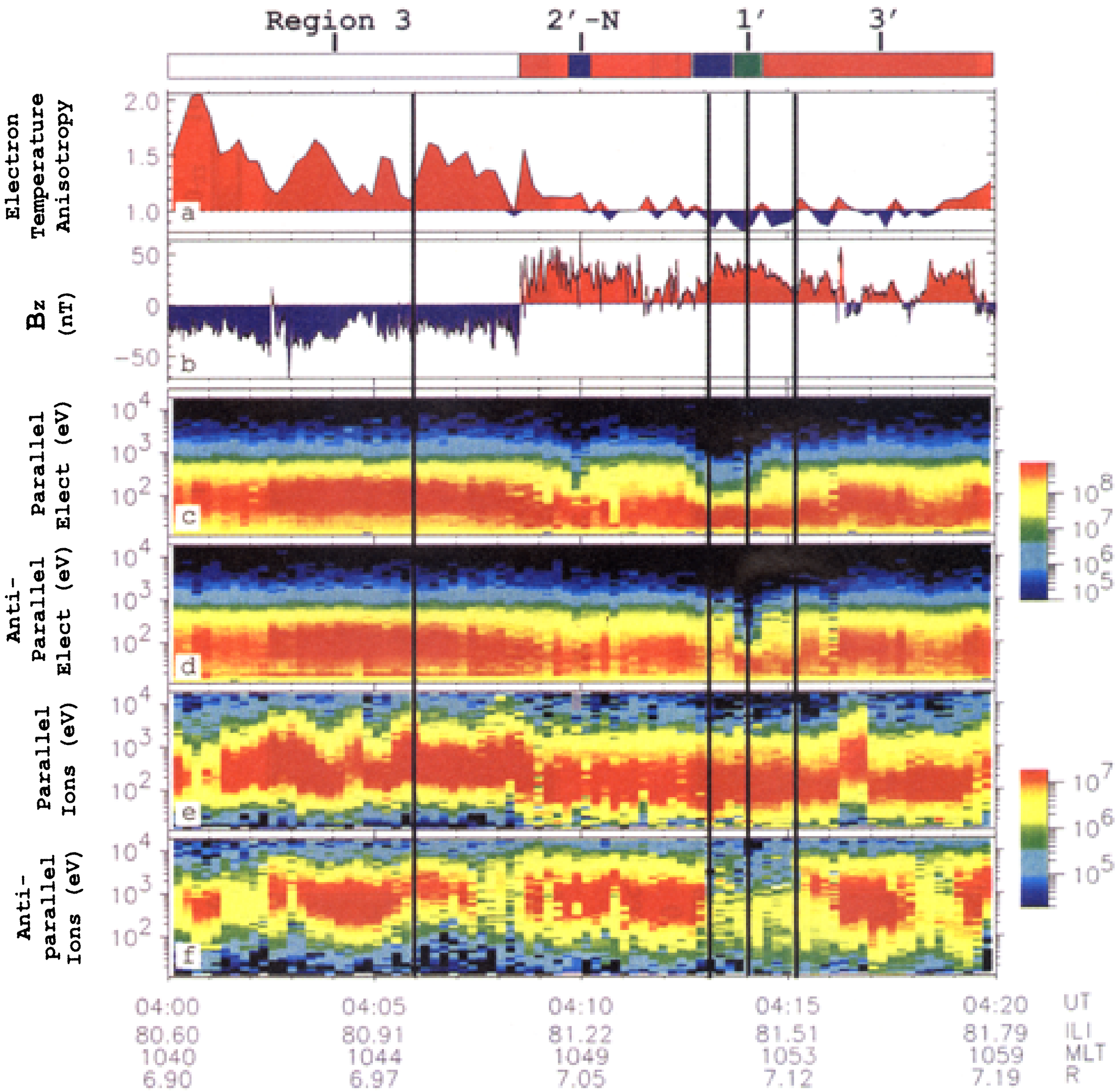

Plate 3. (a) Electron temperature anisotropy ($T_{\parallel}/T_{\perp}$); (b) z component of the magnetic field (GSM coordinates); (c) electron flux with 0°-30° pitch angles; (d) electron flux with 150°-180° pitch angles; (e) ion flux with 0°-30° pitch angles; and (f) ion flux with 150°-180° pitch angles. Electron and ion flux is in units of $cm^{-2}\ s^{-1}\ sr^{-1}\ \Delta E^{-1}\ E$. The approximate regions illustrated in Plate 1a are indicated along the top.

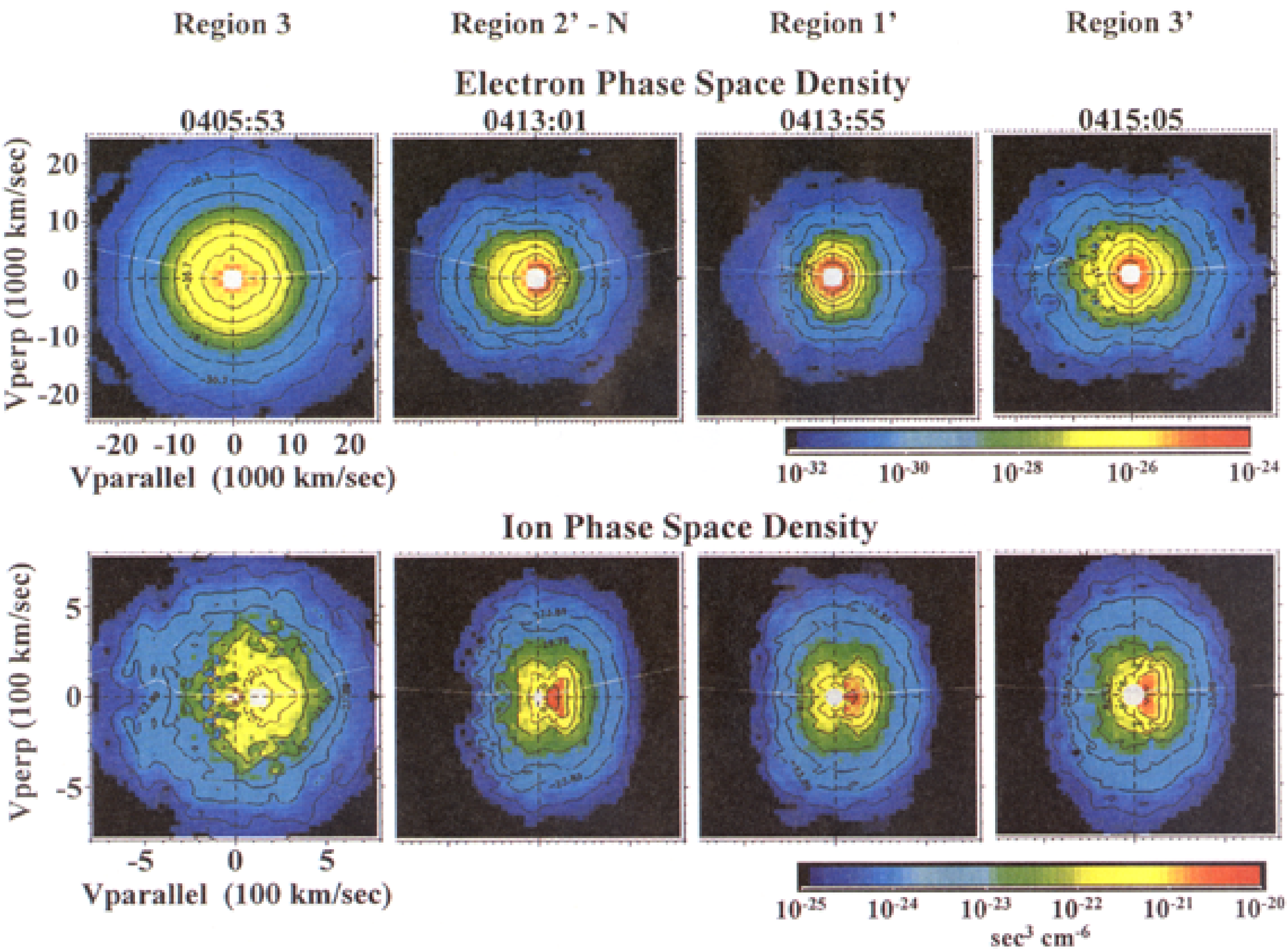

Plate 4. (top) Electron and (bottom) ion phase space density versus parallel and perpendicular speed from the times indicated with the vertical lines in Plate 3. These two-dimensional distributions are plotted in a reference frame moving with the perpendicular bulk velocity. The white lines indicate the minimum pitch angle measured for each distribution function. The gray areas at low energies indicate velocity space regions that were not sampled during the 13.8-s measurement interval.

account for the solar wind travel time from Wind to Earth. The IMF was northward for the entire period shown. Both the x and y components of the field varied considerably above and below zero. The solar wind speed was moderate, remaining below 400 km s^{-1}; however, the density was quite high. This high density was responsible for the high solar wind dynamic pressure that moved the magnetopause to inside the orbit of Polar.

An overview of the regions encountered by the Polar spacecraft on May 29, 1996, is given in Plate 2. Each panel contains, from top to bottom, (1) the electron temperature anisotropy, where values greater than one indicate $T_{\parallel} > T_{\perp}$ (red shading) and values less than one indicate $T_{\perp} > T_{\parallel}$ (blue shading); (2) the z component of the magnetic field in GSM coordinates (positive values are shaded red and negative values are shaded blue); (3) electron flux averaged over all directions; and (4) ion flux averaged over all directions. At the top of each panel, the regions illustrated in Plate 1a are indicated. Between 0200 and 0800 UT, Polar traveled from approximately 0900 MLT to 1800 MLT at invariant latitudes ranging from approximately 68 degrees at 0200 UT to about 84 degrees at 0800 UT. The radial distance of Polar ranged from about 4.6 to 8.9 R_E over this time interval.

During this dawn-dusk trajectory at high latitudes, Polar moved from the closed field lines of the dayside magnetosphere (region 4) to the cusp field lines (region 3) at approximately 0255 UT, as evidenced by the abrupt enhancement in the electron fluxes at energies below about 300 eV and the enhancement of ion fluxes at energies below about 5 keV. These fluxes consist of the dayside magnetosheath particles that entered the magnetosphere following magnetopause reconnection. In addition, the trapped magnetospheric electrons at the higher energies (>10 keV) are seen to decrease in flux on entering the cusp, due to their escape from the magnetosphere across the open magnetopause.

Throughout the entire time period from about 0255 to 0708 UT, the Hydra instrument detected dense magnetosheath-like plasma. During part of this interval, Polar was located within the magnetosphere (regions 2 and 3), i.e., inside the magnetopause, and part of this interval it was located outside the magnetopause on reconnected field lines and in the magnetosheath (regions 1', 2', and 3'). As described below, numerous crossings of the magnetopause and its boundary layers occurred during this time period. Finally, at about 0713 UT, Polar entered the high-latitude extension of the plasma sheet (region 1) and the lobe (region 0), as evidenced by the abrupt decrease in ion and electron fluxes. An important observation that can immediately be made is that the entering magnetosheath plasma was detected over a broad local time extent, from roughly 1000 to 1630 MLT. This indicates that reconnection was occurring on the high-latitude magnetopause over this broad local time range.

Motion of Polar into and out of the magnetosphere across the magnetopause can be seen by the two distinct levels of electron flux, particularly at energies above about 200 eV. The fluxes at these energies were at the higher level within the cusp until about 0437 UT, with brief dropouts beginning at about 0414 UT. The electron fluxes were predominantly at the lower level from approximately 0437 to 0640 UT, with a few brief intervals of higher fluxes indicating transient entry into the magnetopause boundary layer. As described in more detail below, these periods of relatively low electron flux at the higher energies indicate times when Polar was in the magnetosheath and magnetically disconnected from Earth's field. The higher fluxes at the high energies were observed when Polar was magnetically connected to Earth, either inside or outside the magnetopause, or was located very near the diffusion region. This signature of enhanced electrons is due to particle heating at the magnetopause and has been used in previous studies to identify the region of reconnected magnetosheath field lines that lie outside the magnetopause, i.e., the MSBL, as well as the location of the LLBL and magnetopause itself under low-shear conditions [*Onsager and Fuselier*, 1994; *Fuselier et al.*, 1995].

Another established indicator of the magnetopause location is the electron temperature anisotropy [*Paschmann et al.*, 1993]. As mentioned above, the electron distributions in the magnetosheath typically have $T_{\perp} > T_{\parallel}$ (indicated by the blue shading in the electron temperature anisotropy plots in Plate 2) or are nearly isotropic. At the magnetopause and within its boundary layers, the temperature anisotropy reverses, resulting in $T_{\parallel} > T_{\perp}$ (indicated by red shading). This change in temperature anisotropy was found to be one of the most consistent indicators of the magnetopause location under conditions of low magnetic shear [*Paschmann et al.*, 1993]. The time periods shown in Plate 2 when the high-energy electron fluxes were at low levels (approximately 0437-0640 UT) are also the times when $T_{\perp} > T_{\parallel}$, further supporting the conclusion that Polar was within the magnetosheath (region 1'), magnetically disconnected from the magnetopause, at these times. Brief encounters with the magnetopause and/or its boundary layers are seen by the reversal of the temperature anisotropy, indicating the presence of heated electrons streaming away from the magnetopause along the interconnected magnetic field.

In addition to the identification of magnetic connection to the magnetosphere provided by the electron observations, the north-south component of the magnetic field gives an indication of the location of the magnetopause current layer. The high-latitude magnetospheric field is directed southward (shaded blue in the magnetic field plots). On crossing the magnetopause current layer, the magnetic field rotates northward, consistent with the magnetosheath field orientation. As shown in more detail below, both the new closed field lines (region 3') and the MSBL (region 2'), both with $T_{\parallel} > T_{\perp}$, and the magnetically disconnected magnetosheath (region 1'), with $T_{\perp} > T_{\parallel}$, lie outside the magnetopause current layer, as inferred from the north/south orientation of the magnetic field.

The plasma moments and magnetic field over this time period are shown in Figure 2. On entering the cusp just prior to 0300 UT, the density increased and the temperature decreased, consistent with the change from magnetospheric to magnetosheath plasma. This change occurred in two stages, the first between 0300 and 0315 UT and the second following 0315 UT. It is expected that the region of new closed field lines that is being added to the magnetosphere through reconnection will increase in thickness as reconnection continues. The oldest portion of this layer will be located deeper within the magnetosphere at lower latitudes. The difference in plasma properties prior to and following 0315 UT could be the result of reconnection some time earlier, perhaps under different solar wind conditions, or could

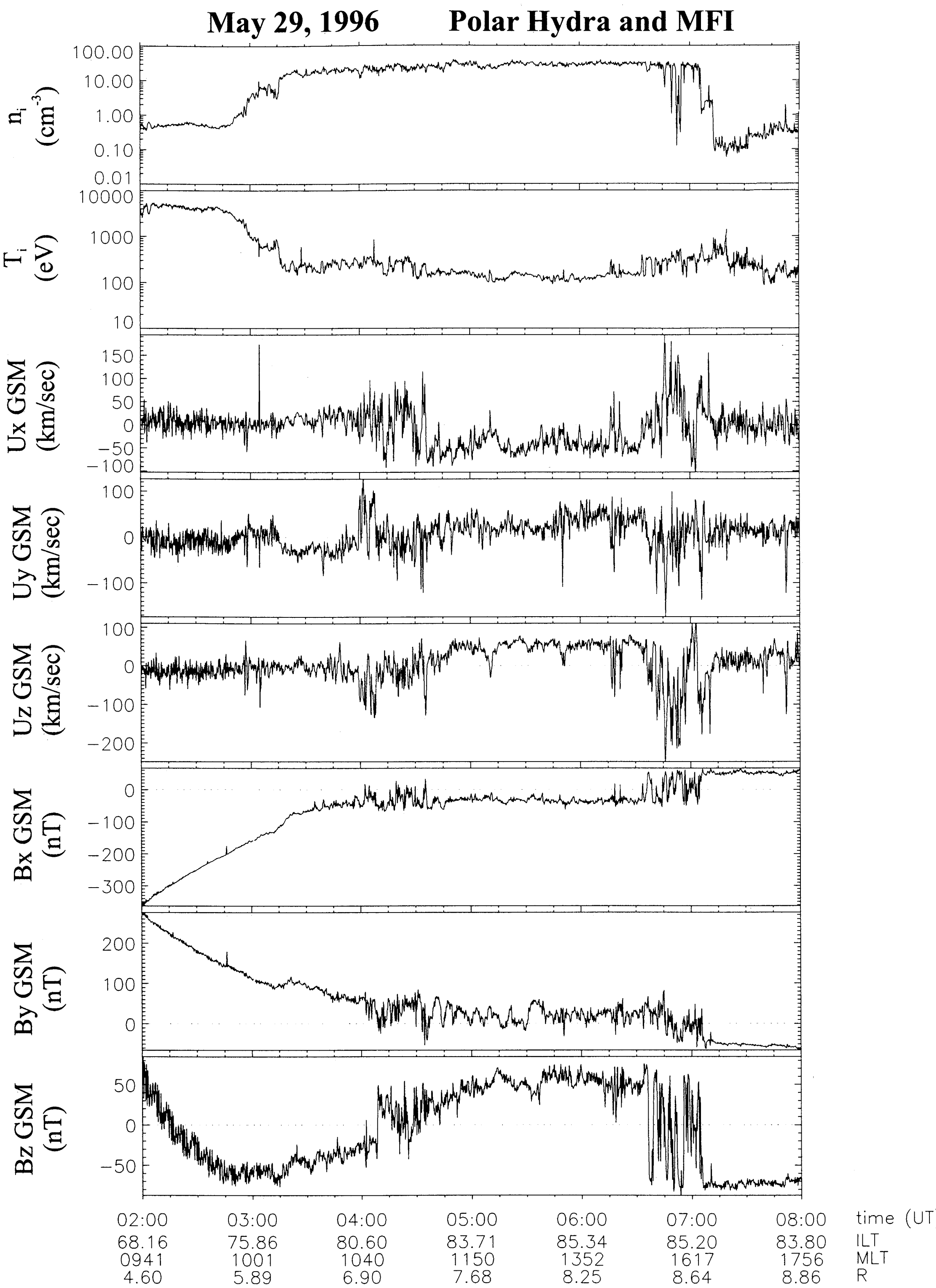

Figure 2. Density, temperature, velocity, and magnetic field as Polar moved from the inner magnetosphere, into the high-latitude cusp, across the dayside magnetopause, and then back into the high-latitude plasma sheet and lobe.

represent the long-time evolution of the closed field lines formed through reconnection.

The initial crossing of the magnetopause current sheet is seen as the abrupt change from negative to positive B_z, which occurred around 0408 UT. Multiple encounters with the current sheet are evident by the large fluctuations in the velocity and field components and continued until approximately 0437 UT. In the magnetosheath, from roughly

0437 to 0635 UT, the plasma and magnetic field were more steady but still underwent considerable fluctuations. Multiple encounters with the magnetopause current were again detected between about 0635 and 0705 UT as Polar returned to inside the magnetosphere.

4. Topological Regions Associated With High-Latitude Reconnection

An excursion across the magnetopause from the high-latitude cusp into the MSBL and magnetosheath is illustrated in Plate 3. During the 20 min shown, Polar initially was in the cusp (region 3), crossed the magnetopause onto field lines that had reconnected in both hemispheres (region 3'), moved briefly onto field lines that had reconnected in only the Northern Hemisphere (region 2'), entered the unconnected magnetosheath (region 1'), and then returned to region 3' and briefly crossed the magnetopause current layer into region 3.

Plate 3 shows the electron temperature anisotropy (Plate 3a, same format as Plate 2); the z component of the magnetic field in GSM coordinates (Plate 3b, same format as Plate 2); the flux of parallel electrons (velocities within 30 degrees of the magnetic field) (Plate 3c); the flux of antiparallel electrons (velocities within 30 degrees of antiparallel to the magnetic field) (Plate 3d); the flux of parallel ions (Plate 3e); and the flux of antiparallel ions (Plate 3f). Plate 4 contains (top) the electron and (bottom) ion two-dimensional distribution functions obtained over 13.8-s intervals at the times indicated by the vertical lines in Plate 3. The distribution functions are plotted as contours of constant phase space density as a function of velocity parallel and perpendicular to the magnetic field.

At the beginning of the time period shown, Polar was located in the high-latitude cusp. The ion distribution function from 0405:53 UT was fairly isotropic at the higher energies and at the lower energies was dominated by parallel-streaming ions, i.e., those directly entering the cusp from the magnetosheath. The electron distributions were relatively hot and isotropic. The magnetopause current layer was crossed at about 0408:30 UT, as seen by the rapid change in the magnetic field direction from negative B_z to positive B_z.

The current layer crossing can also be seen by the small decrease in energy in the parallel ion flux at this time (Plate 3e). Inside the magnetosphere on open field lines, the observed ions of magnetosheath origin are heated somewhat relative to the magnetosheath due to energization that occurs at the current layer. Outside the current layer but still on interconnected field lines (regions 2' and 3'), the parallel-streaming ions have not yet encountered the magnetopause and therefore have a temperature that is the same as that in the magnetosheath. On the other hand, antiparallel ions of sufficiently high energy to have traveled to the ionosphere and returned to the magnetopause in the time since reconnection occurred or ions that have reflected at the magnetopause will have a temperature similar to the ions inside the magnetosphere. The brief increase in parallel ion temperature seen between 0416 and 0417 UT coincides with a brief interval when Polar moved back inside the magnetopause current layer, as also indicated by the brief period of negative B_z.

During most of the interval between 0408:30 and 0420 UT, Polar was outside the magnetopause on field lines that were connected to Earth's magnetic field in both hemispheres (region 3'). This can be seen from the nearly balanced electron fluxes in the parallel and antiparallel directions. At approximately 0410 UT, Polar briefly entered region 2' and then returned to region 3'. In region 2' the electrons with parallel velocities (arriving from below the spacecraft) have notably lower fluxes than in the surrounding regions. This indicates that the parallel electrons had not yet encountered the magnetopause and therefore had magnetosheath temperatures and lower fluxes, most notable above about 200 eV. On the other hand, the antiparallel electron flux levels remain comparable to the levels in regions 3 and 3'. These are electrons that had previously crossed the open magnetopause, mirrored at low altitudes, and returned to the spacecraft from the magnetopause. This observation indicates that reconnection was occurring first in the Northern Hemisphere and then in the Southern Hemisphere. The unidirectional electron flux due to reconnection in the Northern Hemisphere is labeled region 2'-N and is indicated in blue above Plate 3.

An interesting difference between these observations and those from near-equatorial spacecraft is the detection of bidirectional electron enhancements outside the magnetopause current. Observations from the AMPTE/CCE spacecraft of the dayside magnetopause under northward IMF conditions indicated uni-directional electron heating consistent with reconnection in either the Northern or Southern Hemisphere, but bidirectional electron heating was only observed when the magnetopause current layer was encountered [*Fuselier et al.*, 1995]. Although it is not known why bidirectional electron heating was not observed outside the magnetopause in the AMPTE/CCE study, one possible reason is due to the y component of the magnetosheath magnetic field. Note that the dayside field lines in Plate 1a are drawn as projections in the noon-midnight meridian. If there is a y component in the field, the field lines that reconnect in both hemispheres could cross the equatorial plane far from noon and consequently not be detected near noon in the equatorial plane.

An excursion into the unconnected magnetosheath (region 1') occurred around 0414 UT. Polar moved from region 3' to region 2' at approximately 0413 UT, as seen from the decrease in the parallel electron fluxes, and then into region 1' at about 0413:30 UT, as seen by the decrease in the antiparallel fluxes. At about 0414:20 UT, Polar crossed quickly from region 1' to region 3', without a well-resolved interval in region 2'. In fact, there is a suggestion that the high-energy parallel electrons return slightly before the antiparallel ones. This would be consistent with a brief intersection of field lines analogous to region 2', but connected to the Southern rather than the Northern Hemisphere. This would mean that the reconnection rate in the prior interval had been greater in the Southern Hemisphere, such that the order in which the field lines were reconnected was reversed (as inferred for the cusp aurora studied by *Lockwood and Moen* [1999]). This situation is entirely possible because once back in region 3' there is no information on the order in which the two reconnections took place.

When the satellite moves into and out of region 2', the change in the antiparallel electrons is sudden. It is expected that a dispersed electron signature would be present at such a border, but it is likely that this has not been resolved at the time resolution of the instruments. On the other hand, the parallel electrons seen on the region 2-3 boundary do appear to show a persistent dispersed signature in all four cases in Plate 3. This dispersion (with high-energy electrons declining first on entry into region 2' and reappearing last on reentry to region 3') is in the opposite sense to that expected for an electron time-of-flight effect associated with the conversion of a region 2' field line into a region 3' field line by the Southern Hemisphere reconnection site. Thus it appears that this is not a time-of-flight effect but is connected with a spatial structure in the electron heating associated with reconnection.

Electron and ion distributions from regions 2', 1', and 3' from 0413:01, 0413:55, and 0415:05 UT, respectively, are shown in Plate 4. The ion distributions in all three regions show magnetosheath-like distributions, indicating that the ions at the energies measured had not had sufficient time to reach the spacecraft after either reflecting at the open magnetopause or mirroring inside the magnetosphere in the amount of time that the field line had been reconnected. These ion distributions are flowing parallel to the magnetic field with a bulk speed of about 75 km s^{-1}.

Whereas the direction of the flow, in the positive z and negative x direction, is consistent with the magnetosheath flow near noon in the high-latitude dayside magnetosheath, the speed of the flow is smaller than one would anticipate with a simple gasdynamic model. In addition, there is a notable lack of perpendicular ion flux at low energies. It is not known what causes the anomalously low flow speed or the structure in the distribution functions. One possibility is that although these measurements were made outside the reconnection layers, Polar was still very close to the magnetopause and that some processing of the magnetosheath plasma has occurred through its interaction with the magnetosphere prior to reconnection.

The electron distribution at 0413:55 UT shows the electron properties in the unconnected magnetosheath. The electrons have a fairly cold core with a perpendicular temperature that is slightly larger than the parallel temperature, and a slight enhancement at higher energies in the parallel direction. In region 2' (0413:01 UT), on field lines that are only connected to Earth's field in the Northern Hemisphere, the antiparallel flux is enhanced relative to the antiparallel magnetosheath electrons, and the parallel flux is similar to the parallel magnetosheath flux. The flux levels from the different topological regions will be compared more quantitatively below.

In region 3' (0415:05 UT), both the parallel and antiparallel electrons are enhanced relative to the magnetosheath fluxes, due to the fact that electrons traveling both parallel and antiparallel to the magnetic field have crossed the magnetopause current sheet, mirrored within the magnetosphere, and returned to the spacecraft outside the magnetopause. There is also some indication from the high-energy contours in the electron distribution at 0415:05 UT that velocity-filter effect cutoffs are limiting the access of enhanced parallel and antiparallel fluxes to electrons with speeds above some parallel and antiparallel cutoff values. This cutoff speed is lower for the antiparallel fluxes than for the parallel fluxes, indicating that the reconnection site is closer to the spacecraft in the parallel direction than in the antiparallel direction. This observation is expected, given the location of the spacecraft at high latitudes in the Northern Hemisphere.

The distinction between the ions in the cusp (region 3) and in the magnetosheath (region 1') is illustrated in Figure 3. One-dimensional cuts through the distribution functions are shown, including parallel ions (solid), antiparallel ions (dashed), perpendicular ions (dot-dashed), and the average of all look directions (dotted). In the magnetosheath (right panel) the parallel ions show a core-halo structure that is typical of ions downstream from Earth's bow shock [e.g., *Sckopke et al.*,

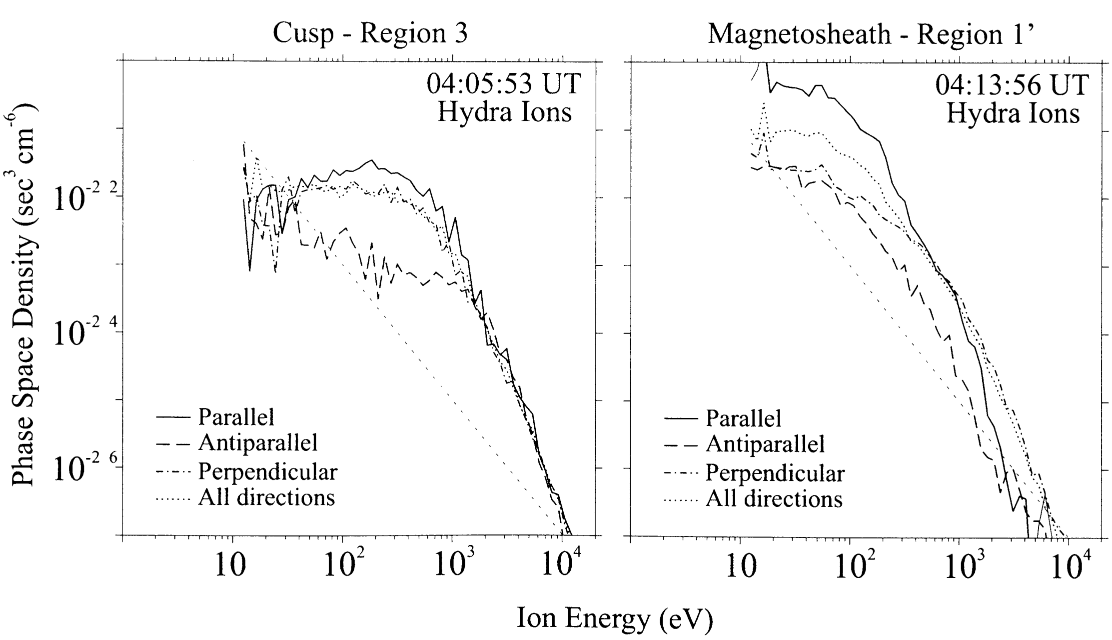

Figure 3. Cuts of the ion phase space density distribution functions from (left) the cusp and (right) the magnetosheath. The curves indicate cuts in the following directions relative to the background magnetic field: solid, parallel; dashed, antiparallel; dot-dashed, perpendicular; and dotted, averaged over all directions. Note that the cuts represent the measured phase space density in the spacecraft rest frame.

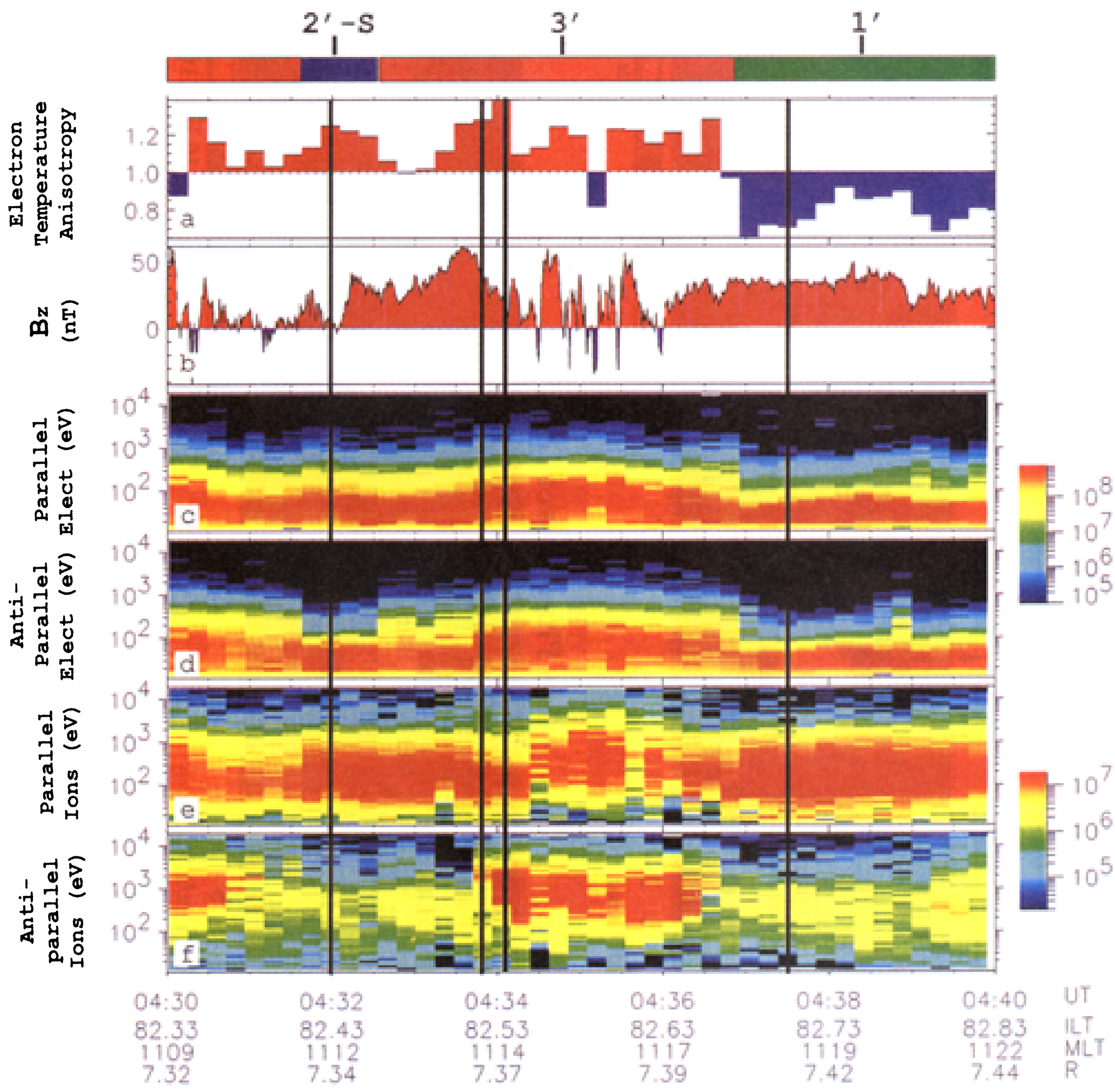

Plate 5. Crossings of the separatrices into the magnetosheath, using the same format as in Plate 3.

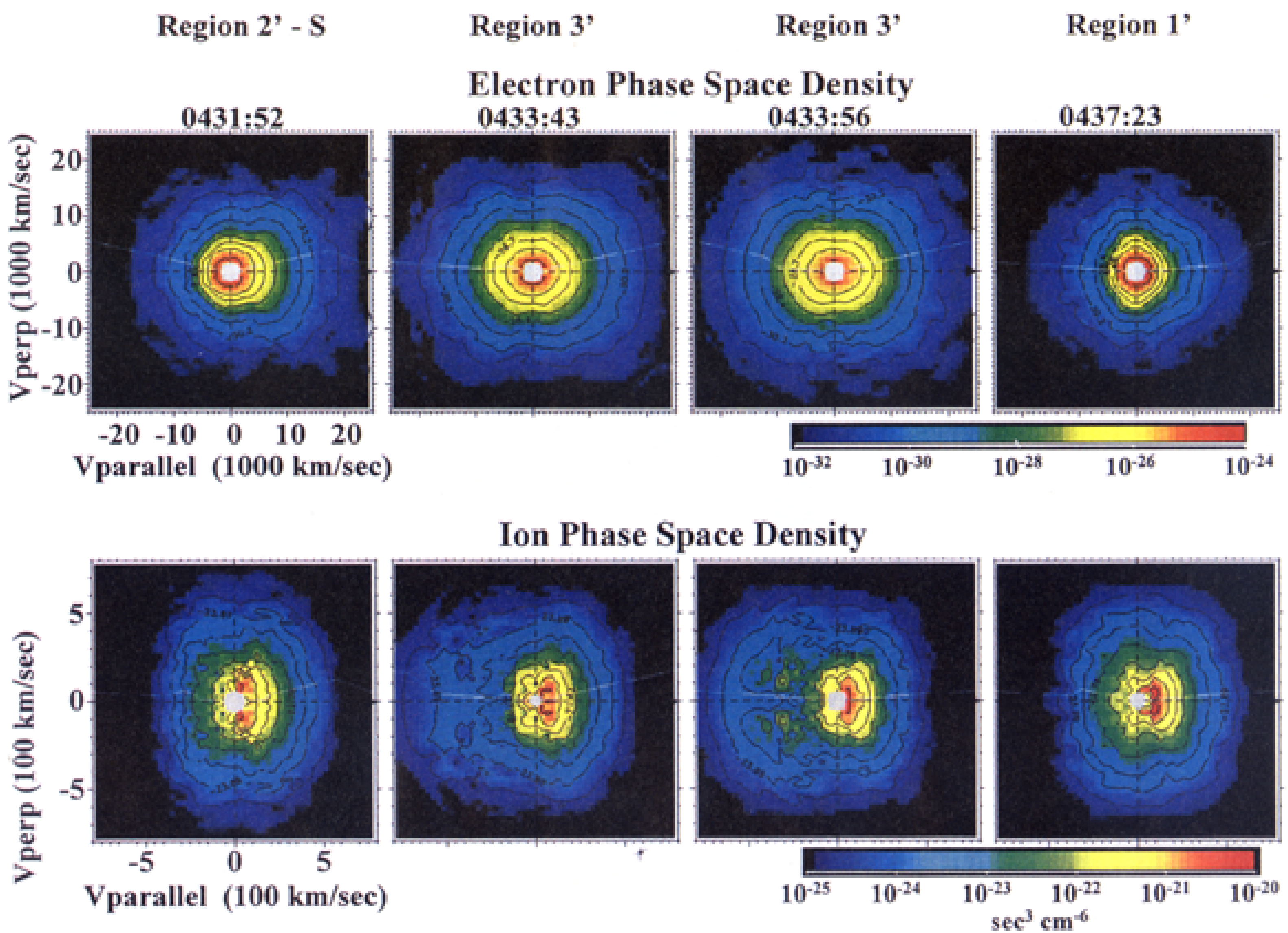

Plate 6. (top) Electron and (bottom) ion phase space density versus parallel and perpendicular speed from the times indicated with the vertical lines in Plate 5. The format is the same as Plate 4.

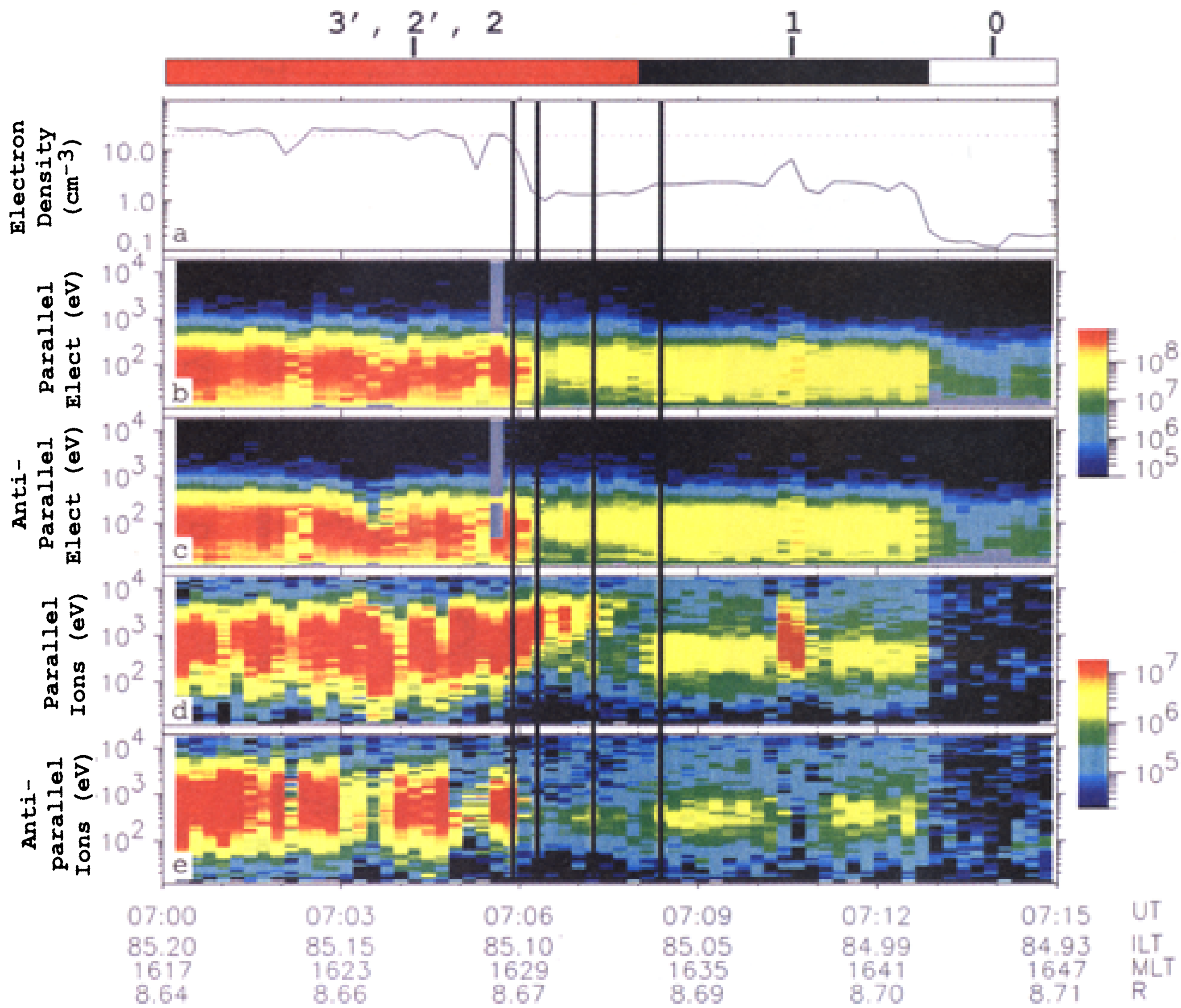

Plate 7. Electron and ion flux during the crossing of the high-latitude cusp and separatrix into the plasma sheet and lobe, using the same format as Plates 3 and 5. The electron density is shown in Plate 7a. The characteristic energy-latitude cusp dispersion is seen in the parallel ion flux (Plate 7d) between 0706 and 0708 UT.

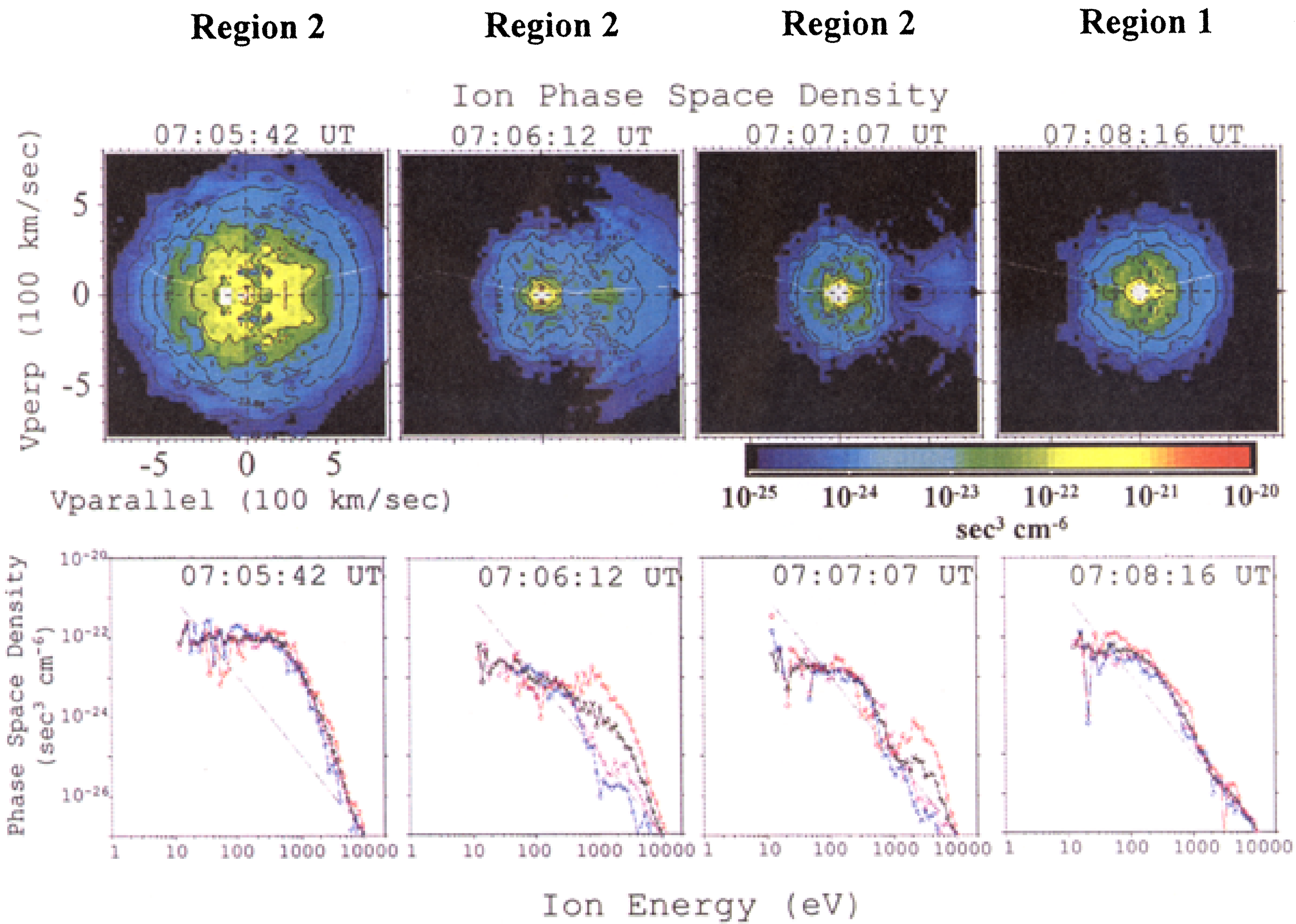

Plate 8. Ion phase space density at the time periods indicated by the vertical lines in Plate 7, using the same format as Plate 4. The curves indicate cuts in the following directions relative to the background magnetic field: red, parallel; blue, antiparallel; purple, perpendicular; and black, averaged over all directions. The ions at 0706:12 and 0707:07 UT show the typical D-shaped distribution for the entering magnetosheath ions at energies above the low-speed cutoffs. As the separatrix is approached, the low-speed cutoff is observed at progressively higher speeds.

1983]. The core component, below about 200 eV, is made up of ions that have transmitted directly across the shock. The hotter, less dense halo component consists of ions that reflected at the bow shock and then transmitted through the shock after gaining some energy through their gyromotion upstream of the shock. The ion phase space density in the antiparallel direction is lower than in the parallel direction, due to the ion bulk flow that is primarily parallel to the background magnetic field.

The ion distribution in the cusp (Figure 3, left panel) shows the parallel flux that has entered directly from the magnetosheath (solid) and the antiparallel flux that originated in the sheath, mirrored at low altitudes, and returned toward to the magnetopause (dashed). There are two important features seen in the ion distributions. First, the ions are considerably hotter in the cusp than in the magnetosheath, due to heating that occurred at the magnetopause. Second, the antiparallel ion flux matches closely the parallel flux above a cutoff energy (about 1-2 keV) and is well below the parallel flux levels below this cutoff energy. The lack of antiparallel ions below the cutoff energy is due to the velocity filter effect, whereby only ions above the cutoff energy have sufficient time to travel from the magnetopause, mirror at low altitudes, and return to the spacecraft in the time that the field lines have been open. The ions seen below the cutoff are the preexisting magnetospheric ions that have not yet escaped along the recently opened field lines [e.g., *Lockwood*, 1997b]. From their phase space densities, these appear to be plasma sheet ions (discussed in more detail below), implying that high-latitude reconnection is occurring between magnetosheath and closed magnetospheric field lines.

The Polar spacecraft also detected the MSBL (region 2') at times when reconnection had occurred first in the Southern Hemisphere, rather than first in the Northern Hemisphere as shown above. In addition, ion reflection off the open magnetopause back into the MSBL was also observed. These observations are shown in Plate 5. These data are from a 10-min period, 0430-0440 UT, and are presented in the same format as Plate 3. Aside from brief intervals where B_z was negative, Polar was located outside the magnetopause current layer throughout this interval, in regions 1', 2', and 3'. At the beginning of the time period shown, the electron measurements (high fluxes in both the parallel and antiparallel directions) and the predominantly positive B_z indicate that Polar was located in region 3', outside the magnetopause current sheet on field lines that were connected to Earth's field in both hemispheres. At roughly 0431:40 UT, the antiparallel electron flux dropped to magnetosheath-like levels, while the parallel electron flux remained at high levels. The electron and ion distributions from 0431:52 UT shown in Plate 6 indicate magnetosheath-like ions, magnetosheath-like electrons in the antiparallel direction, and enhanced electron fluxes in the parallel direction. These measurements indicate that Polar was located in a region analogous to region 2' but that reconnection had occurred in only the Southern Hemisphere.

After returning to region 3' at approximately 0432:15 UT, Polar detected accelerated ions returning back into the magnetosheath from the magnetopause. The ion distribution at 0433:43 UT (Plate 6) shows the initial detection of the accelerated, backstreaming ions. These antiparallel ions are seen only at the highest speeds, above about 500 km s^{-1}. The fact that these accelerated ions are flowing in the antiparallel direction indicates that they have come from the magnetopause poleward of the spacecraft. The next distribution obtained at 0433:56 UT is somewhat deeper in the layer of reconnected field lines, i.e., closer to the magnetopause, as evidenced by the observations of backstreaming ions down to lower velocities, of the order of about 300 km s^{-1}. As Polar approached the current layer between about 0433:40 and 0436 UT, B_z became less positive, and the intense backstreaming ions are seen down to lower velocities (for example, note the low-energy cutoff of the red flux levels in Plate 5f). Polar then detected multiple crossings of the current sheet. Beginning at about 0436 UT, Polar began moving outward relative to the magnetopause, as seen by the gradual reduction in antiparallel ions at the lower energies. At about 0437 UT, Polar had moved into the unconnected magnetosheath (region 1') and remained there for most of the remainder of the time shown.

Cuts through the ion distribution functions measured in the ion edge of the MSBL are shown in Figure 4, using the same format as Figure 3. These ion cuts are from consecutive 13.8-s distributions at 0433:43 and 0433:56 UT, from the same times as the center two distributions shown in Plate 6. The important feature to notice in these ion cuts is that the parallel flux exceeds the antiparallel flux at the lower energies, but above a cutoff energy, the antiparallel flux becomes dominant. This cutoff energy at 0433:43 UT was slightly greater than 1 keV and had dropped to about 400 eV by 0433:56 UT.

It is also important to note that the levels of phase space density for the antiparallel ions above the cutoff energy match closely the phase space density of the heated ions in the cusp (see the 0405:53 UT distribution shown in Figure 3). This suggests that the antiparallel ions are those that have been heated above the spacecraft, either at the reconnection site or in the current sheet, and are detected streaming away from the magnetopause on the open field lines. Because of this heating at the magnetopause, the backstreaming ions at the higher energies are observed to have higher phase space densities than the incident (parallel) magnetosheath ions that have not yet encountered the magnetopause.

Furthermore, since the phase space densities of these backstreaming ions match closely the magnetopause-heated ions observed in the cusp, inside the magnetopause, this suggests that the reflection coefficient for incident magnetosheath ions at the high-latitude magnetopause is roughly 50%. The decrease in the cutoff energy is interpreted as being due to a motion of the spacecraft toward the current sheet, onto field lines that have been reconnected for a longer time. Although as noted above, the field lines at this time had reconnected in both the Northern and Southern Hemispheres (as determined from the electrons), the ions from the Southern Hemisphere magnetopause apparently had not had sufficient time to travel the much longer distance to the spacecraft in the time since reconnection occurred. Therefore no information about the Southern Hemisphere reconnection or current sheet is contained in the ion measurements.

A summary of the electron properties used to identify the different boundary regions outside the magnetopause and a quantitative comparison of the flux levels in these different regions are shown in Figure 5. Each panel in the top row contains the parallel (solid curves) and the antiparallel (dashed curves) cut through the electron distribution function in the four topologically distinct regions discussed above. From left

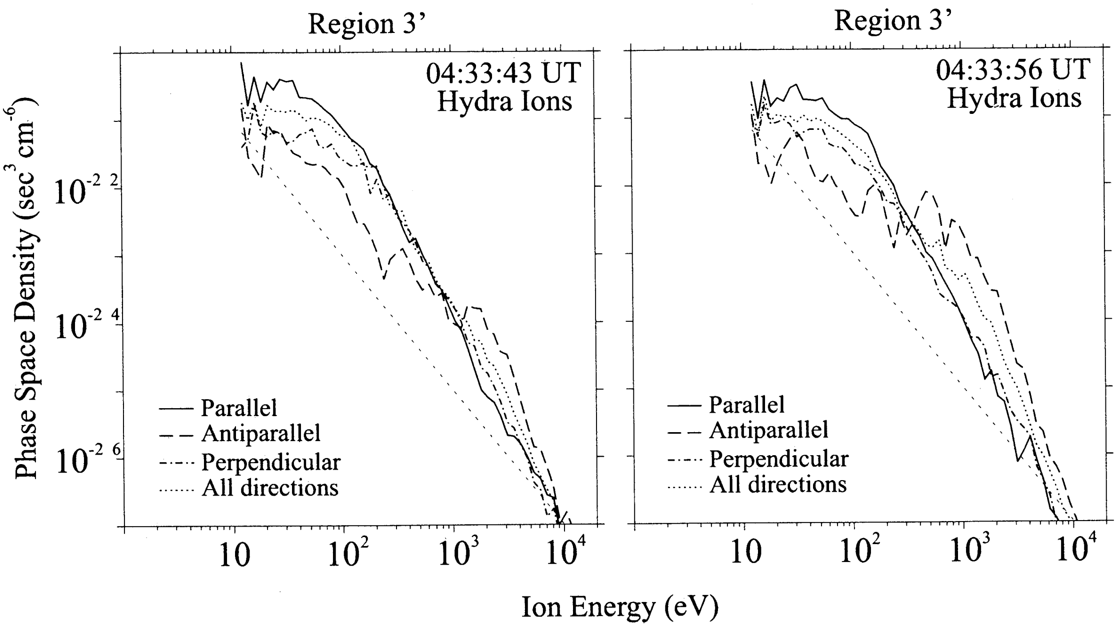

Figure 4. Cuts through the ion phase space density distribution functions at different locations in the ion edge of region 3', using the same format as Figure 3.

to right, the panels contain (1) magnetosheath electrons (1') in a region magnetically disconnected from Earth's field; (2) MSBL electrons (2'-S) where reconnection has occurred in the Southern Hemisphere but not in the Northern Hemisphere; (3) MSBL electrons (2'-N) where reconnection has occurred in the Northern Hemisphere but not in the Southern Hemisphere; and (4) MSBL electrons (3') where reconnection has occurred in both hemispheres. Note that all of these measurements were

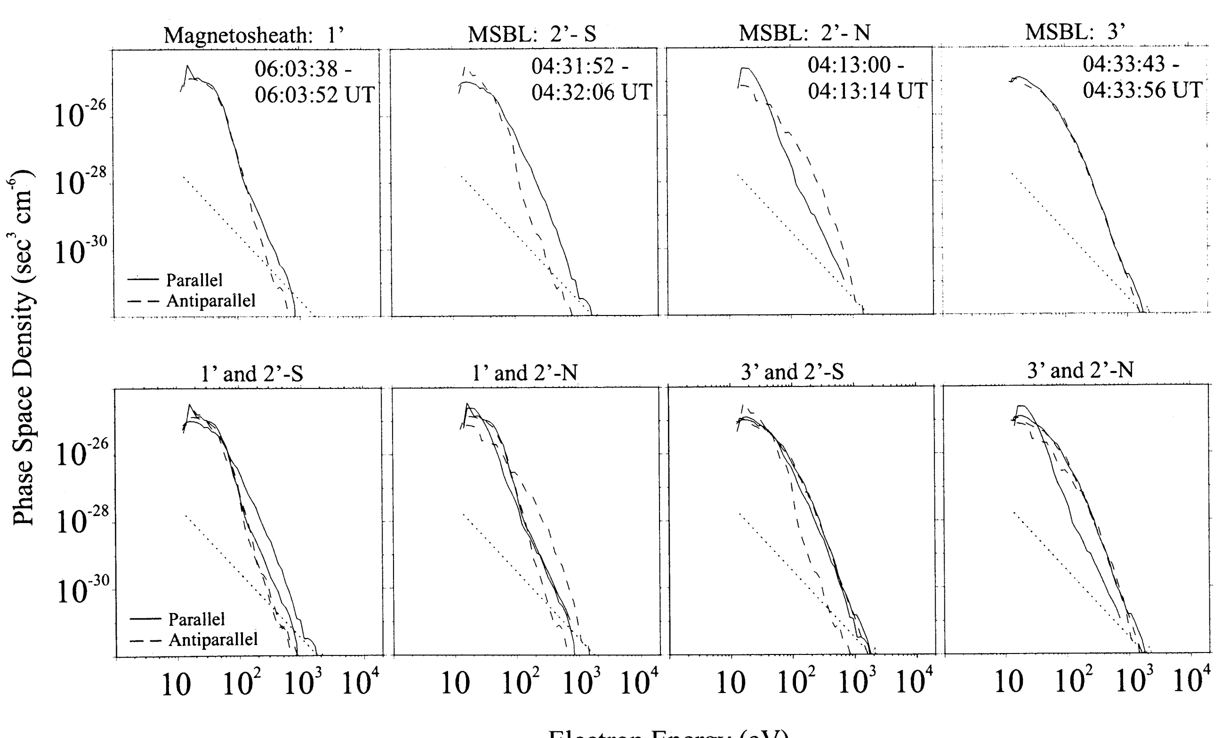

Figure 5. (top) Cuts of electron phase space density parallel (solid curves) and antiparallel (dashed curves) to the background magnetic field in four regions: (left to right) the magnetosheath magnetically disconnected from Earth (1'); the MSBL magnetically connected to Earth's field in only the southern hemisphere (2'-S); the MSBL magnetically connected in only the northern hemisphere (2'-N); and the MSBL connected in both hemispheres (3'). (bottom) Overlays of the cuts from the different regions illustrating the consistency in the enhanced flux levels due to reconnection in either hemisphere.

obtained outside the magnetopause current layer, i.e., where the magnetic field has a northward component.

The primary feature that distinguishes between the different regions is the enhancement of electron flux in either the parallel, antiparallel, or both directions. The electron flux in the magnetosheath is nearly isotropic, with the parallel flux slightly higher than the antiparallel flux. The region connected in only the Southern Hemisphere (2'-S) is identified by the flux enhancement above about 50 eV in the parallel direction relative to the antiparallel direction. The region connected in only the Northern Hemisphere (2'-N) is identified by the flux enhancement in the antiparallel direction relative to the parallel direction. The isotropic electrons enhanced relative to the magnetosheath in both the parallel and the antiparallel directions indicate that reconnection has occurred both above and below the spacecraft (3').

The bottom row in Figure 5 contains overlays of the cuts in the top row to illustrate the similarities and differences in the flux levels in the different regions. The overlay of the electron distributions from regions 1' and 2'-S shows that the antiparallel fluxes are nearly identical, while the parallel fluxes in 2'-S are enhanced. Similarly in region 2'-N, the parallel fluxes are nearly identical to those in region 1' while the antiparallel fluxes are enhanced. The fact that the flux in either the parallel (in 2'-N) or antiparallel (in 2'-S) direction remains nearly identical to that in the magnetosheath demonstrates that the magnetic field in one direction remains disconnected from Earth's field in that region.

The right two panels in the bottom row show comparisons of regions 2'-S and 2'-N with region 3', where the magnetic field is connected in both hemispheres. It is seen that connection in either hemisphere results in enhanced flux levels that match nearly identically to those in region 3' where the fluxes are isotropic and enhanced in both the parallel and the antiparallel directions relative to the magnetosheath.

5. Transition Across the Internal Separatrix to the Plasma Sheet and Lobe

Polar reentered the magnetosphere after roughly 0635 UT and moved from the cusp (region 2) across the separatrix within the magnetosphere into the plasma sheet (region 1) and lobe (region 0) around 0708 UT. This transition across the internal separatrix associated with high-latitude reconnection is shown in Plate 7. The exit of Polar across the most recently reconnected field lines can be seen most clearly in the parallel ion spectra (Plate 7d) between about 0706 and 0708 UT. Prior to 0706 UT, parallel ions are seen over a broad energy range, extending from tens of eV up to nearly 10 keV. After 0706 UT as the separatrix is approached, the flux becomes absent at the lower energies while flux at the highest energies remains. These cusp ions exhibit the typical energy-latitude dispersion caused by the evolution of the plasma on recently reconnected field lines. This energy-latitude dispersion has the properties expected for high-latitude reconnection occurring poleward of the spacecraft [e.g., *Burch et al.*, 1980; *Woch and Lundin*, 1992; *Matsuoka et al.*, 1996]. That is, the most recently reconnected field lines are observed at the highest latitudes, where only entering magnetosheath ions with the highest parallel speeds have access to the spacecraft before being convected equatorward of the spacecraft. On progressively older reconnected field lines (observed earlier than 0708 UT) the entering plasma has a longer time to reach the spacecraft from the magnetopause and therefore is observed down to lower energies.

An important difference between the high-latitude reconnection shown in Plate 7 and the typical situation envisioned under northward IMF conditions is that the plasma sheet or a closed boundary layer region, rather than the lobe, appears to be reconnecting with the magnetosheath. Just inside the separatrix (after 0708 UT extending to about 0713 UT) the plasma density was intermediate to that in the cusp and in the lobe (after 0713 UT). The electron density measurement (Plate 7a) indicates that the density was approximately 20 cm^{-3} in the cusp (region 2), approximately 0.2 cm^{-3} in the lobe (region 0), and approximately 2 cm^{-3} in the region identified as plasma sheet (region 1). It is typically assumed that high-latitude reconnection occurs between the open lobe and the magnetosheath. This separatrix crossing shown in Plate 7 indicates that at times the high-latitude plasma sheet may also participate in dayside magnetopause reconnection. The ion temperature at this time was approximately 300 eV. The ion density and temperature in this plasma sheet-like region are consistent with the cold, dense plasma sheet observations that have been shown to occur during northward IMF conditions [*Fujimoto et al.*, 1998]. In the case shown here, the plasma sheet was observed at about 1630 MLT and 85 degrees invariant latitude, which could result from a contracted polar cap under prolonged northward IMF conditions.

Ion phase space distributions during this crossing of the high-latitude cusp boundary are shown in Plate 8. The ion distribution at 0705:42 UT is nearly isotropic down to low parallel speeds, suggesting that Polar either was close to the diffusion region or near the magnetopause current at this time. Another possibility is that Polar was on field lines that had been open for a sufficiently long time such that even the lower-energy ions were able to mirror at low altitudes and return to the spacecraft. However, given the close proximity of Polar to the separatrix at this time, it is unlikely that it was on field lines that had been open for a long time period. Slightly later in time, at 0706:12 UT, the ion distributions indicated a low-density background population (near the detection threshold of the instrument) and a characteristic D-shaped distribution of entering magnetosheath ions. The low-speed cutoff of the D-shaped component increased as the separatrix was approached, consistent with the velocity-filter effect as Polar moved onto more recently reconnected field lines. Finally, on crossing the separatrix, Polar detected ion distributions more typical of the closed plasma sheet or boundary layer regions, rather than the lobe.

A quantitative comparison of the electron flux in the magnetosheath (1'), MSBL (3'), cusp (2 or 3), and plasma sheet (1) is shown in Figure 6. The magnetosheath region is magnetically disconnected from Earth's field, while the MSBL (3') and the plasma sheet are entirely on closed field lines. The cusp may be either on open field lines (2) or on closed field lines (3). The analysis presented in this paper is not able to distinguish directly the open from the closed cusp, since observations made inside the magnetopause show isotropic, heated electrons regardless of the topology of the field line outside the magnetopause. However, since magnetic connection in both hemispheres is clearly observed outside the magnetopause (region 3'), the cusp must have a portion on closed field lines as well as a portion on open field lines.

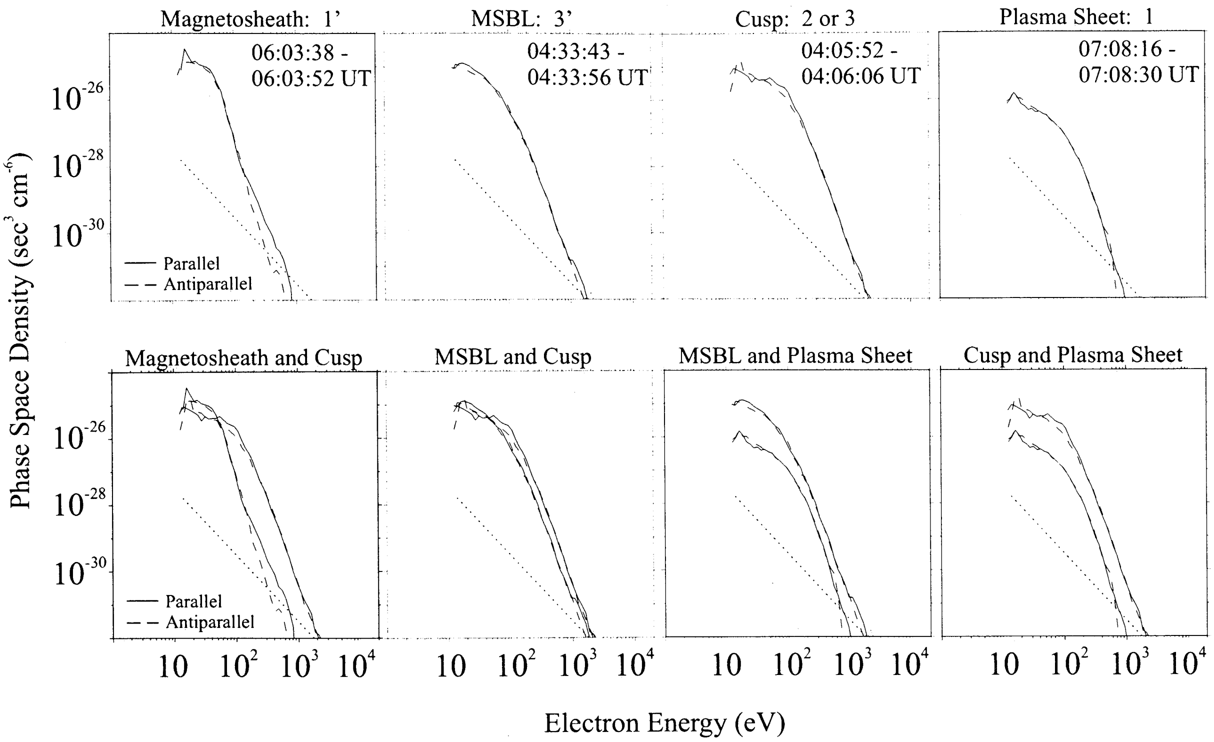

Figure 6. (top) Cuts of electron phase space density parallel (solid curves) and antiparallel (dashed curves) to the background magnetic field in four regions: (left to right) the magnetosheath; the MSBL magnetically connected in both hemispheres (3'); the cusp (2 or 3); and the high-latitude plasma sheet or boundary layer. (bottom) Overlays of the cuts from the different regions.

The comparison of the electron flux in the MSBL (3') and in the cusp (2 or 3) in the bottom row of Figure 6 indicates that the cusp electrons have somewhat higher fluxes at the higher energies and lower fluxes at the lower energies. This difference is perhaps due to the evolution of the cusp plasma on closed field lines and may result from the multiple encounters with the magnetopause current sheet following reconnection in both hemispheres. Finally, the plasma sheet electrons are found to have fluxes below those in the MSBL and in the cusp at all energies. If this plasma sheet population represents the long-term evolution of the closed field lines formed through northward IMF reconnection, these observations indicate that a slight loss of plasma occurs over time, with little change in temperature.

6. Summary and Discussion

The observations presented in this paper have been used to illustrate the electron and ion signatures of magnetopause reconnection during prolonged northward IMF conditions. We have used the electron and ion measurements together with the magnetic field to identify the various boundary layers that form through reconnection. The main conclusions reached are that on May 29, 1996, reconnection was occurring at high latitudes, poleward of the cusp, in both the Northern and Southern Hemispheres. It has been shown that the two reconnections were not simultaneous but occurred first in one hemisphere and then in the other. We have also shown that reconnection can occur first in either hemisphere.

Polar observed a clear nesting of the reconnection layer signatures. Inside the magnetopause current layer, the electrons and ions had typical cusp characteristics, consistent with direct magnetosheath entry on open field lines with some heating at the magnetopause. The cusp ions with velocities parallel to the magnetic field (those directly entering from the nearby magnetopause) were observed down to low velocities, a few tens of eV, where the flux merged with the background detection level of the instrument. On the other hand, the antiparallel ions had a clear low-speed cutoff. Above this cutoff velocity the phase space density matched closely the simultaneously observed parallel phase space density, as these were ions that had entered across the magnetopause, mirrored at low altitudes, and were detected as they returned toward the magnetopause with little change in flux. Below the cutoff velocity the flux of antiparallel ions was considerably lower than the parallel flux, as ions at these lower velocities did not have access to the spacecraft from the magnetopause on these recently open field lines due to their slower speeds.

On crossing the magnetopause current sheet, the ions were observed to have lower temperatures, consistent with being outside the current sheet where the heating occurs. On the other hand, the electron distributions continued to show heating for both parallel and antiparallel velocities relative to the magnetosheath distributions. This indicates that although Polar was located outside the current layer, it was on field lines that crossed the magnetopause in both the parallel and antiparallel magnetic field directions. This is the signature of newly formed closed boundary layer field lines [e.g., *Song and Russell*, 1992]. Farther sunward of the magnetopause, a dropout in the electron flux in either the parallel or antiparallel direction was observed, while the flux in the other direction remained unchanged. This region with a unidirectional flux of heated electrons consists of field lines that are connected to Earth's magnetic field in only one direction, either below (for unidirectional parallel flux) or above (for unidirectional antiparallel flux) the spacecraft. An example was shown where this initial reconnection occurred first above Polar (in the high-latitude Northern Hemisphere), and an example was shown where it occurred first below Polar (in the high-latitude Southern Hemisphere). Finally, Polar moved farther sunward relative to the magnetopause into the region of magnetosheath that was magnetically disconnected from Earth's field, as identified by the lack of enhanced electron flux in either the parallel or antiparallel direction and the change of temperature anisotropy from $T_{\|} > T_{\perp}$ to $T_{\perp} > T_{\|}$.

Another important observation shown here is that Polar observed open field lines in the high-latitude magnetosphere over a broad local time range, from about 1000 to 1630 MLT. This observation indicates that reconnection was occurring over a large local time extent on the high-latitude magnetopause. Although the footprint of the cusp precipitation probably mapped to a fairly small polar cap area in the ionosphere, the open field line source region on the magnetopause was quite extensive.

After its final crossing of the magnetopause back into the magnetosphere, Polar crossed the internal separatrix from the cusp into the plasma sheet and lobe at high latitudes. This crossing of the separatrix within the magnetosphere exhibited the velocity-space dispersion of the magnetosheath ions entering the cusp on the most recently reconnected field lines. The typical D-shaped distributions were clearly observed as the separatrix was approached. One surprising result is that the high-latitude magnetospheric plasma participating in reconnection appeared to be of plasma sheet origin, rather than of lobe origin. At the time of this separatrix crossing, Polar was located at about 85 degrees invariant latitude and 1630 MLT. At this location, it is possible that the high-latitude reconnection had eroded the flank lobes and that the closed plasma sheet or boundary layer field lines were then present at the high-latitude magnetopause.

A number of recent papers have investigated the cusp/magnetopause observations made by Polar on May 29, 1996 [*Savin et al.*, 1998; *Russell et al.*, 1998; *Urquhart et al.*, 1998; *Chandler et al.*, 1999]. Three of these studies concentrated primarily on the magnetic field observations and concluded that high-latitude reconnection was occurring [*Savin et al.*, 1998; *Russell et al.*, 1998; *Urquhart et al.*, 1998]. The study by *Chandler et al.* [1999] provides observations of the ion distribution functions and arrived at quite different conclusions than found in this paper.

The key conclusion made by *Chandler et al.* [1999] is that Polar observed evidence for reconnection equatorward of the cusp over an extended time period from about 0420 to 0645 UT. This is roughly the time period over which the analysis presented in this paper suggests that Polar actually moved sunward of the magnetopause boundary layers and entered the unconnected magnetosheath. Our conclusion that Polar moved fully into the magnetosheath is based largely on the electron observations, which were not included in any of the other papers that investigated this time period. On the other hand, the *Chandler et al.* [1999] observations indicate that the ion bulk flow speed remained quite low during this time period (~60 km s^{-1}), which is much lower than that expected for the high-latitude magnetosheath based on a gasdynamic estimate. Furthermore, a low-energy ion population was observed that was attributed to an ionospheric source, and the proton distributions often showed a D-shaped distribution which could be consistent with being located inside the magnetopause on a field line that had reconnected equatorward of Polar. Some of the observations of enhanced low-energy populations were from times when the analysis in this paper concludes that Polar was located in the magnetosheath.

One possible way to reconcile the *Chandler et al.* [1999] results with those of this paper is that even though Polar spent a considerable amount of time in the unconnected magnetosheath, it was always within a layer where the sheath flow was modified as it approached the magnetopause. It is unclear how this modification takes place, but it perhaps could account for the slow bulk flow speed and the structure seen in the ion distribution function such as the D-shaped distributions and the cold ion population detected by *Chandler et al.* [1999]. The close proximity of Polar to the magnetopause could account for the low-energy ion population as being of magnetosphere/ionosphere origin and having access to Polar by their large ion gyroradii.

Recently, analyses of Polar data on other high-latitude cusp/magnetopause crossings under northward IMF conditions have been interpreted both as evidence for low-latitude reconnection (equatorward of the cusp) [*Fuselier et al.*, 2000] and as evidence for high-latitude reconnection (poleward of the cusp) [*Russell et al.*, 2000]. The results of this paper demonstrate that reconnection was occurring poleward of the cusp on May 29, 1996, although outstanding questions do remain regarding the ion properties in the magnetosheath.

In summary, through a prolonged encounter of the magnetopause by the Polar spacecraft, it has been possible to identify the electron and ion layers associated with high-latitude reconnection under northward IMF conditions. Closed boundary layer field lines were identified that had been formed through reconnection occurring in both the Northern and Southern Hemispheres. It has been shown that reconnection in the two hemispheres does not occur simultaneously and can occur first in either hemisphere. Also, under northward IMF conditions, reconnection is observed to occur over a broad local time extent. On the bases of results shown here, it appears that the magnetosheath in the high-latitude cusp region undergoes considerable preprocessing prior to reconnection occurring. The actual mechanisms responsible for this preprocessing are topics for future research.

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References

Burch, J. L., P. H. Reiff, R. A. Heelis, R. W. Spiro, and S. A. Fields, Cusp region particle precipitation and ion convection for northward interplanetary magnetic field, *Geophys. Res. Lett.*, *7*, 393, 1980.

Chandler, M. O., S. A. Fuselier, M. Lockwood, and T. E. Moore,

Evidence of component merging equatorward of the cusp, *J. Geophys. Res., 104*, 22,623, 1999.
Cowley, S. W. H., Magnetospheric asymmetries associated with the y-component of the IMF, *Planet. Space Sci., 29*, 79, 1981.
Cowley, S. W. H., The causes of convection in the Earth's magnetosphere: A review of developments during the IMS, *Rev. Geophys., 20*, 531, 1982.
Crooker, N. U., Dayside merging and cusp geometry, *J. Geophys. Res., 84*, 951, 1979.
Fujimoto, M., T. Terasawa, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun, Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations, *J. Geophys. Res., 103*, 4391, 1998.
Fuselier, S. A., B. J. Anderson, and T. G. Onsager, Particle signature of magnetic topology at the magnetopause: AMPTE/CCE observations, *J. Geophys. Res., 100*, 11,805, 1995.
Fuselier, S. A., K. J. Trattner, and S. M. Petrinec, Cusp observations of high- and low-latitude reconnection for northward IMF, *J. Geophys. Res., 105*, 253, 2000.
Gosling, J. T., M. F. Thomsen, S. J. Bame, R. C. Elphic, and C. T. Russell, Plasma flow reversals at the dayside magnetopause and the origin of asymmetric polar cap convection, *J. Geophys. Res., 95*, 8073, 1990.
Gosling, J. T., M. F. Thomsen, S. J. Bame, R. C. Elphic, and C. T. Russell, Observations of reconnection of interplanetary and lobe magnetic field lines at the high-latitude magnetopause, *J. Geophys. Res., 96*, 14,097, 1991.
Kessel, R. L., S.-H. Chen, J. L. Green, S. F. Fung, S. A. Boardsen, L. C. Tan, T. E. Eastman, J. D. Craven, and L. A. Frank, Evidence of high-latitude reconnection during northward IMF: Hawkeye observations, *Geophys. Res. Lett., 23*, 583, 1996.
Le, G., and C. T. Russell, ISEE observations of low-latitude boundary layer for northward interplanetary magnetic field: Implications for cusp reconnection, *J. Geophys. Res., 101*, 27,239, 1996.
Lepping, R. P., et al., The Wind magnetic field investigation, in *The Global Geospace Mission*, edited by C. T. Russell, p. 207, Kluwer Acad., Norwell, Mass., 1995.
Lockwood, M., Relationship of dayside auroral precipitations to the open-closed separatrix and the pattern of convective flow, *J. Geophys. Res., 102*, 17,475, 1997a.
Lockwood, M., Energy and pitch angle dispersions of LLBL/cusp ions seen at middle altitudes: Predictions by the open magnetosphere model, *Ann. Geophys., 15*, 1501, 1997b.
Lockwood, M., and J. Moen, Reconfiguration and closure of lobe flux by reconnection during northward IMF: Evidence for signatures in cusp/cleft auroral emissions, *Ann. Geophys., 17*, 996, 1999.
Lockwood, M., and M. F. Smith, The variation of reconnection rate at the dayside magnetopause and cusp ion precipitation, *J. Geophys. Res., 97*, 14,841, 1992.
Lockwood, M., T. G. Onsager, C. J. Davis, M. F. Smith, and W. F. Denig, The characteristics of the magnetopause reconnection X-line deduced from low-altitude satellite observations of cusp ions, *Geophys. Res. Lett., 21*, 2757, 1994.
Maezawa, K., Magnetic convection induced by the positive and negative z-components of the interplanetary magnetic field: Quantitative analysis using polar cap magnetic records, *J. Geophys. Res., 81*, 2289, 1976.
Matsuoka, A., K. Tsuruda, H. Hayakawa, T. Mukai, and A. Nishida, Electric field structure and ion precipitation in the polar region associated with northward interplanetary magnetic field, *J. Geophys. Res., 101*, 10,711, 1996.
Newell, P. T., W. J. Burke, C.-I. Meng, E. R. Sanchez, and M. E. Greenspan, Identification and observations of the plasma mantle at low altitude, *J. Geophys. Res., 96*, 35, 1991a.
Newell, P. T., W. J. Burke, E. R. Sanchez, C.-I. Meng, M. E. Greenspan, and C. R. Clauer, The low-latitude boundary layer and the boundary plasma sheet at low altitude: Prenoon precipitation regions and convection reversal boundaries, *J. Geophys. Res., 96*, 21,013, 1991b.
Nishida, A., Can random reconnection on the magnetopause produce the low-latitude boundary layer?, *Geophys. Res. Lett., 16*, 227, 1989.
Ogilvie, K. W., et al., SWE, a comprehensive plasma instrument for the Wind spacecraft, in *The Global Geospace Mission*, edited by C. T. Russell, p. 55, Kluwer Acad., Norwell, Mass., 1995.
Onsager, T. G., and S. A. Fuselier, The location of magnetopause reconnection for northward and southward interplanetary magnetic field, in *Solar System Plasmas in Space and Time, Geophys. Monogr. Ser.*, vol. 84, edited by J. L. Burch and J. H. Waite, p. 183, AGU, Washington, D. C., 1994.
Onsager, T. G., C. A. Kletzing, J. B. Austin, and H. MacKiernan, Model of magnetosheath plasma in the magnetosphere: Cusp and mantle particles at low altitudes, *Geophys. Res. Lett.*, 20, 479, 1993.
Paschmann, G., W. Baumjohann, N. Sckopke, and T.-D. Phan, Structure of the dayside magnetopause for low magnetic shear, *J. Geophys. Res., 98*, 13,409, 1993.
Russell, C. T., R. C. Snare, J. D. Means, D. Pierce, D. Dearborn, M. Larson, G. Barr, and G. Le, The GGS/Polar magnetic fields investigation, in *The Global Geospace Mission*, edited by C. T. Russell, p. 563, Kluwer Acad., Norwell, Mass., 1995.
Russell, C. T., J. A. Fedder, S. P. Slinker, X.-W. Zhou, G. Le, J. G. Luhmann, F. R. Fenrich, M. O. Chandler, T. E. Moore, and S. A. Fuselier, Entry of the Polar spacecraft into the polar cusp under northward IMF conditions, *Geophys. Res. Lett., 25*, 3015, 1998.
Russell, C. T., G. Le, and S. M. Petrinec, Cusp observations of high- and low-latitude reconnection for northward IMF: An alternate view, *J. Geophys. Res., 105*, 5489, 2000.
Savin, S. P., et al., The cusp/magnetosheath interface on May 29, 1996: Interball-1 and Polar observations, *Geophys. Res. Lett., 25*, 2963, 1998.
Sckopke, N., G. Paschmann, S. J. Bame, J. T. Gosling, and C. T. Russell, Evolution of ion distributions across the nearly perpendicular bow shock: Specularly and nonspecularly reflected gyrating ions, *J. Geophys. Res., 88*, 6121, 1983.
Scudder, J. D., et al., Hydra – A 3-dimensional electron and ion hot plasma instrument for the Polar spacecraft of the GGS mission, in *The Global Geospace Mission*, edited by C. T. Russell, p. 459, Kluwer Acad., Norwell, Mass., 1995.
Song, P., and C. T. Russell, Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field, *J. Geophys. Res., 97*, 1411, 1992.
Song, P., C. T. Russell, R. J. Fitzenreiter, J. T. Gosling, M. F. Thomsen, D. G. Mitchell, S. A. Fuselier, G. K. Parks, R. R. Anderson, and D. Hubert, Structure and properties of the subsolar magnetopause for northward interplanetary magnetic field: Multi-instrument particle observations, *J. Geophys. Res., 98*, 11,319, 1993.
Urquhart, A. L., P. H. Reiff, F. R. Toffoletto, T. W. Hill, T. R. Konkel, C. T. Russell, G. Le, S. P. Savin, and S. A. Romanov, Polar magnetopause crossings of May 29, 1996: Implications for magnetic field modeling, *J. Geophys. Res., 103*, 17,323, 1998.
White, W. W., G. L. Siscoe, G. M. Erickson, Z. Kaymaz, N. C. Maynard, K. D. Siebert, B. U. O. Sonnerup, and D. R. Weimer, The magnetospheric sash and the cross-tail S, *Geophys. Res. Lett., 25, 1605*, 1998.
Woch, J., and R. Lundin, Magnetosheath plasma precipitation in the polar cusp and its control by the interplanetary magnetic field, *J. Geophys. Res., 97*, 1421, 1992.

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