GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 12, PAGES 1665-1668, JUNE 15, 1999

The source population for the Cusp and Cleft/LLBL for southward IMF

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Abstract. The distinction between plasma properties in different dayside regions in the Earth's magnetosphere is of strong interest as it is often indicative of specific physical processes. This is certainly true for the distinction between low latitude boundary layer (LLBL) and cusp plasma, which has been attributed to the effects of plasma diffusion across the magnetopause (LLBL) versus a more direct entry of magnetosheath plasma (cusp). It is also the case, however, that quite different plasma regions can result more simply from a common source plasma, and from different stages of temporal evolution of the plasma associated with magnetospheric convection. In this paper, we show that, for southward interplanetary magnetic field (IMF) conditions, the distinction between the cusp and cleft/LLBL at low altitudes may result from the single process of magnetosheath plasma entry into the magnetosphere on reconnected field lines. The different plasma characteristics of the two regions result from the properties of the source magnetosheath ion distribution and the effects of magnetic reconnection. Using well known properties of the magnetosheath, several predictions concerning the cusp and cleft/ LLBL precipitation are readily derived.

Introduction

The Earth's magnetospheric cusps have long been recognized as a region where shocked solar wind in the magnetosheath has more or less direct access to the magnetosphere. Indeed, the initial identification of the cusps as ionospheric regions where the precipitating plasma had magnetosheath-like properties [*Heikkila and Winningham*, 1971] was recognition of access to these special regions. Later, it became apparent that this somewhat imprecise definition of the cusp had consequences for the interpretation of ion and electron data and, especially, on the mapping of the cusp to the dayside magnetopause. In particular, a cusp that had a significant latitudinal extent and a cusp that had a very narrow latitudinal extent may be formed by different plasma entry processes.

Over a decade after the initial cusp observations, a more precise definition of this region was developed from observations of low altitude ion and electron precipitation (zero pitch angle particles) [*Newell and Meng*, 1988]. The cusp (or cusp proper) was distinguished from the cleft/LLBL and, later, from the mantle [*Newell et al.*, 1991a]. *Newell and Meng* [1988] defined the cusp conceptually as the region in which plasma entry is more direct, with more direct meaning that particles make it to low altitudes and their spectral characteristics are close to those in the magnetosheath. Through the analysis of data from a large number of individual spacecraft passes through the dayside, high latitude region, this conceptual definition was placed on an observational footing. Flux and energy limits for cusp, cleft/LLBL (henceforth simply LLBL), and mantle precipitation were specified. As defined, the cusp had a relatively narrow latitudinal extent.

Figure 1 [from *Newell and Meng*, 1988] illustrates the critical distinction between the cusp and LLBL from a statistical standpoint. The energy spectrum was obtained by determining the peak precipitating ion flux in each average energy bin for many passes of a low altitude satellite through the dayside ion precipitation regions. Fluxes below (above) the break at 3 keV/e were defined as cusp (LLBL). *Newell and Meng* [1988; 1993] use this spectrum as evidence of a distinct cusp and LLBL and they argue that the ~3 keV/e breakpoint between cusp and LLBL flux is reflected in (and indeed derived from) energy spectra from individual spacecraft passes through the dayside, precipitation region.

The flux and energy definitions of the cusp, LLBL, and (later) the mantle form the basis of many statistical studies [e.g. *Newell and Meng*, 1992; *Lundin et al.*, 1991; and references therein]. Also, from these definitions it has been concluded that the LLBL is formed by plasma diffusion across the magnetopause and the cusp is formed by more or less direct entry. Observational results from some of these statistical studies that pertain directly to the cusp and LLBL are:

1)The density of the LLBL precipitation averages about one fifth (20%) of the cusp density [*Newell et al.*, 1991b].

2)In 85% of the cases near local noon, the LLBL is located equatorward of the cusp [*Newell and Meng*, 1988; 1992].

3)Although the ions (Figure 1) shows a break, there is no similar break in the electron spectrum [*Newell and Meng*, 1988].

Shortly after the initial observations of the cusp, it was realized that some properties of the region were consistent with a specific magnetosheath entry process: magnetic reconnection. In particular, the highest (lowest) energy magnetosheath ions precipitate the furthest equatorward (poleward) over a broad latitudinal extent for southward IMF conditions. Recent modeling [e.g., *Onsager et al.*, 1993; *Lockwood and Smith*, 1994] reproduces this energy-latitude dispersion by near subsolar magnetic reconnection and convection of the reconnected magnetic field poleward/tailward under the joint action of magnetic tension and the magnetosheath flow. In essence, the finite extent of the plasma entry region and the convection produces a velocity filter effect. Modeling of this effect has elucidated the flux differences of the mantle and cusp. These differences result from acceleration of magnetosheath plasma and changes in reconnection parameters as the reconnected field convects away from the subsolar region [*Onsager et al.*, 1993; *Lockwood and Smith*, 1994; *Newell and Meng*, 1994]. Thus, although the cusp and mantle are defined separately, they are part of a single broad precipitation region.

These same reconnection models have not been successful in reproducing a break in the energy spectrum at 3 keV/e which has been used to distinguish the cusp from the LLBL. To be sure, the common occurrence of higher energy LLBL precipitation equatorward of lower energy cusp precipitation

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Paper number 1999GL900354.
0094-8276/99/1999GL900354$05.00

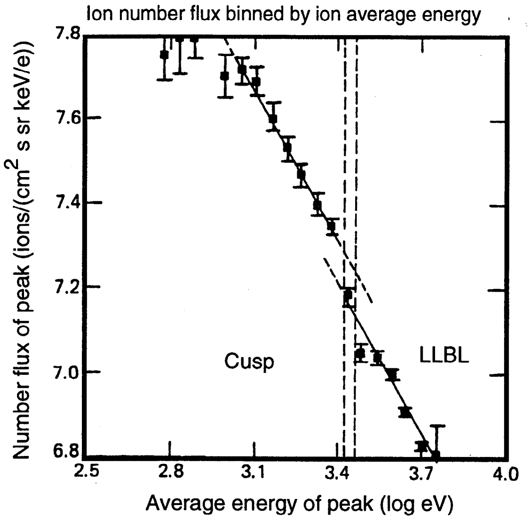

Figure 1. Peak flux spectrum from low altitude passes of a spacecraft through the dayside precipitation region (from *Newell and Meng* [1988]; note that the flux axis has been relabeled from the original figure). The vertical dashed lines are the division between the cusp and cleft/ LLBL precipitation.

is consistent with the velocity filter effect discussed above and suggests that southward IMF conditions dominate the data used to distinguish the cusp and LLBL. However, there has been no satisfactory explanation for a sharp change in flux at 3 keV/e for individual energy spectra or for the averaged spectrum in Figure 1 (e.g., the exchange between *Lockwood and Smith* [1993] and *Newell and Meng* [1993]).

Here, we present an explanation for a break in individual energy spectra at 3keV/e which reconciles the cusp and LLBL definitions with reconnection model for southward IMF. This explanation depends on general properties of the source magnetosheath ions and the effects of magnetic reconnection.

Magnetosheath plasma and cusp precipitation

If energy spectra from the dayside high latitude region commonly exhibit a break at 3 keV/e, then the characteristic shape of these spectra must result from general properties of the magnetosheath ion distribution. Figure 2 shows parallel and perpendicular cuts through a magnetosheath H^+ velocity space distribution. This distribution was observed in the subsolar magnetosheath downstream from the Earth's quasi-perpendicular bow shock [*Fuselier et al.,* 1988] and is a typical distribution observed in this region [e.g., *Sckopke et al.,* 1983]. The flow velocity in the subsolar magnetosheath is very small (~10's of km/s) and the cuts in Figure 2 are shown in the plasma rest frame. The distribution has two components, a relatively cool component and a hotter component with a break in the velocity distribution at about 500 km/s (or about 1.3 keV/e). Extensive studies of the Earth's bow shock have determined the origin of these two components [e.g., *Sckopke et al.,* 1983; *Gosling and Robson,* 1985]. The relatively cool component (<500 km/s) has at least 80% of the total magnetosheath density and is a population of directly transmitted solar wind ions that is heated somewhat greater than adiabatically. The hotter component (>500 km/s) can have up to ~20% of the total magnetosheath density and is a population of ions that reflected off the quasi-perpendicular shock, performed a partial gyration into the upstream region, gained energy through this gyration, re-encountered the shock, and entered the downstream magnetosheath.

In Figure 2, there is a break in the magnetosheath ion distribution and, from the discussion above, the higher energy population is ~5 times less dense than the lower energy population. Thus, the relative densities of the two magnetosheath populations are consistent with the relative densities of the cusp and LLBL precipitation. However, the break in the magnetosheath distribution (Figure 2) is at 1.3 keV/e while the break in the peak flux distribution (Figure 1) is at 3 keV/e.

Near-subsolar magnetopause reconnection changes the ion distribution that enters the magnetosphere along the open field lines. Figure 3 illustrates these changes as viewed from the sun looking at the subsolar magnetopause. The lighter shaded contours show the incident magnetosheath distribution and the solid contours show the distribution just inside the magnetosphere (i.e., in the LLBL). The incident distribution has properties similar to those in Figure 2. In particular, it has two populations and its bulk flow velocity is small compared to the thermal speed of the total distribution.

For a magnetopause that can be approximated by a one-dimensional rotational discontinuity, there is a frame of reference moving along the discontinuity, called the deHoffman-Teller (dHT) frame, where the bulk flow on either side of the discontinuity is field-aligned and at the local Alfven speed ($|V_A|$) [*Hudson,* 1970]. This speed is typically smaller than the thermal speed of the hotter magnetosheath component. For example, in Figure 2, $|V_A|$ is ~100 km/s and the thermal speed of the hotter component is ~500 km/s. On crossing the magnetopause, individual ions conserve energy in the dHT frame [e.g., *Cowley,* 1982]. Pitch angle conservation is an easy way to achieve energy conservation [e.g., *Paschmann et al.,* 1989]. Thus the distribution rotates into the LLBL and is field-aligned and moving at V_A in the dHT frame. In the spacecraft frame, the bulk flow of the distribution has gained ~$2V_A$ across the magnetopause. In the incident distribution, ions with $V >-V_A$ have a chance to cross the magnetopause. An additional effect is the reflection of ~50% of those ions incident on the magnetopause [e.g., *Fuselier,* 1995].

In summary, the LLBL ion distribution (solid contours in Figure 3) is accelerated in the spacecraft frame of reference, reduced by a factor of at least 2 in density from the magnetosheath distribution, and has a characteristic "D" shape [e.g., *Cowley,* 1982; *Fuselier et al.,* 1995]. Although the details of this acceleration process depend on the bulk flow in the magnetosheath (typically small in the subsolar region compared to the thermal speed), the local Alfven speed (also small compared to the thermal speed of the hotter component), and

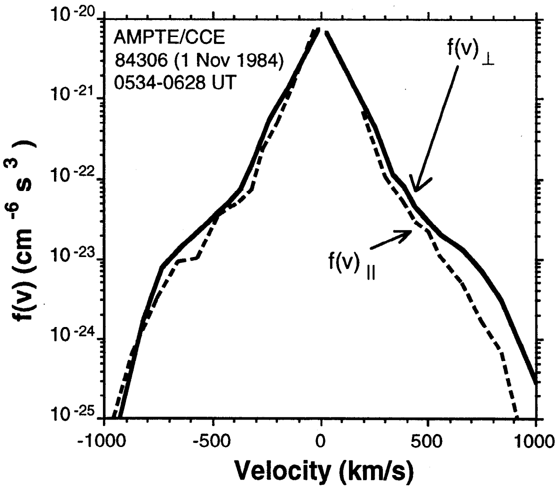

Figure 2. Cuts through a magnetosheath H^+ distribution. The distribution consists of a lower energy component (<500 km/s) which has ~80% of the density and a higher energy component which has the remaining ~20% of the density.

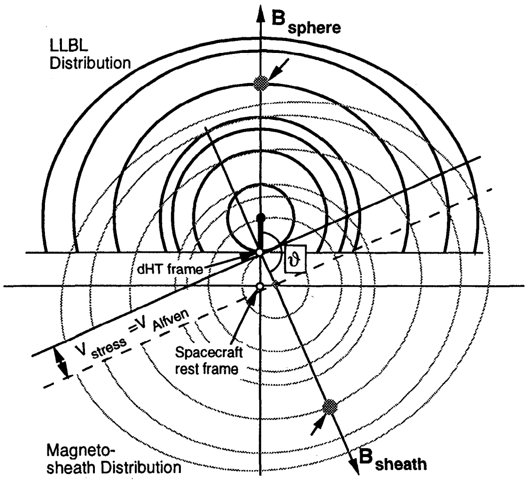

Figure 3. Changes in a magnetosheath ion distribution (lightly shaded contours) by magnetic reconnection and transmission into the open LLBL (solid heavy contours). In the deHoffman-Teller frame, energy and pitch angle are conserved across the magnetopause and the magnetosheath and LLBL distributions are field-aligned and at V_A. In the spacecraft frame, the LLBL distribution is accelerated by ~2 V_A. The large dots along the magnetic field directions show the breakpoint in the two component distribution in Figure 2.

the shear across the magnetopause, the general changes in the magnetosheath distribution are similar to those illustrated in Figure 3. This acceleration of the plasma across the open magnetopause with no net change in energy in the dHT frame is an important element in modeling of cusp ion precipitation [e.g., *Onsager et al.*, 1993; *Lockwood and Smith,* 1994].

The net effect of reconnection is a ~2V_A acceleration of ions crossing the magnetopause (Figure 3). The break in the magnetosheath ion distribution at ~500 km/s along the magnetic field in Figure 2 (i.e., the large dot along B_{sheath} in Figure 3) rotates through the angle ϑ and is at ~500 km/s + 2V_A in the LLBL (i.e., the large filled circle along B_{sphere}). With V_A ~100 km/s, the break point for the accelerated ion population is field aligned at ~700 km/s, or at an energy of 2.5 keV/e. Thus the break in the distribution on open field lines just inside the subsolar magnetosphere and the break in the peak flux spectrum in Figure 1 are at similar energies.

To illustrate this similarity, the distribution in Figure 2 was transformed into an LLBL distribution. First, the parallel cut in the magnetosheath distribution was fit with two Maxwellians. The first, representing the lower energy component, had 82% of the total density and a thermal velocity of 200 km/s. The second, representing the higher energy component, had 18% of the total density and a thermal velocity of 500 km/s. These components were transformed into the LLBL using a construction similar to Figure 3 with an Alfven speed of 100 km/s and a transmission coefficient of 50%.

The open squares in Figure 4 are the resulting flux spectrum assuming that the distribution at zero pitch angle precipitated unchanged into the low altitude cusp. The solid squares are the peak flux (also at zero pitch angle) from Figure 1, normalized to the expected flux of the precipitating magnetosheath distribution at 3 keV/e. This normalization was done to compare the two spectral shapes and is necessary because the peak flux in Figure 1 was obtained from a large sample of low altitude observations while the expected flux is derived from a single distribution in Figure 2 observed during a high density magnetosheath interval [see, *Fuselier, et al.*, 1988].

At energies between 2 and 5 keV/e, the two flux spectra agree very well. This includes the break in the spectra at ~3 keV/e. Below 2 keV/e in Figure 4, the peak flux spectrum begins to deviate from the expected precipitating magnetosheath flux. This low-altitude distribution was constructed assuming a uniform magnetosheath source along the magnetopause surface. In reality, the magnetosheath plasma density and temperature decreases and its bulk velocity increases with distance from the subsolar magnetopause. Thus, cusp ions fluxes at different energies depend on the evolving properties of the magnetosheath plasma. Through this evolution, the low-energy flux is reduced, ultimately giving rise to the distinction between the cusp and the mantle precipitation [e.g., *Onsager et al.,* 1993; *Newell and Meng,* 1994]. Gas dynamic models of the magnetosheath plasma evolution along the magnetopause indicate that the density decreases by a factor of ~4 from the subsolar point to the terminator at high latitudes. This is quantitatively consistent with the difference between the expected and peak fluxes <1 keV/e in Figure 4.

Interest here is centered on the higher energy precipitation near 3 keV/e, where the plasma originates from the subsolar region. The break at 3 keV/e results primarily from the general properties of the magnetosheath ion distribution, with some energy increase occurring as the ions cross the magnetopause. Thus, a break will occur in individual energy spectra from the high latitude region as well as in an average spectrum like the one in Figure 1. The similarity in the high energy portion of the spectra in Figure 4 indicates that both the LLBL and the cusp ion precipitation are accounted for simply from the direct entry of magnetosheath plasma on reconnected field lines.

Conclusions and Predictions

In this paper, it was shown that the fundamental energy and flux distinction between the cusp and the LLBL precipitation can be explained as a natural consequence of the characteristics of the source plasma in the magnetosheath and magnetic reconnection at the dayside magnetopause. By assuming that this source plasma undergoes reconnection for southward IMF, a break in the energy spectrum for individual spectra from the dayside high latitude region is reproduced at ~3 keV/e. Other features, which result from statistical studies using the cusp and LLBL definitions, follow directly from the properties of the magnetosheath plasma and the effects of dayside reconnection and the velocity filter effect. In particular:
1) The density of the LLBL precipitation averages about one fifth (20%) of the cusp precipitation [*Newell et al.*, 1991a] because the density of the higher energy population in the

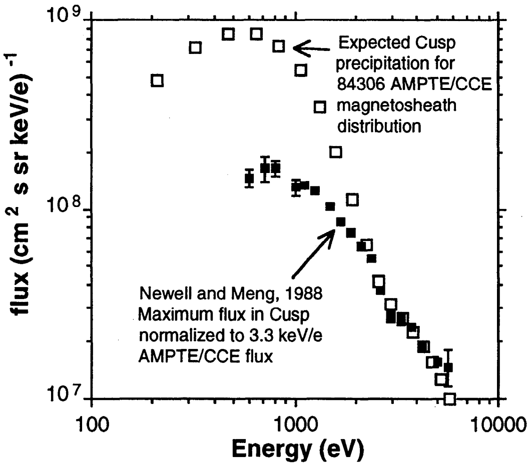

Figure 4. Expected precipitating magnetosheath flux into the cusp compared to the peak flux spectrum from Figure 1. The peak flux was normalized to the expected flux at 3 keV/e. The two spectra compare well for E>2 keV/e including the break at ~3 keV/e. At lower energies, the two curves deviate.

magnetosheath is typically $\sim$20% of the density of the lower energy population [e.g., *Fuselier and Schmidt*, 1994].

2) Near local noon, the LLBL is typically located equatorward of the cusp [*Newell and Meng*, 1988; 1992], because the LLBL plasma has higher energy and therefore will precipitate equatorward of the lower energy cusp precipitation for southward IMF conditions. The intervals used by *Newell and Meng* [1988; 1992] likely occurred under both southward and northward IMF conditions. However, 85% of the time, the cusp was observed poleward of the LLBL; a condition consistent with southward IMF. It is well known that the energy-latitude precipitation pattern reverses for northward IMF, so that the most energetic ion precipitate furthest poleward. The model described here would require important modification to investigate this condition. This modification includes the addition of a substantial magnetosheath flow in Figure 3 to be consistent with a high latitude reconnection site. Also, the mapping from the entry point to low altitudes would require knowledge of the electric field to the extent that an electric field model could be constructed similar to those used for southward IMF mapping [e.g., Onsager et al., 1993]. No modification of the magnetosheath population is required since it is independent of IMF clock angle. Therefore, the break in the energy spectrum in Figure 2 may survive to low altitudes regardless of IMF orientation.

3) There is no similar break in the precipitating electron spectrum [*Newell and Meng*, 1988] because the magnetosheath electron distribution does not have a break in the flux spectrum like the ion distribution in Figure 2 [e.g., *Feldman,* 1985].

Because magnetosheath properties are well known, several predictions are easily derived from the above interpretation of cusp and LLBL precipitation for southward IMF. These predictions are readily tested with large data sets of cusp and solar wind observations or, for some predictions, magnetosheath and cusp ion observations. Predictions include:

1) The energy at which the break in the flux spectrum occurs will depend on the thermal velocity of the lower energy magnetosheath population, the upstream solar wind speed (which determines thermal velocity of the higher energy magnetosheath population), and the reconnection parameters at the magnetopause (i.e., V_{Alfven}, the magnetic shear, etc.)

2) The density of the LLBL precipitation will be a function of upstream Mach number. This is because as the magnetosonic Mach number decreases from 4 (typical of the solar wind) to 1, the specularly reflected/transmitted ion density decreases from $\sim$20% to 0% [e.g., *Fuselier and Schmidt*, 1994].

3) When the subsolar region is downstream from the quasi-parallel shock, the flux spectrum will change considerably and a break in the flux spectrum at $\sim$3 keV/e may not be observed. Downstream from this type of shock, a two population ion distribution such as in Figure 2 is less evident but a third population, with $\sim$1% of the total density and a thermal energy of $\sim$10 keV/e is ubiquitously present [e.g., *Gosling et al*., 1989]. Recently, this energetic solar wind ion population was identified in the cusp [*Chang et al*., 1998]. An energetic population may also be produced by reflection of magnetospheric ions off the Alfven wave internal to the magnetopause in the subsolar region [*Lockwood et al*., 1996]. Composition measurements in the cusp should distinguish this magnetospheric population from an energetic solar wind population.

Acknowledgments: Research at Lockheed Martin Advanced Technology Center is supported by NASA under contract NAS5-30302.

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(Received Jan. 25, 1999; revised May 4, 1999; accepted May 6, 1999)