# HIGH-LATITUDE PARTICLE PRECIPITATION AND ITS RELATIONSHIP TO MAGNETOSPHERIC SOURCE REGIONS

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Received February 25, 1997; Accepted in final form May 23, 1997

**Abstract.** Two central issues in magnetospheric research are understanding the mapping of the low-altitude ionosphere to the distant regions of the magnetsphere, and understanding the relationship between the small-scale features detected in the various regions of the ionosphere and the global properties of the magnetosphere. The high-latitude ionosphere, through its magnetic connection to the outer magnetosphere, provides an important view of magnetospheric boundaries and the physical processes occurring there. All physical manifestations of this magnetic connectivity (waves, particle precipitation, etc.), however, have non-zero propagation times during which they are convected by the large-scale magnetospheric electric field, with phenomena undergoing different convection distances depending on their propagation times. Identification of the ionospheric signatures of magnetospheric regions and phenomena, therefore, can be difficult. Considerable progress has recently been made in identifying these convection signatures in data from low- and high-altitude satellites. This work has allowed us to learn much about issues such as: the rates of magnetic reconnection, both at the dayside magnetopause and in the magnetotail; particle transport across the open magnetopause; and particle acceleration at the magnetopause and the magnetotail current sheets.

**Key words:** Magnetosphere, Ionosphere, Low Latitude Boundary Layer, Cusp, Mantle, Polar Rain, Plasma Sheet, Plasma Sheet Boundary Layer, Particle Precipitation

## 1. Introduction

The high-latitude ionospheric regions are typically described in terms of the measured particle populations that, due to particles moving freely along the magnetic field in a collisionless plasma, give an indication of the properties of the distant magnetospheric regions. The magnetospheric regions are discussed primarily from the viewpoint of low-altitude particle measurements. The regions are: the low latitude boundary layer (LLBL), the cusp, the mantle, the polar rain, the plasma sheet boundary layer (PSBL), and the plasma sheet, including the dayside and nightside boundary plasma sheet (BPS) and the central plasma sheet (CPS). Progress in these and other related research areas has recently been reviewed (Lyons, 1995; Newell, 1995; Galperin and Feldstein, 1996; Smith and Lockwood, 1996).

An important advantage of the low-altitude measurements over those made in the magnetospheric source regions, either near the magnetopause or in the magnetotail, is that in a relatively short time (seconds to minutes) a low-altitude satellite

*Space Science Reviews* **80**: 77–107, 1997.

can cross magnetic field lines that extend over broad areas in the magnetosphere. The spacecraft then can obtain snapshots of the large-scale magnetospheric regions and the boundaries separating them. This contrasts with high-altitude spacecraft that can take considerably longer (hours to days) to traverse these same regions and boundaries. By investigating the particle properties in the low-altitude regions and comparing the measured velocity-space distributions with those expected under either steady or temporally varying conditions, it is possible to differentiate between the different regions and to study remotely the processes occurring in the distant magnetosphere.

A key point to be addressed relates to the identification of the various low-altitude precipitation regions. Vasyliunas (1979) considered the ionospheric precipitation regions to be the field-aligned projections of magnetospheric source regions, and they are usually given the same names as a result. Furthermore, the classification scheme for the different regions is largely based upon this philosophy, because in its derivation, particle energy spectra at low altitudes were compared to those at high altitudes. Thus, for example, Newell and Meng (1992) regarded their map of the ionospheric regions as a map of the magnetosphere.

This philosophy, however, neglects magnetospheric convection and particle motion in the crossed electric and magnetic fields that, in many cases have a dominant effect on the observed plasma properties (e.g., Rosenbauer et al., 1975; Hill and Reiff, 1977; Onsager et al., 1993; Lockwood and Smith, 1993). Using a frozen-in-flux, ideal-MHD formulation, the existence of a convection electric field means that although particles move along magnetic field lines, the particles also convect perpendicular to the magnetic field. Thus the trajectories are not field-aligned but rather depend on the energy and pitch angle of the particle. Indeed, this is the very basis of the observed velocity filter effects described below. Thus not only does a spectrum of different-energy particles (at one pitch angle) from one point in the magnetosphere map to a spread of locations in the ionosphere, but also a spread of energies seen at any one point in the ionosphere maps to a spread of source locations in the magnetosphere. Similarly, a spread of pitch angles at one energy also reveals an extended source region.

This effect is highly significant for low-energy magnetosheath ions, and velocity filter effects associated with electron flight times have also been detected. It is also significant for the magnetosheath electrons, since, although high-energy electrons do have much smaller flight times and thus much more field-aligned trajectories, the fluxes of electrons are modified by those of the ions in order to maintain quasi-neutrality (Burch, 1985). This means that any classification scheme that depends on either the fluxes of ions or electrons, or both, is subject to strong influence by this effect. As described below, all these cusp effects also have a corresponding analogue on the nightside of the Earth at the boundary between the polar cap and the plasma sheet.

In this review, the low-altitude dayside and nightside ionospheric precipitation regions are discussed in terms of the magnetospheric regions they map to magnetically, and in terms of the evolution of the plasma in the convection electric field. Recent advances in describing the low-altitude precipitation in terms of the distant source regions are also discussed, and progress in using the low-altitude measurements to sense remotely the properties of the distant magnetosphere are examined. Considerable advances have been made in utilizing dayside low-altitude measurements to estimate quantitatively key properties of the reconnection process under southward Interplanetary Magnetic Field (IMF) conditions, for which the cusp signatures are well understood (e.g., Lockwood and Smith, 1992; Lockwood et al., 1994; Newell and Meng, 1995a). Progress has also been made in characterizing and understanding some of the more complex cusp signatures (e.g., Yamauchi and Lundin, 1994), cusp signatures under northward IMF conditions (e.g., Woch and Lundin, 1992a; Matsuoka et al., 1996), and the high-latitude precipitation regions near dawn and dusk (e.g., Woch and Lundin, 1992b; Nishida et al., 1993; Lyons et al., 1996).

A primary emphasis here is on the identification of magnetic separatrices, and on a description of the plasma regions in terms of their evolution following magnetic reconnection, either on the dayside magnetopause or in the distant magnetotail. Of course, not all observations of low-altitude particle precipitation can be described by this scenario, but it does provide a useful framework that accounts for the commonly observed features, and it can serve as a point of reference to compare with observations that appear to require additional physical mechanisms. It has also been demonstrated that when interpreted in this way, the observations often allow quantitative estimates to be made of the reconnection process, including its rate and location, and the plasma properties in the vicinity of the reconnection site.

## 2. Dayside Precipitation Regions

The dayside particle precipitation regions can be understood most simply by considering the evolution of magnetospheric plasma following magnetic reconnection on the dayside magnetopause and the subsequent evolution of the open flux it produces. For southward IMF, the open flux moves tailward into the lobe under the action of the magnetosheath flow and the magnetic tension force; for northward IMF, the tension force can act in the opposite direction to the magnetosheath flow. In general, the reconnected field lines evolve in a complex manner, depending on the balance between these two influences (e.g., Cowley and Owen, 1989). The dayside precipitation regions that will be discussed in this way are the Central Plasma Sheet (CPS), the Boundary Plasma Sheet (BPS), the Low Latitude Boundary Layer (LLBL), the cusp, the mantle, and the polar rain. These regions are illustrated in Figure 1, from Newell and Meng (1992). The CPS precipitation consists of magnetospheric plasma on closed field lines; and the cusp, mantle, and polar rain precipitation are generally considered to occur on open field lines. As described

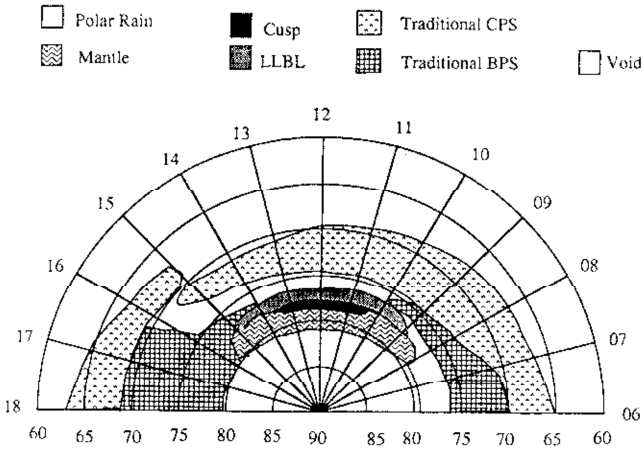


*Figure 1.* An illustration of the regions of low-altitude dayside particle precipitation, from Newell and Meng (1992).

in more detail below, there is still an active debate on the association of BPS and LLBL plasma with open or closed field lines.

## 2.1. Cusp - Mantle - Polar Rain

If one considers, for example, a reconnection X-line extending across the dayside magnetopause in the equatorial plane (for a purely southward orientation of the IMF), the low-altitude footprint of the X-line in the ionosphere will, broadly speaking, be the boundary between plasma precipitation characteristic of the closed magnetosphere (the CPS) and the plasma characteristic of the magnetosheath/solar wind (the cusp, the mantle, and the polar rain). When the magnetosheath magnetic field interconnects with the magnetospheric field, particles will cross the magnetopause by flowing along the magnetic field that interconnects across the magnetopause. The previously trapped CPS plasma will escape out across the open magnetopause, and the magnetosheath plasma will flow into the magnetosphere. As the particle velocities parallel to the magnetic field allow the plasmas to intermix freely across the magnetopause, the magnetosheath flow and the tension force give a boundary-tangential electric field that convects the open flux tube along the magnetopause toward the magnetotail. The combination of the parallel velocities of the particles and the perpendicular convection will result in the trajectories sketched in Figure 2, from Gosling et al. (1990a). Note that for both entering and escaping particles, not all are transmitted through the boundary, but some are scattered by the current sheet and reflect back into the magnetosheath or magnetosphere.

Near the subsolar magnetopause, the magnetosheath typically has its highest density and temperature and its lowest bulk velocity (e.g., Spreiter and Stahara, 1985). The magnetosheath density and temperature decrease and the boundary-

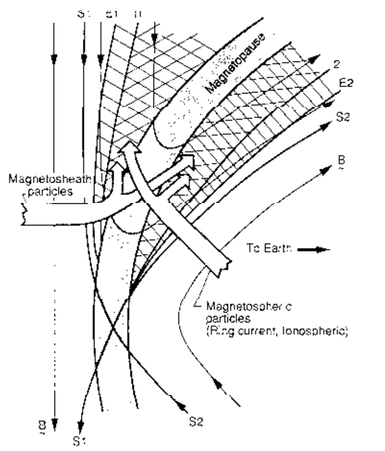


*Figure 2.* An illustration of the particle layers that form inside and outside the magnetopause on recently-reconnected field lines, from Gosling et al. (1990a).

tangential velocity increases with distance away from the subsolar point. Therefore when open field lines thread the magnetopause near the subsolar region, the highest fluxes of magnetosheath plasma will be injected into the magnetosphere by flowing across the magnetopause. This region of high-density magnetosheath plasma inside the magnetosphere and in the ionosphere is identified as the cusp (e.g., Newell and Meng, 1992). As the magnetopause crossing point of the flux tube convects away from the subsolar point, the magnetosheath plasma outside the magnetopause will decrease in density and temperature and increase in downtail velocity. These changes in the magnetosheath source population will result in reduced particle fluxes and energies in the ionosphere and magnetosphere, and the fluxes will decay to levels that are identified as mantle, and then to lower levels identified as polar rain (e.g., Winningham and Heikkila, 1974; Fairfield and Scudder, 1985; Wing et al., 1996).

The cusp, whose defined location is based on particle flux and average energy levels, will then be spatially localized and confined to the magnetic field lines that map to the most dense portion of the dayside magnetosheath. Moving in local time or in latitude away from connection to the subsolar magnetosheath will result in reduced fluxes and average energies, eventually reaching levels below the threshold for identification as cusp. This spatial localization will occur even if the entire magnetopause is open to magnetosheath entry; no localization of particle entry is required to account for the commonly observed cusp features.

The flux levels of precipitating magnetosheath plasma are also affected by particle acceleration as the magnetosheath plasma crosses the magnetopause current layer (Hill and Reiff, 1977; Cowley, 1982). The theory of particle distributions resulting from current sheet acceleration Cowley (1982) has been highly successful in predicting the ion distribution functions seen at the dayside magnetopause

(Smith and Rodgers, 1991; Fuselier et al., 1991; Gosling et al., 1990a) and in predicting the cusp and mantle precipitation of magnetosheath-like plasma resulting from magnetopause reconnection (Onsager et al., 1993; Lockwood and Davis, 1996a). As discussed earlier, the result of the velocity filter effect is that the spectrum of energies seen in the magnetosphere and ionosphere at a single location arises from a spread of magnetopause injection locations. The spectrum seen at any one point and time is then a convolution of many effects; the spatial distribution of the source magnetosheath plasma, the magnetopause acceleration, and the time-of-flight velocity filter. The above calculations of particle precipitation allow for these factors, as has recently been discussed in detail by Lockwood (1995).

An important application of our understanding of the particle signatures that result from the reconnection process has been the quantification of the reconnection rate. Observations in the ionosphere have a great advantage since they can exploit the fact that the ionosphere is "incompressible" - the magnetic field is dominated by currents in the Earth's interior and remains at roughly $5x10^4$ nT, independent of the magnitude of the currents that flow as part of solar-terrestrial interactions. This means that the transfer of magnetic flux from one region to another in the magnetosphere must correspond to the changing of the area of the regions in the ionosphere. This is the basis of a method that allows cusp and mantle dispersion signatures to be used to calculate the recent history of the magnetopause reconnection rate (Lockwood and Smith, 1992).

This theory has also been used to compute the ion precipitation characteristics seen for a variety of reconnection rate behaviors from mid- and low-altitude spacecraft moving either latitudinally or longitudinally (Lockwood and Smith, 1994; Lockwood and Davis, 1996a). The modeled signatures agree well with many of the observed signatures, and they depend critically on the speed of the satellite motion normal to the open-closed field line boundary, as a ratio of convection speed in the same direction. The synthesized precipitating ion spectra have been used to test the accuracy of the method for computing the reconnection rate from experimental data (Lockwood and Davis, 1996a).

The low-altitude particle data have been used to reconstruct the source distribution in the vicinity of the reconnection site also, and to infer numerous properties of the reconnection process (Lockwood et al., 1994). By combining the low-altitude measurements with solar wind data, it was possible to estimate: the density, flow, magnetic field, and Alfven speed of the magnetosheath; the magnetic shear across the X-line; the magnetospheric field; and the transmission factor for the magnetosheath ions across the open magnetopause. The ion heating at the magnetopause and the reconnection rate were also estimated.

Based on these same velocity filter effect concepts, the measured particle spectra have also been used to estimate the length of time that reconnection may cease at the dayside magnetopause (Newell and Meng, 1995b). The results suggested that reconnection is nearly always occurring. An upper limit of about 1 min was put on the duration that reconnection could cease and still be consistent with the observed particle precipitation. However, one of their examples was also studied by Lockwood and Davis (1996b) who computed the reconnection rate directly with calculated uncertainties. These authors found a much longer interval (about 5 min) during which the reconnection rate was less than the detectable threshold.

These quantitative estimates of the reconnection process described above have been made under conditions when the cusp/mantle ion distributions are well described by the velocity filter effect following reconnection on the dayside magnetopause with a dawn-to-dusk directed magnetospheric electric field. It is also the case, however, that many satellite passes through the cusp indicate a much more complex ion precipitation or, as in cases when the IMF is directed northward, a velocity filter dispersion with the ion energy/latitude progression consistent with high-latitude reconnection and a dusk-to-dawn directed electric field. A recent study of cusp signatures under both northward and southward IMF conditions has found evidence for current sheet acceleration on the most recently reconnected field lines in both cases (Woch and Lundin, 1992a). The acceleration was observed at the low-latitude edge of the cusp when the IMF was southward and at the high-latitude edge of the cusp when the IMF was northward, consistent with the expected sense of dispersion for these two cases.

Reconnection configurations that give rise to the observed particle acceleration and velocity dispersion are illustrated schematically in Figure 3, which contrasts the situation of subsolar reconnection during southward IMF (3a) with two of several possibilities during northward IMF (3b and 3c). In each case the left-hand diagram shows a view of the magnetosphere from the dusk flank, and the right-hand diagram shows the corresponding convection flow streamlines in the northern polar ionosphere. In all cases the numbers relate to the locations of newly opened field lines (o) as they evolve after reconnection.

The evolution of the field lines causes evolution of the particle precipitation along the flow streamlines. In (3a), the tailward progression of open flux gives rise to an antisunward dispersion signature in the precipitating particles. Namely, the highest acceleration due to particle motion across the current-sheet will be observed near the low-latitude edge of the cusp on the most recently reconnected field lines, and the particle precipitation will have progressively lower energies with anti-sunward distance along the flow streamlines.

In (3b), field lines that had been opened during a prior period of southward IMF are reconfigured through high-latitude reconnection causing a "stirring" circulation of open flux and a precipitation dispersion signature that is opposite to that observed under southward IMF conditions. The reconnection in the northern hemisphere lobe generates "overdraped lobe" field lines (Crooker, 1992) that drape over the dayside magnetosphere. In this case, a large acceleration on the most recently reconnected field lines will be observed on the high-latitude edge of the cusp, with the lower-energy precipitation observed sunward along the flow streamlines. In (3c), the overdraped lobe field lines (ol) generated through reconnection in the northern hemisphere are later re-closed by reconnection in the southern lobe. The

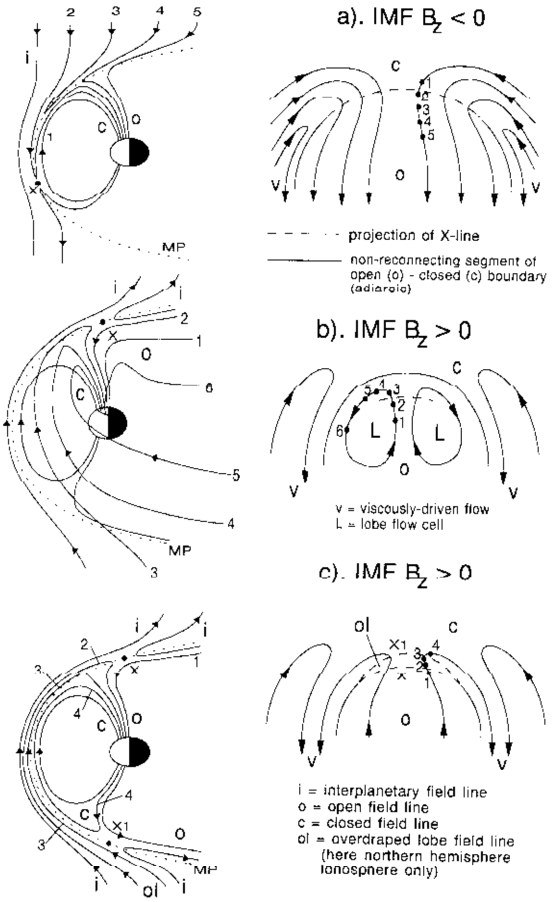


*Figure 3.* An illustration of field-line evolution along the magnetopause (left) and flow stream-lines in the ionosphere (right). Reconnection occurring near the subsolar magnetopause under southward IMF conditions (3a) is contrasted with reconnection occurring at high latitudes under northward IMF conditions (3b and 3c).

occurrence of reconnection at high-latitudes in both hemispheres has been suggested as a source of high-altitude LLBL plasma on closed field lines (Song and Russell, 1992). Signatures of the overdraped lobe topology have been reported at the dayside magnetopause (Fuselier et al., 1997).

An extensive survey of ion precipitation in the polar cap under northward IMF conditions has also found that the ion energy dispersion in regions of sunward ionospheric flow is consistent with high-latitude reconnection and the velocity filter effect (Matsuoka et al., 1996). Because of the high latitudes where these events were observed, the magnetosheath flow velocity at the estimated reconnection locations was estimated to be super-Alfvenic. In order to explain the sunward ionospheric convection, a mechanism was postulated where feedback from the ionosphere results in a slowing of the magnetosheath flow on the recently reconnected field lines to sub-Alfvenic, allowing the tension force to overcome the magnetosheath flow.

An important variation to the straighforward cusp/mantle dispersion described above is the observation of multiple, overlapping ion injections in the cusp (e.g., Yamauchi et al., 1995; Norberg et al., 1994). The various dispersion signatures have recently been catagorized in detail, including both the large-scale energy/latitude dispersion and the smaller scale structure seen within the large-scale patterns (Yamauchi and Lundin, 1994). Some of this more complex cusp structure may be the result of changing IMF conditions and a reconfiguration of the cusp during the satellite pass through it (Yamauchi et al., 1995). These signatures could also arise from pulsed reconnection with violation of frozen-in-flux by curvature and gradient-B drifts giving regions of overlapping precipitation (Lockwood and Smith, 1994). Other explanations have been proposed (e.g., Yamauchi and Lundin, 1994) which do not fit easily into the basic scenario outlined above for the simple, single cusp dispersion signatures. Thus, it is still unclear if the overlapping signatures are a complication of the open magnetosphere model or represent an entirely different mechanism.

### 2.2. Low Latitude Boundary Layer - Boundary Plasma Sheet

As described above, the combination of current sheet acceleration and the velocity filter effect provides a quantitative explanation for much of the commonly observed cusp and mantle precipitation. The plasma in these regions consists of the directly-entering magnetosheath particles. The region identified as LLBL at low altitudes has a lower density and a somewhat higher temperature than the cusp, and is found just equatorward of the cusp (Newell et al., 1991a). The low-altitude LLBL, therefore, is thought to correspond to the high-altitude LLBL, located just inside the magnetopause, that is observed to have a mixture of magnetosheath and magnetospheric plasma. In the classification of low-altitude precipitation regions by Newell et al. (1991a), the BPS region is not uniquely defined, consisting of plasma populations that did not fit well into the other defined catagories. This region typically has ions with energies higher than found in the cusp, often resembling the nightside plasma sheet.

An interesting aspect of the LLBL/BPS ions is that in many cases these ions are seen to exhibit a continuous velocity dispersion ramp with the cusp ions, suggesting that the generation and transport of both the dayside BPS and the LLBL ions are at times intimately linked with that of the cusp ions. However, the current sheet acceleration described above that provides some energization to the entering magnetosheath ions that form the cusp typically is not adequate to explain the high fluxes of the most energetic LLBL/BPS ions. For example, the open magnetosphere models of the cusp by Onsager et al. (1993), Lockwood and Smith (1994), and Lockwood and Davis (1996a) all give a plateau of peak ion energies (with detectable fluxes) of only 7 to 10 keV. In many of the cases presented (e.g., Pinnock et al., 1993; Newell and Meng, 1994), a region equatorward of the cusp classed as either LLBL or dayside BPS contains ions with energies elevated well above those of the shocked solar wind plasma in the magnetosheath, up to well over the 30 keV limit of the ion instrument.

Several ideas have been proposed to explain the energetic LLBL/BPS ions. Newell and Meng (1992) regard the dayside BPS as an extension of the night-side BPS, implying that the ions are accelerated on newly-closed field lines in the tail, as initially implied by Vasyliunas (1979). Alem and Delcourt (1995) suggested an explanation in terms of chaotic orbits in a closed field-line magnetic cusp topology, and Curran and Goertz (1989) also considered chaotic ion orbits within an open LLBL as a mechanism to accelerate the magnetosheath protons. None of these mechanisms, though, would produce ions with an energy dispersion that is continuous with that of the ions in the cusp region, which is clearly the case for several observed examples (Newell et al., 1991b; Pinnock et al., 1993; Newell and Meng, 1994). The closed magnetic cusp topology invoked by Alem and Delcourt is also not consistent with the cusp precipitation seen poleward of the BPS on open field lines.

Using a generalization of the theory of magnetopause particle distributions by Cowley (1982), a different description has recently been supplied to explain both the BPS and LLBL ions in terms of the open magnetospheric model (Lockwood et al., 1996). This explanation invokes acceleration by reflection of magnetospheric ions off of two Alfven waves at the magnetopause. The resulting reconnection layer has a form shown schematically in Figure 4, where "S" refers to the magnetic separatrices, "E" refers to the exterior Alfven wave, and "I" is the interior Alfven wave. The interior Alfven wave is launched by the reconnection site into the inflow region where magnetospheric plasma flows towards the reconnecting magnetopause. An exterior Alfven wave is also launched into the magnetosheath side of the boundary and stands in the magnetosheath inflow. The majority of the field rotation takes place at the exterior wave, which can then be identified as the main magnetopause current sheet.

The interior wave forms the inner edge of the reconnection layer (also called the open LLBL), and its existence can be inferred from the fact that the field in the LLBL has a slightly different orientation to that of closed field lines in the magnetosphere proper (Cowley et al., 1983; Hapgood and Bryant, 1992). It has been shown that the effect of the waves is to produce accelerated ions that precipitate into the low-altitude LLBL and BPS regions and that are continuous in their dispersion with the magnetosheath ions injected along the open field lines and seen in the cusp precipitation region at low altitudes (Lockwood et al., 1996). By reflection off the magnetopause (exterior) wave, magnetospheric ions can achieve energies of about 15 keV with fluxes detectable by current instruments; energies slightly above the 7 - 10 keV plateau predicted for injected sheath ions can then be generated. Because of the lower plasma density on the magnetospheric side of the boundary, however,

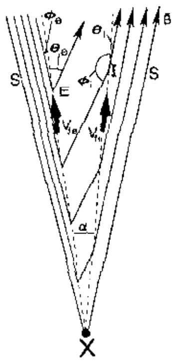

*Figure 4.* Illustration of a reconnection layer formed by two Alfven waves (dashed lines), from Lockwood et al. (1996). The interior Alfven wave (I) travels at a higher speed than the exterior Alfven wave (E), and, therefore, particles that reflect off the interior wave will undergo a larger acceleration than those that reflect off the interior wave.

the interior wave has a much higher speed and can generate detectable fluxes up to the order of 30 keV. By invoking partial reflection of the magnetospheric plasma at each of the Alfven waves, it was possible to quantitatively reproduce the LLBL/cusp transition for the satellite observations originally presented by Newell et al. (1991b) (which has been the subject of a great many of the other studies mentioned above; specifically, Onsager et al. (1993), Lockwood et al. (1994), and Alem and Delcourt (1995) all discussed this one example). Lockwood and Moen (1996) have applied the theory of Lockwood et al. (1996) to explain another example of BPS and LLBL ions, as reported by Moen et al. (1996).

### 2.3. Are LLBL Field Lines Open or Closed?

The open magnetosphere model predicts that the precipitation at low altitudes evolves from cusp to mantle and then to polar rain as the field line evolves over the magnetopause away from the reconnection site and into the tail lobe (Cowley et al., 1991b; Lockwood and Smith, 1993, 1994; Onsager et al., 1993; Lockwood, 1995). This evolution is seen in full along the flow streamlines in the steady-state case and so may sometimes be seen if the satellite follows the flow streamline quite closely. Recently, several authors have suggested the low-altitude LLBL precipitation is also on open field lines (e.g. Lockwood and Smith, 1993; Lyons et al., 1994; Lockwood et al., 1996; Moen et al., 1996). It has been argued that the velocity filter effect makes it impossible to place the open-closed field line boundary between the adjacent cusp and LLBL precipitations, at least near noon where convection is poleward into the polar cap (Lockwood and Smith, 1993).

At the magnetopause current sheet (which is associated with the exterior Alfven wave), application of tangential stress-balance tests to particle and field data [e.g., Paschmann et al., 1986, Sonnerup et al., 1986) reveals that there is an open LLBL, i.e., a layer of accelerated magnetosheath plasma mixed with magnetospheric plasma which is formed by the two populations flowing along newly-opened field lines at the local Alfven speed in the rest frame of the field lines (i.e., the Whalen relation is found to apply). Other observations, like the directions of the accelerated flows (Gosling et al., 1990b), the form of their ion distribution functions (Smith and Rodgers, 1991; Fuselier et al., 1991) and electron and ion edges due to time-of-flight dispersion effects (Gosling et al., 1990a) leave little doubt that at least part, and at time perhaps all, of the LLBL is on newly-opened field lines.

Other magnetopause observations have shown a mixture of magnetosheath-like and magnetosphere-like plasmas on northward-pointing field lines and have been interpreted as an LLBL on closed field lines (Eastman and Hones, 1979; Eastman et al., 1976; Mitchell et al., 1987, Traver et al., 1991; Lotko and Sonnerup, 1995). That these field lines are genuinely closed is not certain because the use of particle distributions to infer the magnetic topology is notoriously difficult. This is because of the effects of particle flight times and of magnetic mirrors on open field lines (Scholer et al., 1982; Daly and Fritz, 1982; Cowley and Lewis, 1990).

In addition, unlike the open LLBL, the mechanisms responsible for introducing magnetosheath plasma into a closed LLBL are not clear. It has been pointed out that the observed wave amplitudes are not adequate to drive the cross-field diffusion required to populate closed field lines with sufficient fluxes of magnetosheath plasma to explain the LLBL (Sonnerup, 1980). This finding has been confirmed by later studies (Owen and Slavin, 1992; Winske et al., 1995; Treumann et al., 1995].

Other mechanisms proposed for populating a closed LLBL involve the opening and re-closing of magnetic flux at the magnetopause. Nishida (1989) proposed a mechanism where reconnection may be responsible for plasma populations on a closed LLBL when the IMF points northward. He invoked highly patchy reconnection, where field lines that opened at one reconnection site were re-closed at a later time elsewhere. During the time that the field line was open, magnetosheath plasma was free to flow in and magnetosphere plasma to flow out, giving the observed plasma mixture. Recently Song and Russell (1992) and Song et al. (1990) proposed a similar mechanism, but involving only two large-scale reconnection sites, poleward of the cusps. Numerical simulations by Richard et al. (1994) indicate that magnetosheath plasma could indeed get onto closed field lines in this way.

It is important here to draw a distinction between the high-altitude and the low-altitude LLBL populations; namely, that the low-altitude LLBL precipitation consists of particles largely within the loss cone. Thus for the low-altitude LLBL to persist, there must be a continuous source of particles to refill the loss cone. After the reclosure of open flux, as suggested by Nishida (1989) and Song and Russell (1992), the LLBL will only persist for a time scale on the order of the ion bounce time. Whereas the high-altitude LLBL ions may be observable on both open and closed field lines, the low-altitude LLBL will only be observable on open field lines, and then for a brief period after field-line closure.

The low-altitude ionospheric precipitation classed as LLBL shows many features that are consistent with an open LLBL at the magnetopause. For example, Hill and Reiff (1977) and Woch and Lundin (1992a) have shown that the cusp ion energies increase in the low-altitude velocity-filter dispersion ramp to energies above those in the magnetosheath, providing evidence that the highest energy ions of the accelerated ion flows at the magnetopause do indeed appear in the ionosphere close to the magnetic separatrix, the boundary between open and closed field lines. However, the direct association between the plasma measurements made in the high-altitude LLBL near the magnetopause and in the low-altitude LLBL can also be complicated by the velocity filter effect. The models of Onsager et al. (1993), Lockwood and Smith (1994), and Lockwood (1995) stress the role of the velocity filter effect and show that the precipitation at any one point in the ionosphere arise from a spread of locations on the magnetopause. Lockwood and Smith (1993) used realistic field line velocities over the magnetopause to show that the spread of magnetopause source locations supplying ions to one point in the ionosphere was very large, being of order 10-20 Earth radii ($R_E$). The expected low-altitude signatures resulting from an open and a closed LLBL will be contrasted in the following section.

The above studies on low-altitude LLBL precipitation have concentrated mainly on observations within a few hours of local time on either side of noon. Recent results have also provided interesting new insights on the precipitation of magnetosheath plasma in the dawn and dusk regions that could map to the high-altitude LLBL on the flanks of the magnetosphere. A region of high-latitude ion precipitation has been identified and referred to as circumpolar ion precipitation (CPIP) (Nishida et al. 1993; Nishida and Mukai, 1994). Some of the interesting characteristics of this regions are: the presence of energetic ion precipitation, electron precipitation that suggests open field lines, and sunward convection. A potentially related region has also been identified in the morning and afternoon high-latitude ionosphere and referred to as the soft electron zone (SEZ) (Lyons et al., 1996). This region contains magnetosheath-like electron and ion precipitation and is suggested to be largely on open field lines. The SEZ region is likely, therefore, to correspond to the low-altitude signature of the open LLBL. A strong dawn-dusk asymmetry of the SEZ region is observed and has been correlated with the IMF $B_y$ component. In addition, the identification of LLBL plasma has been further extended along the flanks to within 3 to 4 hours from midnight (Woch and Lundin, 1993). These observations by the Viking spacecraft identify a magnetosheath-like ion component having a density correlated with the solar wind density extending from near noon well into the night sector.

## 2.4. Comparisons of Different Separatrix Locations

The debate about the magnetic topology within the LLBL at the magnetopause certainly has implications for the precipitation classed as LLBL at low altitudes, even though the relationship between the two is not always clear. Figure 5, from Lockwood (1997), contrasts two possible relationships of the dayside precipitation regions (shaded according to code bar) to the ionospheric convection streamlines (thin lines with arrows) and to the open-closed boundary (thick line). The key difference between the two plots in Figure 5 is the location of the open-closed field line boundary and, in particular, the consequent topology of field lines within the ionospheric LLBL and BPS regions. In Figure 5a, the LLBL and BPS precipitations are on closed field lines, whereas in Figure 5b they are on open field lines. The open/closed boundary is dashed where magnetic flux is transferred across it (i.e. at the "merging" gap which maps to the magnetopause reconnection X-line) and solid where it is not (i.e. an adiaroic segment, meaning "not flowing across" (Siscoe and Huang, 1985)). In Figure 5a, the open-closed boundary is at the boundary between cusp and LLBL, whereas in Figure 5b it is further equatorward than this and lies near the poleward edge of the CPS. Both cases are drawn for the steady-state limit, with strongly southward interplanetary magnetic field ($B_Z < 0$) which has no major dawn-dusk component ($B_Y \approx 0$). The figures could readily be adapted to non-steady situations, for example during the growth phases of a substorm when the polar cap is expanding and the adiaroic segments of the boundary migrate equatorward (Siscoe and Huang, 1985; Cowley and Lockwood, 1992) and/or for large IMF $|B_Y|$ (Cowley et al., 1991a, b).

The regions of precipitation shown in Figure 5 are broadly as sketched by Newell and Meng (1992; 1994) (see Figure 1). However, the region near noon between the CPS and the LLBL that previously has been characterised as "void" (Newell and Meng, 1992) has not been included in Figure 5. This has been done because void can occur when and where the flux falls below the one-count level, which depends on the instrument geometric factor (and thus its sensitivity threshold) as much as on the geophysical conditions. From the occurrence frequency of the void classification it is clear that it usually arises because either the BPS and/or CPS fluxes are below the one-count level. In addition, Newell and Meng (1994) are careful to note that the void region between the CPS and LLBL is often not devoid of precipitation, but that the precipitation present cannot be easily identified with any of the other classifications. The occurrence frequency plots by Newell and Meng (1992; 1994) show that the minimum occurrence probability of BPS is around noon but is still of order 25%. Indeed, the examples given by Pinnock et al. (1993), de la Beaujardiere et al. (1993) and Ohtani et al. (1995) all show precipitation classed as BPS close to noon. Consequently, we here re-classify the void region near noon (between CPS and LLBL) as being part of the dayside BPS which therefore extends across all MLT around noon.

There are a number of difference in these two schematics of boundary locations that have implications for the interpretation of the observed precipitation characteristics, such as: the local time extent of the different regions, the convection pattern in the cusp, and the location of the open-closed field line boundary relative to the observed particle signatures. For example, the statistical results of Newell

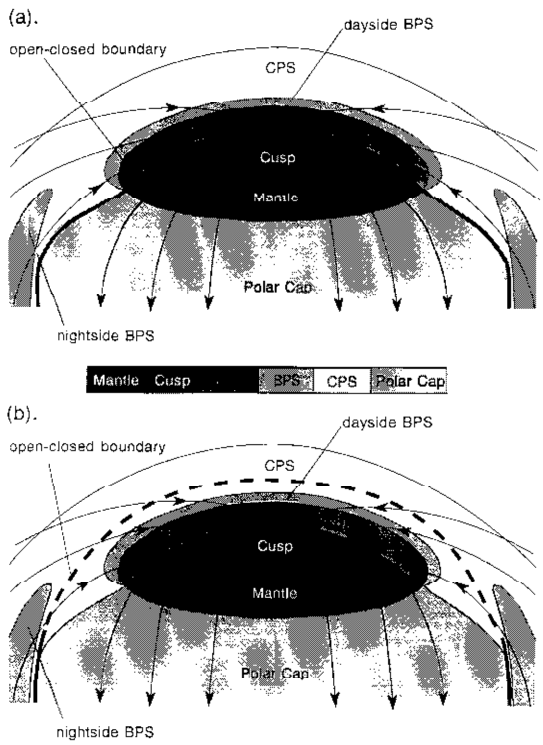


*Figure 5.* Comparison of ionospheric flow and precipitation regions for two open-closed field line boundary locations, from Lockwood (1997). The upper panel illustrates the ionospheric regions under the assumption that the LLBL, BPS, and CPS occupy closed field lines, with the longitudinal width of the cusp corresponding to the width of the separatrix. In the lower panel, the separatrix is taken to lie within the CPS, at its poleward edge. Under these conditions, the longitudinal width of the cusp is determined from the magnetosheath properties.

and Meng (1992; 1994) show the cusp precipitation occurrence to cover a relatively small range of MLT (about 3 hours), compared to the mantle and LLBL which both cover about 7 hours. This has been reflected in Figure 5. In Figure 5a the narrow cusp extent is set by the length of the merging gap. The LLBL, being on closed field lines and populated by a different mechanism, does not share this extent. However, the results of Newell and Meng indicate that the LLBL has roughly the same length in MLT as the mantle on open field lines. This has to be attributed to coincidence in Figure 5a. On the other hand, in Figure 5b the widths of the LLBL and the mantle both reflect the MLT extent of the merging gap. As described earlier, the smaller longitudinal extent of the cusp is due to the limited region in the dayside magnetosheath where the plasma densities and temperatures are high enough to produce low-altitude flux levels above the criteria for identification as cusp.

Another difference between Figures 5a and 5b relates to the poleward flow speeds in the cusp and the reconnection voltage. The observed transpolar voltage, and its dependence on the orientation of the IMF, show that magnetopause reconnection produces a voltage of order 110 kV when the IMF points strongly southward (e.g., Cowley, 1984). If the cusp represents the location of newly-opened field lines and if the LLBL is closed, then all the flow streamlines in the polar cap must first channel though a narrow constriction, often referred to as the "throat" (Heelis et al., 1976.), as in Figure 5a. This requires a voltage of order 110 kV across the cusp and, for the longitudinal width of 1000 km suggested by the statistics of Newell and Meng (1992; 1994), a poleward flow speed through the cusp of order 2 km/s. Such a speed is somewhat higher than is typically observed for this component of the flow and the throat flow pattern is not often seen. Rather, the flow pattern tends to show a broad convection reversal throughout the dayside as reported by Jorgensen et al. (1984) and reproduced in statistical models of the convection pattern (e.g. Heppner and Maynard, 1987; Shue and Weimer, 1994; see also discussion by Lockwood (1991)). As shown in Figure 5b, the broader region of flow reversal into the polar cap is consistent with the idea that the LLBL is not closed but rather that it is on the most recently opened field lines. The extent of the LLBL of order 2000 km implied by the statistics of Newell and Meng gives a more reasonable poleward plasma speed of 1 km/s for the transpolar voltage of 110 kV.

Many definitions of precipitation regions use the electron characteristics as well as those of the ions. When we allow for the velocity filter effect, this causes some conceptual difficulties because the electrons generally have much smaller flight times and so are swept a smaller distance downtail than are ions of comparable energy. Thus for adiabatic scatter-free motion of both ions and electrons, the two populations seen by a satellite at any one point and time would not share a common source. However, the situation is more complex than this because quasi-neutrality is maintained at all points along the field lines, and therefore the ions do exert an influence on the electrons. It is not fully understood how this balance is achieved, requiring that caution be exercised when using electron characteristics as identifiers of precipitation regions.

The location of the electron edge of the LLBL observed at low latitudes also has implications for the low-altitude LLBL identification. This electron edge (Gosling et al., 1991a) would be seen just poleward of the LLBL-cusp boundary in Figure 5a, whereas in Figure 5b it would be near the CPS-BPS border. At the electron edge, a satellite flying from closed to open field lines notes a loss of high-energy field-aligned magnetospheric (CPS) electrons for the first time: these are lost by flowing out along the newly-opened field lines through the magnetopause. Very shortly thereafter, lower-energy magnetosheath-like electrons, flowing in the opposite direction, are seen for the first time. However, fluxes of the incoming sheath electrons are restricted by the slower ions so that charge neutrality is maintained (Burch, 1985). Low-altitude observations often reveal the energetic CPS electrons very clearly and, when they are seen, their loss is evident and is equatorward of the LLBL and near the CPS-BPS border, as discussed by Lockwood et al. (1996). This can also be seen, for example, in Figure 2 of Watermann et al. (1993), Plates 1 and 3 of Newell et al. (1991a), Plates 1a-1c of de la Beaujardiere et al. (1993), and Plates 1, 3 and 4 of Ohtani et al., (1995). This feature is sometimes referred to as the trapping boundary (e.g. Nishida et al., 1993) and is never, by definition of the LLBL, poleward of the LLBL. Thus if we associate this observed feature (on the dayside) with the electron edge discussed by Gosling et al. (1990a), its ionospheric location calls for the situation in Figure 5b, and Figure 5a cannot apply.

In Figure 5b, some magnetospheric-like electrons must persist poleward of the electron edge, particularly at large pitch angles, giving a double loss cone type distribution on open field lines. This has frequently been used to argue that the BPS and the LLBL are closed. The extension of some of the CPS electron population onto the most recently opened field lines could have a number of causes, including: electron scattering at the magnetopause current sheet; magnetic mirroring due to the field strength being larger near the magnetopause crossing point of the field line than closer to Earth in the cusp; gradient and curvature drifting of electrons from closed field lines onto open ones; and electrostatic potential differences associated with the maintenance of quasi-neutrality. Such effects would mean that electron fluxes (at low energies and large pitch angles) would decay away over an extended region poleward of the initial loss of high energy, low pitch angle electrons at the electron edge (CPS-BPS boundary). Using the definition of Newell et al. (1991), the decay of this remnant CPS population would cause the BPS classification to evolve into LLBL. Thus, if the above processes can be shown to be sufficient, the electron characteristics would also be consistent with Figure 5b.

## 3. Nightside Precipitation Regions

The nightside precipitation regions exhibit many of the same velocity-filter effect signatures that are observed throughout the dayside regions, and have provided important clues as to the dynamics of the magnetotail. While the dayside features often reflect the evolution in plasma following the opening of magnetic flux on the dayside magnetopause, the nightside features can often be associated with the closing of magnetic flux at a distant magnetotail reconnection site and its subsequent evolution. Among the issues that can be addressed from the low- and mid-altitude particle measurements are: the location of the open/closed field line boundary, the location of the distant reconnection site, the rate of reconnection in the magnetotail, and the downtail source regions of auroral arcs.

### 3.1. Low-Altitude Polar Cap - PSBL - Plasma Sheet Transition

As with the above description of the dayside precipitation regions, the discussion here will concentrate on conditions when the IMF is directed southward. Under these conditions, the polar cap electron fluxes are either below the detection threshold of typical spacecraft instruments, or the fluxes are at a low and spatially unstructured level that is referred to as polar rain (e.g., Winningham and Heikkila, 1974; Fairfield and Scudder, 1985; Wing et al., 1996). On the other hand, under northward IMF conditions the polar cap tends to fill with intense, spatially localized fluxes of low-energy electrons (e.g., Winningham and Heikkila, 1974; Hardy et al., 1984). The average energy of the precipitating electrons is found to be on the order of 100 eV, suggesting a magnetosheath source (Obara et al., 1996). In addition, at these times the plasma sheet tends to cool and become quite structured, with a characteristic energy that can decrease to 100 eV or below (Sandahl and Lindqvist, 1990). Under these conditions, the distinction between the open polar cap and the closed plasma sheet becomes difficult to determine from the precipitation measurements.

When the spatially-uniform polar rain electrons are present, or when the polar cap is void of electron precipitation, low-altitude spacecraft typically detect an abrupt transition between the open field lines in the polar cap and the closed plasma sheet or plasma sheet boundary layer (e.g., Zelenyi et al., 1990; Fukunishi et al., 1993; Bosqued et al., 1993a; Onsager and Mukai, 1995). This transition is thus an indicator of the open-closed field line boundary that maps to the distant reconnection site, provided reconnection is occurring in the tail at the relevant local time. The low-altitude footprint of the separatrix is thus often clearly identifiable from the observed particle precipitation, although allowance must be made for the fact that even highly energetic electrons will be displaced equatorward by the dawn-dusk electric field. The properties of the precipitating electrons and ions and their variation with latitude provide clues as to the downtail properties of the distant plasma sheet and the variation of the plasma sheet with distance earthward from the X-line.

An illustration of the typical electron and ion precipitation observed in the nightside auroral zone is shown in Figure 6, from Fukunishi et al. (1993). For the discussion given in this paper, we have concentrated on the high-latitude regions, corresponding to the regions in Figure 6 labeled Polar Cap, PSBL, and Outer CPS, and we refer to the Outer CPS as simply the plasma sheet. As a spacecraft moves from the high-latitude polar cap toward lower latitudes, the first indication that the separatrix has been crossed is seen as a decrease in the polar rain electron flux (when the polar rain is present). The flux decrease is first seen at the highest energies, followed by a decrease at progressively lower energies. Slightly equatorward of the initial decrease in polar rain flux, the higher-energy (> 1 keV) electrons of plasma sheet origin are first detected. This plasma population is reasonably continuous down to lower latitudes where the field lines map to the earthward edge of the plasma sheet. The electron flux levels are consistent with the expected plasma sheet electron densities and temperatures. The gradual increase in flux levels with decreasing latitude reflects a gradual increase in the plasma sheet density and temperature with earthward location in the neutral sheet (Onsager and Mukai, 1995).

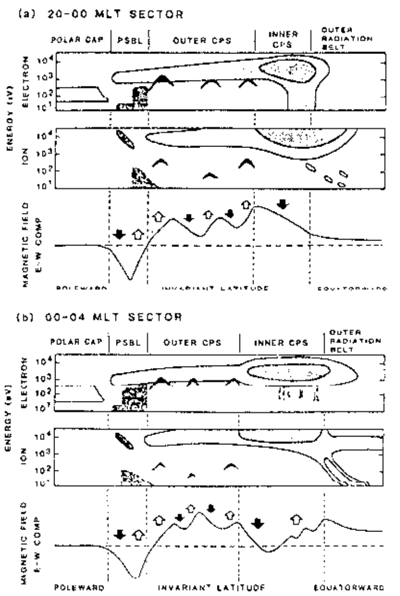


*Figure 6.* Diagram of the high-latitude electron and ion precipitation regions in the nightside auroral region, from Fukunishi et al. (1993). The spatial relationship between the polar cap electron precipitation, the PSBL ion beams, and the CPS precipitation are illustrated.

Equatorward of the high-latitude edge of the plasma sheet electrons is the region of velocity-dispersed ion precipitation, referred to as the Velocity Dispersed Ion Signature (VDIS) (Zelenyi et al., 1990; Saito et al., 1992; Bosqued et al., 1993a). The VDIS are produced by the velocity filter effect due to the equatorward ExB drift of plasma sheet boundary layer ions as they travel earthward along the magnetic field from the distant neutral sheet. It is interesting to note that the velocity versus latitude curve that one obtains from the VDIS smoothly matches the velocity versus latitude curve seen in the decrease of polar rain electron flux at slightly higher latitudes (Maezawa, private communication, 1995). An example of this can be seen in Plate 3d of Fukunishi et al. (1993). This observation strengthens the above mentioned association of the decline in polar rain flux with the separatrix location.

Further equatorward of the VDIS there is typically a region with a minimum in ion precipitation, referred to as the gap (Bosqued et al., 1993a), followed by ion precipitation that can be identified with the plasma sheet. Calculations of the expected low-altitude precipitation equatorward of the gap based on a model of plasma sheet sources and transport (Spence and Kivelson, 1993) have been shown to agree well with observations and have illustrated the local time dependence of the low-altitude precipitation (Hirsch et al., 1996).

The observations summarized above indicate the following evolution of magnetic topology and low-altitude particle precipitation. In the open polar cap, only polar rain electron precipitation is observed, consisting of the high energy tail of the solar wind electron distributions. When reconnection occurs at the distant X-line, the open lobe field lines become closed plasma sheet field lines. The solar wind electron source is thereby disconnected; and any lobe, mantle, or ionospheric plasma contained on the newly closed flux tube will, in its field-aligned bounce motion, have the opportunity to encounter the distant neutral sheet where particle energization may occur. The decrease in polar rain flux and the arrival of the plasma sheet electron and ion flux will then be observed with the characteristic velocity filter signature as the flux tube evolves equatorward at low altitudes and earthward in the distant neutral sheet, as expected with a cross-tail electric field directed dawn to dusk.

The latitudinal variation in the nightside precipitation has a number of features similar to those seen in the dayside precipitation. In both cases, the distinctive particle signatures can be described well in terms of the evolution of plasma following reconnection. There are, however, many low-altitude satellite passes where these particle signatures are not detected. For example, it has been estimated that the probability of observing the VDIS on an individual nightside satellite pass is about 15%, based on AUREOL-3 data (Bosqued et al., 1993b) and about 45%, based on Akebono data (Saito et al., 1992). These can be considered lower limits to the occurrence probability of active reconnection in the distant tail, since there will be times when the velocity-dispersed particle fluxes will be below the instrument detection threshold. While the observations are able in many cases to provide the location of the separatrix at a given local time, the longitudinal extent of the separatrix at low altitudes corresponding to the cross-tail extent of the distant reconnection line cannot be inferred from these measurements. Combined use of ground-based instruments, low-altitude satellites, and polar images are likely to lead in the future to more comprehensive estimates of the global magnetic flux transport in the magnetotail.

### 3.2. Downtail Lobe - PSBL - Plasma Sheet Transition

The characteristic features of the electron and the ion distributions in the magnetotail (roughly 10 - 20 $R_E$ downtail from Earth) show a strong correspondence to particle features seen at low altitudes. A similar spatial ordering of the plasma is also present at these downtail distances in the transition from the lobe, to the PSBL, and to the plasma sheet as observed, for example, by ISEE 1 and 2 (e.g., Forbes et al., 1981; Takahashi and Hones, 1988; Onsager et al., 1991) and by AMPTE-IRM (Nakamura et al.. 1992). These observations are summarized by the illustration shown in Figure 7, after Takahashi and Hones (1988). Figure 7 illustrates schematically the earthward and the tailward field-aligned electron and ion fluxes encountered as a spacecraft traverses from the lobe (top), across the separatrix, through the PSBL, and into the plasma sheet (bottom).

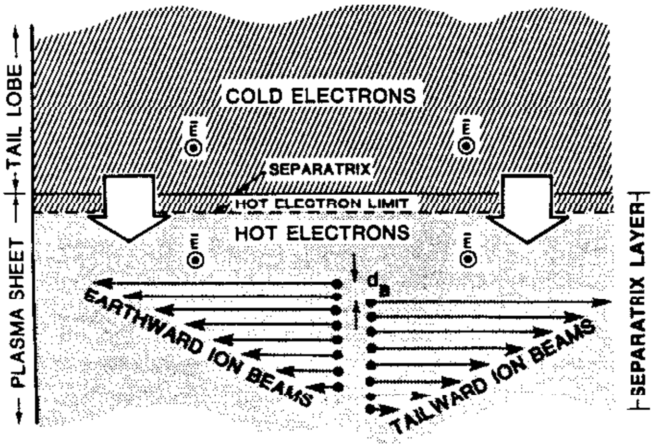


*Figure 7.* Diagram of the electron and ion regions at the downtail interface between the lobe and the plasma sheet, from Takahashi and Hones (1988). The high-latitude edge of the separatrix layer (PSBL) is identified by the hot plasma sheet electrons. Further equatorward, ion beams corresponding to the low-altitude VDIS are observed.

The first indication that the separatrix has been crossed is seen in the electron distributions, corresponding to the high-latitude edge of the > 1 keV PSBL electrons shown in Figure 6. These are electrons that presumably are streaming earthward from near the distant reconnection site on the most recently reconnected field lines. More equatorward of the separatrix, the velocity-dispersed ion beams are observed. The ion beams are observed equatorward of the electrons due to their slower field-aligned speeds and due to the fact they have undergone a larger ExB drift in traveling from the distant neutral sheet to the location where they are detected. The ions are first detected flowing earthward from the downtail acceleration region, and then flowing tailward after mirroring in the strong magnetic field near Earth. The velocity dispersed ion beams correspond to the VDIS observed at low altitudes. Recent calculations have demonstrated that a specified downtail plasma sheet profile in the equatorial plane can account for both the low-altitude and the downtail PSBL electron and ion measurements described above (Onsager and Mukai, 1996).

The close correspondence between the low-altitude and the downtail PSBL measurements clearly demonstrates the global nature of these features. And in addition to the large-scale spatial structure seen throughout the magnetotail, the detailed velocity-space features at low altitudes and downtail show similar distinctive features. The velocity-space features have been used to provide quantitative estimates of the plasma properties in the distant neutral sheet and estimates of the location of the distant reconnection site. From the VDIS observed at low altitudes, the downtail reconnection site source was estimated in one case to be located about 70 $R_E$ downtail (Saito et al., 1992). The distribution function reconstructed from the latitudinally dispersed ions had a temperature and a bulk energy of approximately 460 eV and 6.7 keV, respectively, consistent with the PSBL measurements downtail (Takahashi and Hones, 1988) and with previous theoretical calculations based on current sheet acceleration (Lyons and Speiser, 1982). In addition, the measured distribution functions in the downtail PSBL have been used to infer the plasma properties in the distant neutral sheet and to estimate the temporal variability in the reconnection site location (Elphic et al., 1995).

### 3.3. Downtail Plasma Sheet

Large advances have been made recently in understanding the average plasma convection in the equatorial plasma sheet and the average locations of the distant and the near-Earth neutral lines (Nishida et al. 1996a,b). These statistical results from the Geotail mission have provided a large-scale view of the net transport of northward and southward magnetic flux over downtail distances ranging from 36 $R_E$ to 169 $R_E$ during geomagnetically active times. A clear transition in the transport of magnetic flux is observed at about 140 $R_E$ downtail. Earthward of this location, a net earthward transport of northward magnetic flux is observed, while tailward of this location a net tailward transport of southward flux is observed. The interpretation is that during active times, the distant X-line on average resides in the vicinity of 140 $R_E$ downtail of Earth. The net earthward transport of northward magnetic flux is consistent with the dawn-dusk electric field required to account for the ion energization and the velocity filtering observed at low altitudes and in the mid-tail.

Results from recent statistical studies of energetic particle distributions in the magnetotail are consistent with the above estimates of the reconnection site location. Energetic ion measurements by Geotail have shown that earthward of 70 - 100 $R_E$ downtail, flux levels are roughly comparable for both earthward- and tailward-directed fluxes (Christon et al., 1996). However, tailward of 100 $R_E$, the tailward fluxes dominate. The tailward fluxes do not decrease with further downtail distance (observed to 208 $R_E$) whereas the earthward fluxes continue to decrease with downtail distance. The dominance of tailward-directed energetic ion flux downtail of roughly 100 $R_E$ is consistent with the statistical location of the distant reconnection site of about 140 $R_E$ mentioned above (Nishida et al., 1996a).

### 3.4. Estimates of the Magnetotail Reconnection Rate

The high-latitude particle precipitation, and in particular the sharp discontinuity between the polar rain and the plasma sheet precipitation, has allowed the separatrix location and the reconnection electric field to be estimated from ground observations (de la Beaujardiere et al., 1994; Blanchard et al., 1996). In one technique, the separatrix was identified from the gradient in the ionospheric E region density, using incoherent scatter radar (de la Beaujardiere et al., 1994). The radar also measures the ExB drift of the plasma, yielding the rate of flux transport across the separatrix, or the reconnection electric field.

In a more extensive analysis, the separatrix location was inferred from 630 nm optical emissions produced by the precipitating plasma sheet electrons (Blanchard et al., 1996). The ionospheric flow velocities were determined from incoherent scatter radar measurements. Estimates of the reconnection rate were obtained at all nightside magnetic local times and over varying solar wind conditions. Averaged over all levels of geomagnetic activity, reconnection electric fields were measured at all nightside local times and were found to peak over a 4-hour local-time sector centered on 2330 MLT. A weak correlation was found between the magnitude of the reconnection electric field and the southward component of the interplanetary magnetic field. The maximum correlation occurred with a 70 min lag, corresponding roughly to the time for open flux in the ionosphere to convect from the dayside reconnection site across the polar cap. The ratio of the estimated reconnection electric field to the solar wind electric field was found to be about 0.1, similar to estimates of the efficiency of dayside reconnection.

### 3.5. Source Regions for Auroral Activity

As illustrated schematically by the inverted V's in Figure 6, localized electron acceleration can be detected throughout the low-altitude extension of the plasma sheet. There is often evidence, however, that auroral activity is concentrated at the high-latitude and at the low-latitude edges of the plasma sheet. Two distinct locations of auroral luminosity have been described as the double auroral oval (Elphinstone et al., 1995a). From images taken by the Viking spacecraft, the presence of a nightside band of auroral luminosity near the open-closed field line boundary and a second band at lower latitudes has been described. This double oval is commonly observed during the late expansion and the recovery phases of substorms. The high-latitude auroral luminosity is likely to correspond to the electron acceleration that was shown to be colocated with the VDIS and with a region at the low-latitude boundary of the VDIS characterized by a void in ion precipitation, i.e., the gap (Bosqued et al., 1993a).

Two interpretations for the ion precipitation gap have been presented, with implications for the magnetotail processes responsible for the electron acceleration observed at high latitudes near the transition between the VDIS and the main plasma sheet. In one interpretation, the gap is due to strong non-adibatic motion in the neutral sheet (Bosqued et al., 1993b; Ashour-Abdalla et al., 1992). The magnetic field configuration expected to cause the non-adiabatic particle trajectories typically exist roughly 10-15 $R_E$ downtail from Earth. This interpretation would place the high-latitude portion of the double oval, and therefore also the separatrix, at roughly this downtail location. However, recent calculations of ion motion in the plasma sheet have contradicted this interpretation of the gap (Delcourt et al., 1996). In this study, it is argued that the near-Earth plasma sheet (roughly 10-15 $R_E$

downtail) should be the site of sufficient pitch angle scattering to maintain the ion precipitation, and therefore would not be the location of a gap in ion precipitation. It is suggested that the ion dynamics that could create a minimum in ion flux are likely to occur in the more downtail plasma sheet.

Another interpretation of the ion precipitation gap is that it maps to the transition from fast, earthward, post-reconnection flows in the distant plasma sheet to the more slowly convecting plasma sheet nearer Earth (Onsager and Mukai, 1995; 1996). The lack of ion precipitation is due simply to the low density and low temperature in the distant plasma sheet. The auroral arcs that were found to be co-located with the gap (Bosqued et al., 1993a) would then map to the location in the plasma sheet where there is a sharp gradient in the earthward convection speed in the neutral sheet. This high-latitude arc system mapping to just earthward of the distant reconnection site would be well separated from the low-latitude arc system, which presumably maps to the near-Earth edge of the plasma sheet, thus accounting for the observed double oval.

In the region equatorward of the open-closed field line boundary, interesting features are often observed in the form of equatorward-drifting auroral arcs (Persson et al., 1994a, b; Gazey et al., 1995). These are seen in the late growth phase and early expansion phase of substorm activity; however, their importance in the overall sequence of substorm events is not yet clear. What is known is that the poleward expansion of the substorm aurora does not alter their equatorward drift nor their luminosity, implying that they are formed in a region which is quite distinct from the substorm onset region where the cross-tail current is initially disrupted.

The formation of these arcs has been monitored by de la Beaujardiere et al. (1994) who associated them with weak bursts of reconnection at the distant reconnection site in quite times. The arcs do indeed appear to be on closed field lines. The electrons that cause these arcs are seen poleward of the persistent aurora that intensifies at onset (Elphinstone et al., 1995b) but equatorward of the field-aligned currents on the open-closed field line boundary (Fukunishi et al., 1993).

## 4. Summary

This article has described some of the recent advances in understanding the high-latitude, low-altitude particle precipitation in terms of the large-scale processes occurring in the magnetosphere. The discussion has concentrated primarily on our understanding of the low-altitude particle signatures in terms of the evolution of plasma following the occurrence of magnetic reconnection, either at the dayside magnetopause or in the magnetotail. Although it is certainly the case that not all observations can be understood by this simple paradigm, the commonly observed precipitation regions are typically well described in this way. Furthermore, the identification of the particle signatures as being the result of plasma evolution following reconnection has led to a number of important advances in our ability to identify separatrices locations and to quantify the rate and effects of reconnection.

In the dayside ionosphere, the cusp, mantle, and polar rain have all been shown conclusively to lie on open field lines. The particle flux levels and their spatial and temporal variability have been described quantitatively in terms of magnetosheath transport across open magnetic field lines. The specific features of the velocity-space distribution functions have provided important clues on the details of the reconnection process and on plasma transport across the magnetopause.

A debate still exists, however, on the location of the dayside separatrix relative to the low latitude boundary layer. There is considerable observational evidence near the low-latitude magnetopause to support both the open and the closed interpretation of the LLBL. The ambiguities near the magnetopause are further complicated at low altitudes by the convection of the magnetospheric and ionospheric plasma that spread the plasma originating from a given location in the distant magnetosphere over a broad region in the ionosphere.

In this paper, two possible separatrix locations in the ionosphere relative to the particle precipitation regions have been contrasted. In one case, the low-altitude CPS, BPS, and LLBL regions have been assumed to be on closed field lines, which is the more conventional interpretation. In the other case, the separatrix has been assumed to be within the CPS region, just equatorward of its polarward boundary. The local-time extent of the various regions, the ionospheric convection, and the precipitation features throughout the dayside ionosphere have been discussed for these two separatrix locations. It is argued here that the separatrix location within the CPS provides a more consistent description of the high-latitude ionospheric regions.

The discussion of the nightside precipitation regions has emphasized the clear transition from the open polar cap to the closed plasma sheet that is expected when reconnection is active in the magnetotail. The distinctive low-altitude plasma signatures have been compared with the commonly observed features in the downtail PSBL and with observations in the distant neutral sheet. From the observations in these different regions it is possible to demonstrate the global coherence over large distances of the processes occurring in the magnetotail.

From the identification of the low-altitude separatrix and the distinctive velocity space features measured in the particle precipitation, it has been possible to estimate remotely the properties of the distant tail reconnection. The rate of reconnection, the location of the reconnection site, and the properties of the plasma in the distant neutral sheet have all been obtained from the low-altitude measurements.

In addition, the location of the nightside particle precipitation regions relative to auroral luminosity have provided clues as to the regions in the magnetosphere where the auroral arcs map. The existence of the double auroral oval and the association of auroral arcs with the VDIS and the ion precipitation gap at its equatorward boundary indicate that this high-latitude arc system maps to the distant magnetotail, just earthward of the distant reconnection site. The low-latitude portion of the double oval maps presumably to the near-Earth plasma sheet and is the region of auroral luminosity where substorm onset is seen.

## Acknowledgements

The authors would like to sincerely acknowledge the support for this research provided by the International Space Science Institute. The collaborative workshops held at the Institute allowed for a critical exchange of ideas that contributed greatly to this manuscript. We would also like to thank the reviewers for their helpful comments and suggestions.

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