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THE MAGNETOSPHERIC CUSP: STRUCTURE AND DYNAMICS

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ABSTRACT

Understanding the polar cusps is essential for a thorough understanding of the entire physics of the magnetosphere, and of the dynamical interaction between the solar wind and any planetary magnetosphere. Energetic electrons are unique to fully assess magnetic field-line topology and thus should be able to clearly delineate regions of open and closed magnetic field lines in the high latitude regions and contributed crucially to understanding and resolving an internal debate going on between groups measuring only the lower energy (< 20 keV) plasma. Energetic electrons with high and stable flux were observed in the high latitude boundary/cusp region when the IMF had a predominate positive B_z component. With measurements at larger separations and more coordination of multiple satellite measurements for particular cusp crossings will it become more evident what the true nature of the cusp is and what roles the cusps play. The boundary normal, velocity and timing analysis obtained by all four spacecraft indicates that the multiple cusp phenomena is most likely caused by the oscillation of the single northern cusp which was shifted back and forth. Cusp oscillating with a period of 22 min are observed by Cluster satellite in the high latitude region, in the meantime, the cold-dense plasma with fluctuations (20 min period) are observed in the dusk-side of the tail plasma sheet by Geotail satellite. This is consistent with the idea that the high latitude reconnection during northward IMF is the responsible mechanism of the formation of the cold-dense plasma sheet.

1. BRIEF HISTORY ON THE CUSP

- *~Qin dynasty (221-206 B.C.) Magnetic compass discovered in China. The first person recorded to have used the compass as a navigational aid was Zheng He (1371-1435),*

from the Yunnan province in China, who made seven ocean voyages between 1405 and 1433.

- *1600 William Gilbert publishes in London "De Magnete" ("on the magnet"). His explanation of the compass: the Earth is a giant magnet.*
- *Maxwell (~1880) showed that a perfect conductor adjacent to a dipole formed an image dipole*
- *Chapman and Ferraro (1931) first induced the basic nature of the Earth's magnetosphere, its 2-D and 3-D topology has indicated the existence of a dayside magnetic cusp.*
- *Spreiter and Summers (1962) predicted a stagnation flow in the cusp region by using a gas dynamics model*
- *Heikkila and Winningham (1971) and Frank (1971) showed a high-latitude band of low-energy particle precipitation with magnetosheath-like properties on the dayside at low altitudes which have been accepted as the first evidence to discover the magnetospheric cusp.*

2. INTRODUCTION TO THE CUSP

The boundaries of the magnetosphere including the polar cusp are key regions for the transfer of mass, momentum and energy from the solar wind into the magnetosphere no matter IMF is southward or northward. The first identification of a thin layer of magnetosheath plasma located immediately inside the magnetopause was made by Hones [1972] who also

introduced the term "Boundary Layer". Since then, the morphological characteristics as well as plasma properties of the magnetospheric boundary layer have been studied rather intensively [Rosenbauer et al., 1975; Eastman et al., 1976; Haerendel, 1978; Lundin et al., 1985a, 85b; Newell et al., 1988, 1998]. The term "Low-latitude boundary layer", was apparently introduced by Haerendel [1978] to distinguish the very different properties observed at latitudes below about 50° - 60° on the magnetopause surface. In addition there are three more boundary regions (in the high latitude) which are assumed to connect directly to the magnetosheath: They are the plasma mantle, the entry layer and the exterior cusp or stagnation region, seen in Figure 1.

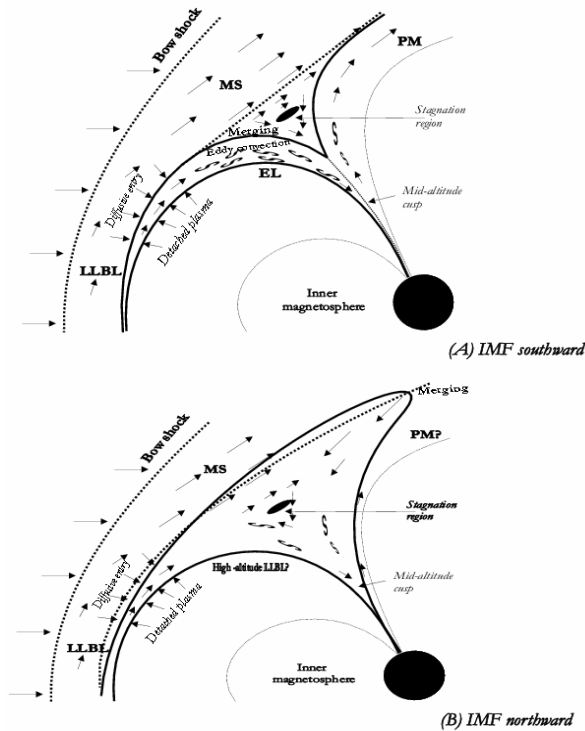


Figure 1. Sketch of the dayside boundary regions related to the polar cusp field lines during southward (after Haerendel, 1978) and northward IMF. MS – magnetosheath; PM – plasma mantle; LLBL – low latitude boundary layer; EL – entry layer.

The plasma mantle is located on the open field lines where the injected magnetosheath plasma continues tailward which was first reported by Rosenbauer et al. [1975]. The plasma density in this region towards sheath density level and the $\beta \ll 1$. The entry layer [Paschmann, 1976] is located on the magnetospheric field lines just equatorward of the cusp. It is a region of diffusive, turbulent entry of magnetosheath plasma onto field lines that map to the low-altitude cusp. It has been so termed because it appears to be the region of dominant plasma entry into the magnetosphere. The transport mechanism is likely to be achieved through eddy convection which manifests itself in the irregular,

low speed plasma flow, and may be incited by the turbulence in the adjacent exterior cusp [Haerendel et al., 1978]. The exterior cusp / stagnation region is bounded on the inside by the cusp-like indentation of the magnetopause and outside by the free-flow stream line of the magnetosheath flow which Sckopke et al. [1976, 1981] constitutes a pocket of hot and 'stagnant', possibly turbulent plasma. In fact, as early as 1960's, the stagnation region is already predicted by gas dynamics models [Spreiter et al., 1967, 1980]. Furthermore, this picture has been corroborated by HEOS 2 measurements [Sckopke et al., 1976; 1981]. The stagnation region cannot be linked to the plasma mantle or LLBL in a simple way. A qualitative explanation was given by Haerendel et al. [1978] who noted the similarity of the situation near the cusp to hydrodynamic flow around a corner, in which vortex formation and separation are known to occur and to initiate some level of turbulence (Figure 1). The exterior cusp region appears to be a steady high pressure center of "stagnant" magnetosheath plasma, the flow in this region is rather turbulent, both in magnitude and direction.

The mantle is generally thicker for southward than northward IMF Bz [Sckopke et al. 1976]. These original researchers believed that the plasma mantle is open, and the LLBL is closed. It has been indicated that in the HLBL (Entry layer) the plasma density is almost as high as the magnetosheath but generally lacks the strong antisunward plasma flow. In fact, even sunward flow has been reported by Paschmann [1976]. Lundin et al. [1985] suggested that one of the characteristic features of the entry layer is the strong variability of magnetosheath plasma entry with frequent plasma injections. On the basis of Defense Meteorological Satellite Program (DMSP) F2 data, Newell et al. [1987] indeed observed that the cusp low-altitude latitudinal extent is narrower when Bz is southward than when Bz is northward. This has been interpreted that the enhanced convection flow is too rapid to allow the plasma to reach low altitudes. In non-reconnection models the cusp position and extent are less sensitive to the IMF, but more strongly dependent on the solar wind ram pressure.

Only a few satellites such as HEOS-2, Prognos-7, Hawkeye and Polar have made in-situ observation in the high-latitude boundary layer regions where the proposed entry for the northward IMF takes place. The high latitude boundary layer has scarcely been studied compared to the region around the subsolar point.

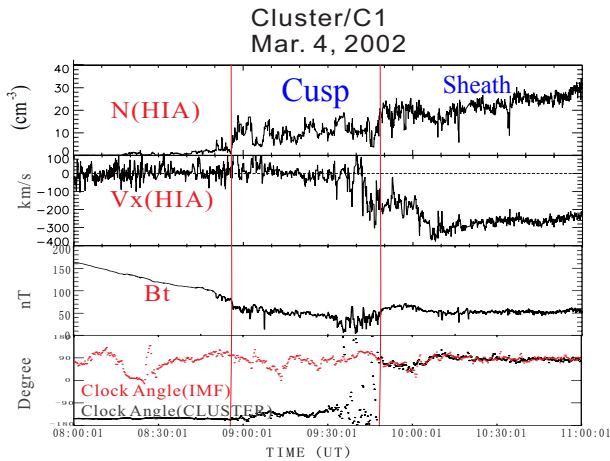


Figure 2: A typical cusp observed by Cluster satellite: CIS plasma moment and magnetic field obtained by Cluster (Rumba) from 08:00 to 11:00 UT, Mar. 4, 2002. The plasma density and plasma velocity V_x are given in the first and second panels. The magnetic field magnitude (in nT) are shown in the third panel. The magnetic field clock angle obtained by ACE (IMF) and Cluster satellites (local) are plotted in the bottom panel.

3. THE DEFINITION OF THE MAGNETOSPHERIC CUSP

In the text book, the polar cusps are usually defined as funnel-shaped areas in the high latitude of both hemispheres with near zero magnetic field magnitude. They provide a direct entry for the magnetosheath plasma into the magnetosphere [e.g., Reiff et al., 1977; Marklund et al., 1990]. However, the definition of the cusp used by MHD simulation [Siscoe et al., 2005] is "a weakening of the magnetic field owing to a pool of magnetosheath plasma within the magnetosphere - since the current is the plasma's diamagnetic current associated with the field weakening" or in concept as "a region of open field lines extending poleward from the open/closed boundary (which is tied to the dayside merging region on the magnetopause) to where particles no longer are able to directly enter". However, there is not always a clear distinction between such a conceptual definition, some observational identifications, and actual determinations of when the cusp is really being observed by a given spacecraft. The primary and the most widely used method of identifying the cusp is by means of a combination of plasma and magnetic field observations, although just plasma or magnetic field measurements have been used in the past in some cases. Using both sets of observational data the cusp has been defined as a high latitude region with a population of particles of shocked solar wind energies and density somewhere within or near the local noon sector, the criteria are:

- I. turbulent and depressed magnetic fields,
- II. High density plasma (\sim sheath level),
- III. Stagnant plasma flow ($V_x \sim 0$),
- IV. The clock angle criterion (the Cusp clock angle should be different with the IMF's), an example of observed cusp is shown in Figure 2.

A number of questions that now need to be investigated in detail: What is the importance of the cusp to the physics of the magnetosphere and the topology of the front side high-latitude magnetopause? What's the nature of the boundaries between different regions? What's the plasma transport mechanism through the cusp and the boundary layers? Are the observed double or triple cusps temporal or spatial effect? How are they formed? What's the role of the cusps in supplying plasma to the plasma sheet? Are there multiple cusps active at a given time? Or does a single region move around more and faster than its low altitude counterpart? Only with measurements at larger separations and more coordination of multiple satellite measurements for particular cusp crossings will it become evident what the true nature of the cusp is and what roles the cusps play. Understanding the polar cusps is essential for a thorough understanding of the entire physics of the magnetosphere, and of the dynamical interaction between the solar wind and any planetary magnetosphere.

4. ENERGETIC PARTICLES IN THE HIGH LATITUDE BOUNDARY/CUSP REGION

4.1 OBSERVATIONS

Figure 3 shows the different regions -- southern HLTR/cusp, radiation belt and northern HLTR/cusp as obtained by Cluster/RAPID during these two consecutive orbits. The geomagnetic index Dst is shown in the top panel. The first two cusp crossings (1 and 2) happened during a rather quiet time period; the Dst indices were small and positive. The later two crossings (3 and 4) occurred in the main phase of a strong magnetic storm. As we can see from Figure 3, the high latitude magnetosphere (both northern and southern HLTR/cusp) regions are two of three locations that energetic particle are encountered. Both southern and northern high latitude boundary and/or cusp regions can be distinguished easily by the fact that (1) the ion flux increased sharply in all energy channels from 30 to 400 keV, whereas (2) the energetic electron flux which appeared during quiet time was not present during disturbed time.

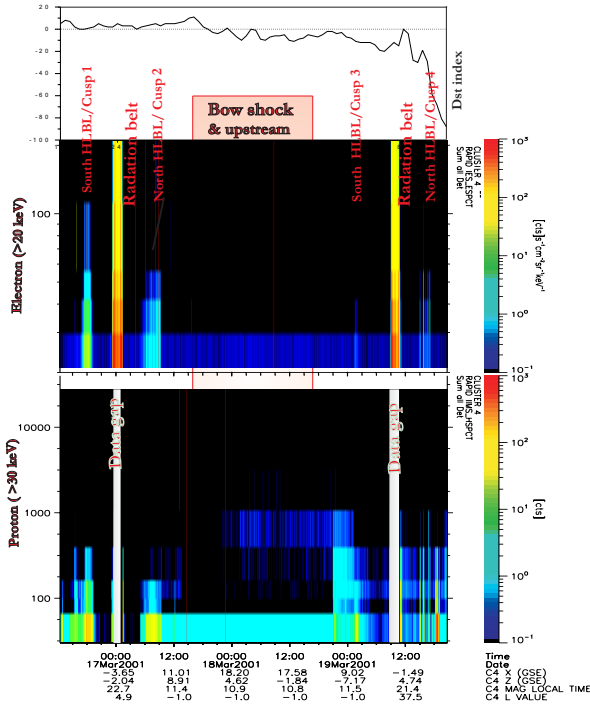


Figure 3: An overview of RAPID data from 09:00 UT, March 16 to 21:00 UT, March 19, 2001 together with geomagnetic activity Dst index. From the top the panels show: Dst index; electron spectra from 20 to 400 keV; and proton spectra from 30 to 2000 keV. The marks indicate the different regions -- the southern HLBL/cusp, the radiation belt and the northern HLTR/cusp which Cluster experienced during a full orbit. The 'cusp' here refers all the high latitude magnetospheric regions, the 'radiation belt' here refers all inner magnetospheric regions, and two data gaps are indicated [Zong et al., 2005].

During the above two quiet time high latitude boundary/cusp crossings, there were pronounced fluxes of electrons in the high latitude boundary/cusp region, indicating either a closed field line geometry in the cusp region, a special open field line configuration that could trap electrons very efficiently for a long time or a long-lived source supplying these electrons to open field lines. These electrons lasted about 2 hours (from 1706 to 1907 UT, 16 March 2001) and 3 hours 20 min (from 0600 to 0920 UT, 17 March 2001), respectively. Furthermore, no obvious substorm injections were observed by the Los Alamos satellites for both of the above quiet time high latitude boundary/cusp crossings. Further, there were no energetic electron events observed by ACE in the upstream interplanetary space during 16-19 March. Thus, these observed electrons should not be solar energetic electrons as described by

Lin [1985] and Klassen et al. [2002]. The lack of substorm activity and high fluxes of electrons upstream at ACE indicates that the observed electrons are locally trapped electrons rather than substorm injected electrons drifting to the high latitude region or solar flare related electrons. In contrast, two consecutive HLBL/cusp crossings during geomagnetically disturbed times are.

4.2 SINGLE PARTICLE SIMULATION

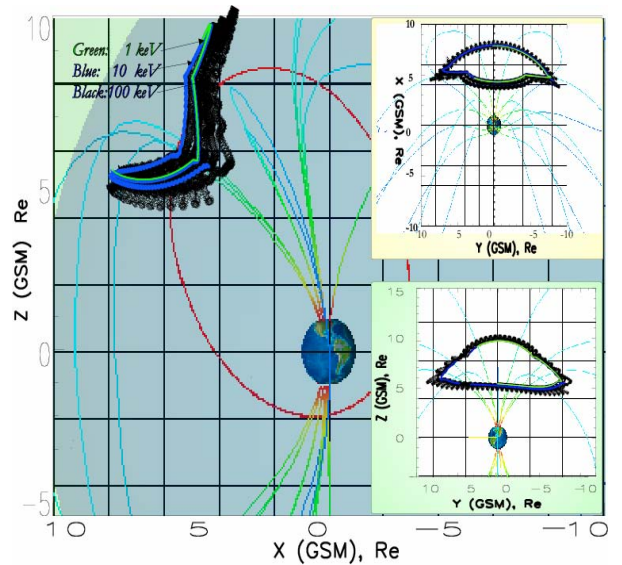


Figure 4: The trajectory of protons (1, 10 and 100 keV) with 90° pitch angle in the Tsyganenko 96 model.

We have seen in session 4.1 there are energetic particles in the high latitude boundary/cusp region during northward IMF. Statistical study showed that energetic ions have been observed in the cusp region during most of the crossings (80%) [Zhang et al., 2005]. This indicates that those particles are trapped in the high latitude region. In this session, we will interpret this observation with single particle simulation.

According to the traditional dipole field model, the dayside high latitude or cusp region cannot trap particles [Roederer, 1970; 1977]. The cusp region of the ideal dipole field is not an "excluded region" in the Störmer theory [Störmer, 1911]. This means that, in the high latitude region, the particles cannot be trapped for much longer than the bounce time; the E X B drift will take the particles away. However, the dipole field can be modified fundamentally by interaction with the solar wind. The outer cusp regions where the magnetic field lines either close in the dayside sector or extend into the night side sector over the polar cap could be caused by

reconnection. This region is a region of weak magnetic field, which is directly from the interaction of the solar wind with the geomagnetic field predicted by Chapman and Ferraro [1931] by using a simple image dipole, as shown by the magnetic field model of Antonova and Shabansky [1968].

Instead of a dipolar field, the cusp region appears to be quadrupolar. However, the importance of the existence of an off-equatorial B-minimum in the outer cusp has been underestimated for a long time, although it could be of extreme importance for understanding the behavior of energetic particles in the magnetosphere. Antonova and Shabansky [1968] and Shabansky [1968] noted that, with a minimum magnetic field existing off the equator in the outer cusp region, charged particles would not drift but rather branch off towards the magnetic field minimum at high latitudes. This has also been supported by in situ magnetic field measurements [Zhou et al., 1997].

Shabansky [1971], Antonova and Shabansky [1975] provided observational evidence for the trapping of energetic particles (of several tens of keV, up to a few hundreds of keV) in the high latitude region. Sheldon et al. [1998] pointed out that an energetic electron will drift on a closed path around the front of the magnetosphere, and found that electrons could be trapped in the outer cusp. In fact, a temporary trapping in the cusp field minimum was first examined by Delcourt et al. [1992]. Further, Delcourt and Sauvaud [1998, 1999] pointed out that, under the effect of the cuspward mirror force near the dayside magnetopause, energetic plasma sheet particles initially mirroring near the equator are expelled from low latitudes and subsequently swept into the boundary layer at high latitudes.

Figure 4 shows trajectories of test protons (1, 10, 100 keV) launched with 90° pitch angle from the cusp region. The trajectory tracing was performed using the Tsyganenko 96 model. In this calculation, the full particle dynamics have been considered, not just the guiding center computation; the calculation was performed using a fourth-order Runge-Kutta technique with a time step adjusted to some fraction of the particle gyration periods. It can be seen from Figure 8 that the test protons launched from the local minimum magnetic field region encircle the outer cusp region; all of the protons experience a pronounced bouncing motion in the high latitude region which differs from mirroring motion on either side of the equator (as ring current ions). Figure 4 shows that the ion trajectories in the outer cusp region are somewhat similar to those on L shells of a dipolar magnetic field. The limiting second invariant of these trapped orbits occurs when the mirror

point B_{min} approaches the dayside equatorial field strength; in the local gradient field they drift away from the cusp.

These ion trajectories exist both on the dayside (equatorward, with closed magnetic field lines) and the mantle region (poleward, with open magnetic field lines). This behaviour follows from the existence of a local B minimum during the drift path from the closed field lines region to the open field line region in the frontside magnetosphere.

It should be pointed out that large-scale magnetospheric convection is not accounted for in the present modelling results in the trajectory computation. If convection is accounted for, as pointed out by Delcourt and Sauvaud [1999], these closed drift paths in the outer cusp may be opened (see Figure 13 of Delcourt and Sauvaud [1999]). However, the present modelling results could apply to quiet times when magnetospheric convection is reduced and the convection electric field may be only 5% of its value during active times.

The observed energetic electrons in the high latitude boundary region may be provided by tail plasma sheet particles because of a minimum magnetic field existing off equator in the high latitude region of the magnetosphere. Delcourt and Sauvaud [1998, 1999] pointed out that under the effect of the cuspward mirror force near the dayside magnetopause, energetic plasma sheet particles initially mirroring near the equator are expelled from low latitudes and subsequently swept into the boundary layer at high latitudes. Both electrons and ions can be stably trapped in the high latitude region during quiet periods. This conclusion is supported by both the observations and the modelling results mentioned above. As magnetospheric convection is enhanced, the electrons initially trapped in the high latitude region could be de-trapped [Delcourt and Sauvaud, 1998, 1999]. In fact, no stable trapped electrons were observed during active times (see Figure 3). These de-trapped electrons could further form an electron layer just outside the magnetopause as observed [e.g., Meng and Anderson, 1970 and Baker and Stone, 1977].

5. THE BOUNDARY BETWEEN THE CUSP AND MAGNETOSHEATH

The high latitude boundaries include boundary between the magnetosheath and cusp, the boundary between the magnetosheath and the High Latitude Trapping Region (HLTR) which is the closed field line region on the dayside in the high latitude region, the boundary between cusp and HLTR and the boundary between

mantle and cusp. The properties of the high latitude boundaries vary rather dramatically under different solar wind conditions. We present statistical results based on 4 years of data obtained by Cluster when these spacecraft were in the vicinity of the dayside magnetopause. During northward Interplanetary Magnetic Field (IMF), the interfaces between the magnetosheath and cusp are rather clear. The changes of the energetic particle flux, plasma temperature, density and velocity across the magnetopause under northward IMF were analyzed by superposed epoch analysis. The plasma flow and density decrease and the proton temperature increases across the magnetopause from the magnetosheath into the cusp. Further, during extreme storm times, the cusp is more turbulent than during quiet times and there is no clear plasma density change across the magnetopause.

5.1 BOUNDARY AND CLOCK ANGLE OF THE IMF

The boundary between the magnetosheath and the cusp has been studied by Lavraud et al. We have found that the boundary between the magnetosheath and the cusp is clear sometimes but unclear at other times. The definition for a clear boundary is: There is a jump in plasma flow ($> 30 \text{ km/s}$) (e.g., a flow change from 100 km/s to 0) and at least two components of the magnetic field ($> 5 \text{ nT}$) (e.g., the magnetic B_y and B_z change from -10 nT to $+10 \text{ nT}$).

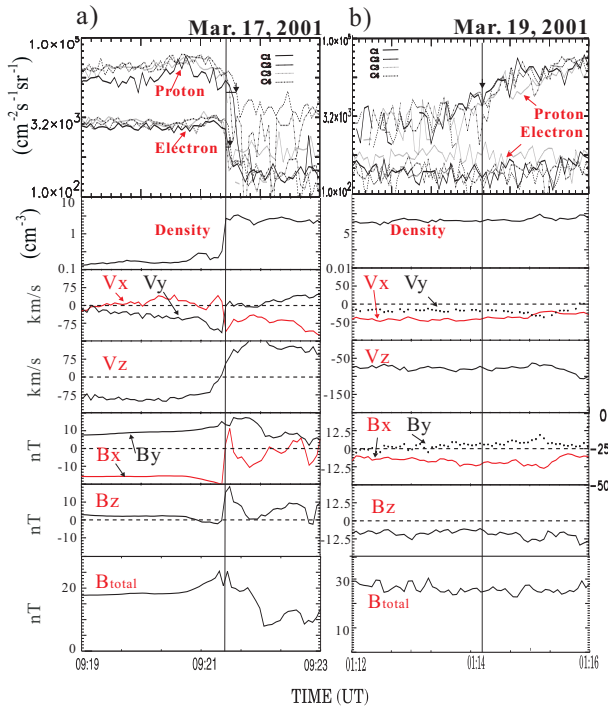


Figure 5: Examples for clear and unclear boundary. a) Clear boundary on Mar. 17, 2001 b) Unclear boundary on Mar. 19, 2001. From the top, the panels indicate

integral electron and proton fluxes; plasma ion density, plasma ion velocity V_x , V_y and V_z (in km/s), and superposed magnetic field B_x , B_y and B_z components for spacecraft 1 (Rumba).

Figure 5 shows an example for a clear and unclear boundary. Figure 5 a) shows a clear boundary observed by Cluster when it travels outbound from the northern magnetosphere into the magnetosheath on March 17, 2001. From this figure we can see that all the parameters including energetic proton and electron flux, plasma density, velocity and magnetic field have clear boundaries. Figure 5 b) shows an unclear boundary observed by Cluster when it travels inbound from the magnetosheath into the southern magnetosphere on March 19, 2001. We can see from this figure that all the parameters except energetic proton flux have no clear boundaries. We don't know exactly where the boundary is since the parameters change smoothly from the magnetosheath in the magnetosphere if we look at the plot for a longer time which is not shown here, so we put the vertical line which indicates the boundary location at the location where energetic proton flux changes a lot.

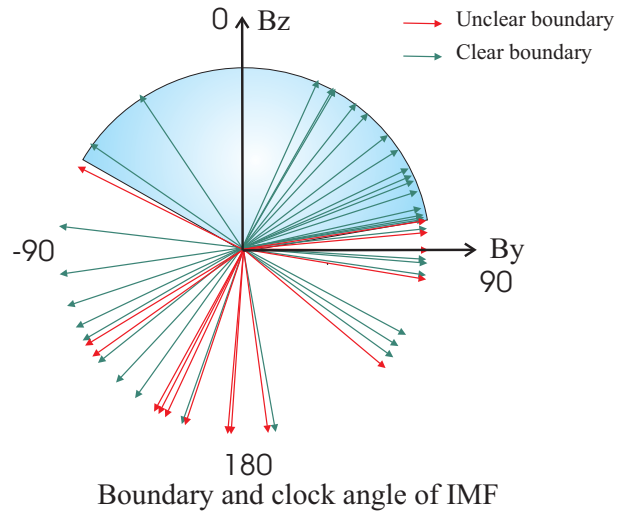


Figure 6: The IMF clock angle dependence of the boundary between the magnetosheath and cusp.

We have surveyed Cluster data in 2001 and 2002 and found that almost all the boundaries between the HLTR and the magnetosheath are clear (looks like Figure 5 a)). However the boundary between the cusp and magnetosheath is more complicated. Sometimes it's clear and sometimes it's unclear (looks like 5 a) and b) respectively). It's found that there is some relationship between the boundary and the clock angle of the IMF. In Figure 6, all the boundaries between the cusp and the magnetosheath in 2001 and 2002 are shown. The arrows

indicate the IMF direction projected in the GSE YZ plane. The red arrows indicate unclear boundaries and green arrows indicate clear boundaries. In the shaded region, all the arrows are green which means when the IMF clock angle is between -65 and 81 degree, the boundary between the magnetosheath and the cusp is clear.

5.2 QUIET TIME VS. EXTREME STORM TIME

The properties of the high latitude boundaries vary rather dramatically under different solar wind conditions. In order to study the average variations of key plasma parameters in the vicinity of the magnetopause under different conditions, we perform a superposed epoch analysis. We present statistical results based on 4 years of data obtained by Cluster when these spacecraft were in the vicinity of the dayside magnetopause.

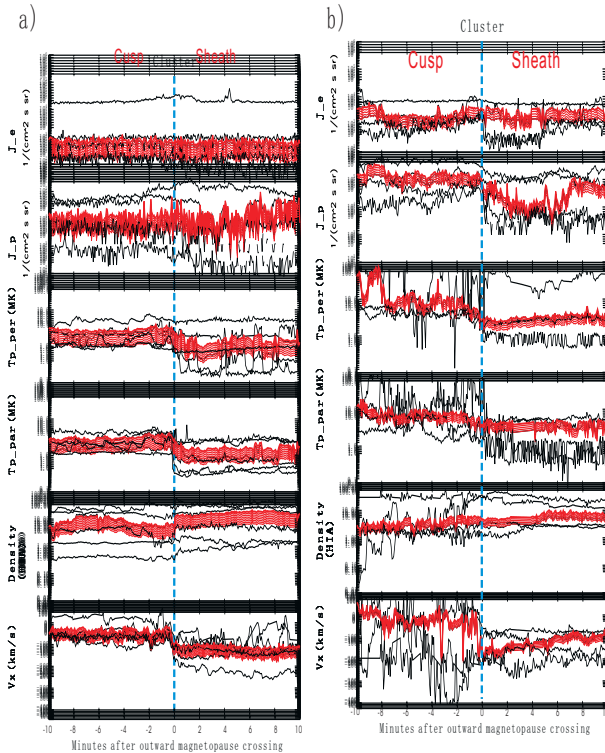


Figure 7: Superposed epoch analysis of the energetic particle flux, the plasma temperature, density, and velocity change from cusp region across the magnetopause a) under northward IMF; b) during extreme storm time ($Dst < -100$ nT).

Figure 7a) shows superposed epoch analysis of the energetic particle flux, the plasma temperature, density, and velocity change from cusp region across the magnetopause under northward IMF in northern hemisphere. The vertical dashed line marked the

magnetopause position which is identified by the jump in plasma parameters including temperature, density and velocity. The x axis is the minutes after outward magnetopause crossing. The time interval in this plot is 20 minutes, 10 minutes before and 10 minutes after the magnetopause crossing. During northward IMF, the interfaces between the magnetosheath and the cusp are rather clear. The plasma flow and density increase and the proton temperature decreases across the magnetopause from the cusp into the magnetosheath.

Figure 7 b) shows superposed epoch analysis of the same parameters as a) but during extreme storm time ($Dst < -100$ nT). By saying a event is during extreme storm time we means that the most negative Dst during one storm is < -100 nT and the event is observed during the storm time (initial phase, main phase or recovery phase). In Figure 7 b) all the events during extreme storm time from 2001 to 2004 are included. If the magnetopause crossing is in the southern hemisphere, we reverse the time sequence so that the crossing is still from the magnetosphere into the magnetosheath. Compare Figure 7 b) and Figure 7 a), we can see that during extreme storm times, the cusp is more turbulent than during quiet times. We also noted that there is no clear plasma density change across the magnetopause during extreme storm time.

6. THE CUSP DYNAMICS

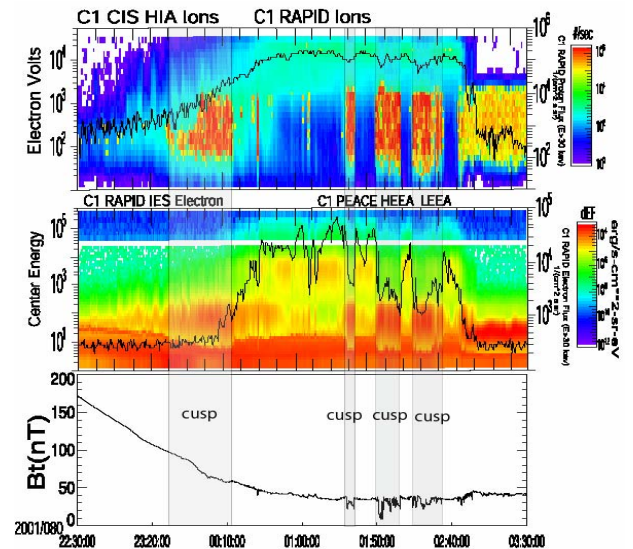


Figure 9: Four-fold cusp observed by CLUSTER. Plasma ion and electron spectra are over-plotted with energetic particle in the first two panels. Last panel shows the total magnetic field.

Unraveling the structure of the dayside cusp is a major CLUSTER objective. Four cusp-like regions were observed consecutively in about five and half hours on March 21–22, 2001 by all four CLUSTER spacecraft

when the IMF was northward with a significant B_y component. The four-fold cusp (Figure 9) was surrounded by the dayside magnetosphere rather than the magnetopause. Evidence was presented indicating that the multiple cusps were probably a temporal sequence. The boundary normal, velocity and timing analysis for six clear boundaries of the cusps indicated that the observed cusps encounters are mostly caused by oscillation of the single cusp which was shifted back and forth between the dayside magnetosphere/trapping region and the cusp region. The normal velocities at boundary interfaces for exits from the cusp were found to be almost three times as large as that for entry into the cusp.

These observations suggest that the shape and location of the cusp is often changing as a result of dynamic processes in the high latitude regions. Furthermore, by combining the four Cluster spacecraft positions and crossing times at the interfaces, we are able to determine the normal velocity and direction of the discontinuity based on the triangulation method [Russell et al., 1983]. Assuming planar discontinuity and the speed of the discontinuity was constant in time and space over the Cluster separation distance, the equation is simply given by

$$Rl \cdot n = Vn \cdot tl$$

Here Vn is the normal velocity of the discontinuity, $Rl = (r12, r13, r14)$ is a tensor with r_{ij} being the spacecraft separation vectors and $tl = (t_{12}, t_{13}, t_{14})$ consists of the differences between the crossing times of the corresponding spacecraft. The obtained normal speeds for the six interfaces are given in Figure 10 (between panel 2 and 3). As we can see from panel 3 and 4, the polar θ angles shows little change in the first 4 interfaces, however, they change signs for the last two interfaces. The wavelike motion can be more clearly seen in the ϕ angle, the direction of exiting the cusp at 2, 4, 6 is opposite to the entering direction based on the azimuthal angle.

Although Cluster observed four cusp regions, the analysis shows that three of these cusps (later three cusps), which are located in the lower-latitude, are a temporal feature which can be attributed to cusp boundary movements or possibly wave activities.

During this event, the IMF was steady with IMF $B_z > 0$, and IMF B_y is slightly larger or comparable with IMF B_z . Between 0100 and 0330 UT on March 22, 2001, the solar wind speed was 300 km/s and the radial dynamic pressure was around 3 nPa obtained by Wind satellite located at GSM (-11.7, -183.6, -109.6) Re, see Figure 11. The time lag between Cluster and Wind is about 6 min

with Cluster in advance. A solar wind pressure pulse encountered the Earth at ~0058 UT, Mar.22, 2001, shortly before the second cusp was observed by Cluster while there was a change of solar wind azimuthal flow (shown in Figure 11). The solar wind East/West flow changed from 6 degree to about 2 degree, and the V_x change from -280 km/s to -310 km/s. The Earth's magnetosphere bears an analogy to the windsock response to changes of the solar wind component flow as suggested by Zong et al. [2004]. When the solar wind azimuthal flow encountered the Earth, the ratio of the Y and Z components of the solar wind dynamic pressure to solar wind thermal pressure P_{dy}/P_{th} became 29%. Therefore, the position of the cusp will be changed. Cluster spacecraft entered the cusp, then the solar wind dynamic pressure or other effects shift the cusp back and forth three times as if Cluster flew through three cusps.

On the other hand the second and third observed cusps don't seem to have clear links with the solar dynamic pressure or flow components. Nevertheless, the mentioned solar wind pressure pulse could trigger the magnetospheric boundary wave [Sibeck et al., 1998].

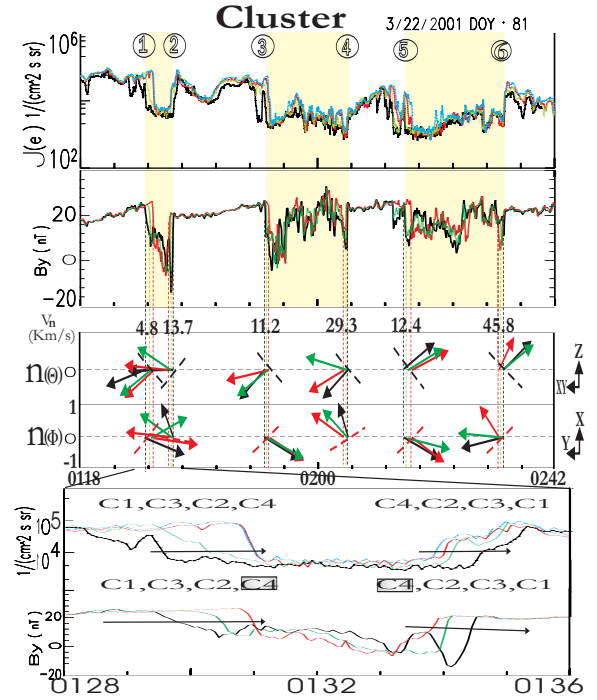


Figure 10: Electron flux, Magnetic field B_y component measured by the four Cluster spacecraft during the time period from 01:00 to 03:30 UT on Mar 22, 2001. The boundary normals were determined by MVA for all available spacecraft during cusp crossings. One of the three cusps is expanded to see the spacecraft crossing order more clearly.

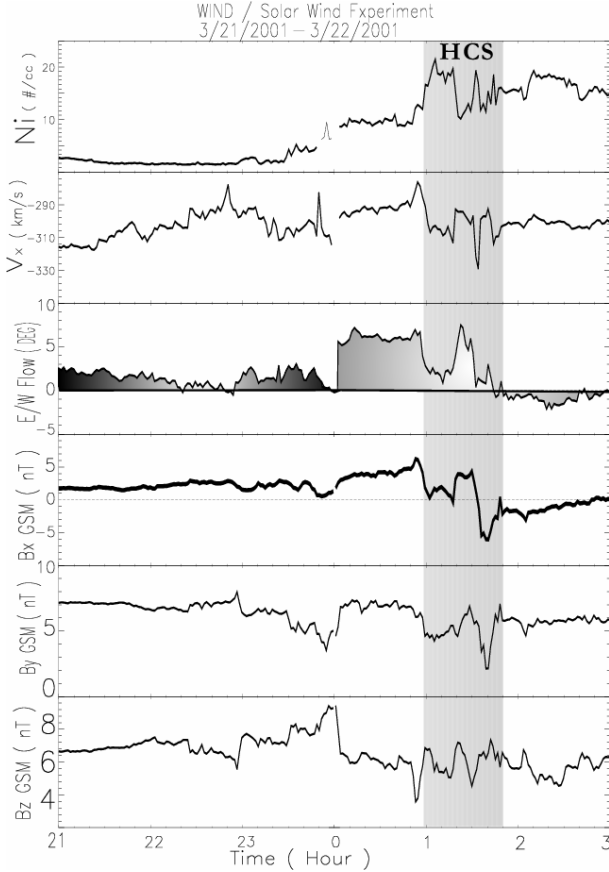


Figure 11: Solar wind and IMF observed by the Wind satellite. The Heliospheric Current Sheet (HCS) which is identified by the high plasma density and sign change of the IMF Bx is marked. The time of this Figure is shifted according to the solar wind velocity.

When the IMF is northward, a cold and dense plasma sheet is often observed [baumjohann et al., 1989, Fujimoto et al., 1996, Fujimoto et al., 1998, Terasawa et al., 1997]. The magnetosheath plasma near the cusp region is relative cold comparing with magnetospheric plasma, dense and almost stagnant. When cusp reconnection occurs, the newly reconnected flux tubes tailward of the cusps in both hemispheres sink and contract into the magnetosphere. Subsequently it sweeps around the flank, and is convected tailward. As the plasma is captured and transported to the tail, it is moderately heated near the reconnection site, and the temperature is just below 1 keV [Song et al., 1992]. The density in the captured flux tubes is characteristic of cold, dense and almost stagnant plasma. The values of temperature, density and low flow speed for the captured plasma are in good agreement with Geotail observations in the dusk flank as shown in Figure 12.

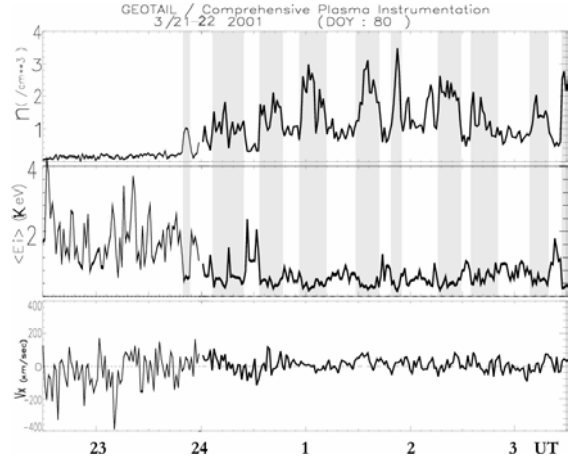


Figure 12: Geotail observations at the duskside tail-flank. From top, the ion density, average energy (temperature, in keV), and the ion bulk flow Vx in km/s. bursty-like cold-dense plasma are observed.

It should be noted, however, the cold dense plasma sheet is also waving. The period is about 20 min. This agrees with the cusp oscillating period (a rough period of 22 min.) very well. This is an additional evidence to support the idea that the cold dense plasma sheet observed by Geotail is closely related the oscillating cusps which are probably formed by high latitude reconnection during the extended northward IMF period.

7. CONCLUSIONS

Energetic ions and electrons have been observed during quiet time (IMF Bz has a predominate positive component). The energetic electrons disappeared during storm time. Single particle simulation shows that energetic ion could be temporally trapped in the High Latitude/Cusp Region whereas electron could not be.

When IMF is northward, the interfaces between the magnetosheath and magnetosphere are rather clear. However, this interface will become uncertain when IMF turns southward. The plasma density decrease and the proton temperature increases across the magnetopause from the magnetosheath into the cusp. During extreme storm time, the cusp is more turbulent than quiet time and there is no clear plasma density change across the magnetopause.

Multiple Cusps are observed by Cluster satellite in the high latitude region, in the meantime, the cold-dense plasma with fluctuations are observed in the dusk-side of the tail plasma sheet by Geotail satellite. This is consistent with the idea that the high latitude reconnection during northward IMF is the responsible

mechanism of the formation of the cold-dense plasma sheet. The observed multiple cusps are very possibly temporal sequence. The cusp was shifted by the solar azimuthal dynamic pressure or wave back and forth three times in about 5 and half hours interval as if Cluster flew through the cusp four times. Further we suggest that the solar wind azimuthal flow is the controlling factor of the cusp position and is as strong as, potentially even stronger than, that of the IMF B_y/B_z component. The importance of the solar wind azimuthal and north/south flow as a dynamic driver of the cusp, and even the whole magnetosphere has been more or less neglected or underestimated.

The full impact of the cusp is going to be evident when we have multiple satellites displaced from one another by large distances (from a large fraction of an Earth's radius to a few Earth radii), as well as satellites located within 100 km of one another and observing using interferometric techniques. New Cluster orbits will make possible study of the nature of particle boundaries within the cusp and high latitude regions to resolve the mechanisms that transport, and possibly accelerate, the thermalized plasma and energetic particles in and through the cusp and boundary layers. The multi-scale Cluster separations will help to resolve the issue of whether the observed multiple cusps are a temporal or spatial effect, as well as determining the size of the cusp. The question of how multiple cusps are formed will be addressed. An outstanding question is the role and importance of the cusp in supplying plasma to the plasma sheet and the relationship between high latitude reconnection and the appearance of cold dense plasma within the plasma sheet.

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8. REFERENCES

1. Anderson, K. A., H. K. Harris, and R. J. Paoli, Energetic electron fluxes in and beyond the Earth's outer magnetosphere, *J. Geophys. Res.*, **70**, 1039-1050, 1965.
2. Antonova, A. E., and V. P. Shabansky, Structure of the geomagnetic field at great distance from the Earth, *Geomagn. Aeron.*, **8**, 801-811, 1968.
3. Antonova, A. E. and V. P. Shabansky, Particles and the magnetic field in outer noon magnetosphere of the Earth, *Geomagn. Aeron.* **15**, 243-247, 1975.
4. Aparicio, B., B. Thelin, and R. Lundin, The polar cusp from a particle point of view: A statistical study based on the Viking data, *J. Geophys. Res.*, **96**, 14,023-14,031, 1991.
5. Baker, D. N., and E. C. Stone, The magnetopause electron layer along the distant magnetotail, *Geophys. Res. Lett.*, **4**, 133-136, 1977a.
6. Baker, D. N., and E. C. Stone, The magnetopause electron layer along the distant magnetotail, *Geophys. Res. Lett.*, **4**, 395-398, 1977b.
7. Baker, D. N., and E. C. Stone, The magnetopause energetic electron layer 1. observations along the distant magnetotail, *Geophys. Res. Lett.*, **4**, 395-398, 1977c.
8. Balogh, A., et al., The Cluster magnetic field investigation, *Space Sci. Rev.*, **79**, 65-91, 1997.
9. Baumjohann, W., G. Paschmann and C. A. Cattell, Average plasma properties in the central plasma sheet, *J. Geophys. Res.*, **94**, 6597, 1989.
10. Chang, S. W., et al., Cusp energetic ions: A bow shock source, *Geophys. Res. Lett.*, **25**, 3729-3732, 1998.
11. Chang, S. W., et al., Energetic magnetosheath ions connected to the earth's bow shock: Possible source of CEP's, *J. Geophys. Res.*, **105**, 5471, 2000.
12. Chapman, S., and V. C. A. Ferraro, A new theory of magnetic storms, *Terr. Magn. Atmos. Elect.*, **36**, 77, 1931.
13. Chen, J., et al., Cusp energetic particle events: Implications for a major acceleration region of the magnetosphere, *J. Geophys. Res.*, **103**, 67-78, 1998.
14. Delcourt, D. C., T. E. Moore, J. A. Sauvaud, and C. R. Chappell, Nonadiabatic transport features in the outer cusp region, *J. Geophys. Res.*, **97**, 16,833-16,842, 1992.
15. Delcourt, D. C., and J.-A. Sauvaud, Recirculation of plasma sheet particles into the high-latitude boundary layer, *J. Geophys. Res.*, **103**, 26,521, 1998.
16. Delcourt, D. C., and J.-A. Sauvaud, Populating of cusp and boundary layers by energetic (hundreds of keV) equatorial particles, *J. Geophys. Res.*, **104**, 22,635-22,648, 1999.
17. Eastman, T. E., The plasma sheet boundary layer, *Geophys. Res. Lett.*, **3**, 685-688, 1976.
18. Formisano, V., Properties of energetic electrons of magnetospheric origin in the magnetosheath and in the solar wind, *Planet. Space Sci.*, **27**, 867, 1979.
19. Fritz, T. A., The role of the cusp as a source for magnetospheric particles: A new paradigm, in *Proc. Cluster-II workshop on Multiscale/Multipoint Plasma Measurements*, pp. 203-209, Eur. Space Agency Spec. Publ., SP - 449, ESA, 2000.

20. Fritz, T. A., The cusp as a source of magnetospheric energetic particles, currents, and electric fields: new paradigm, *Space Sci. Rev.*, **95**, 469-488, 2001.
21. Fritz, T. A., J. Chen, R. B. Sheldon, H. E. Spence, and J. F. Fennell, Cusp energetic particle events measured by polar spacecraft, *Physics and Chemistry of the Earth*, **24**, 135-140, 1999.
22. Fujimoto, M., A. Nishida, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun, Plasma entry from the flanks of the near-earth magnetotail: Geotail observations in the dawnside LLBL and the plasma sheet, *J. Geomagn. Geoelectr.*, **48**, 711, 1996.
23. Fujimoto, M., T. Terasawa, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun, Plasma entry from the flanks of the near-earth magnetotail: Geotail observations, *J. Geophys. Res.*, **103**, 4391, 1998.
24. Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, The frontside boundary layer of the magnetopause and the problem of reconnection, *J. Geophys. Res.*, **83**, 3195-3216, 1978.
25. Haskell, G. P., Anisotropic fluxes of energetic particles in the outer magnetosphere, *Planet. Space Sci.*, **74**, 1740-1748, 1969.
26. Hones, E. W., S. I. Akasofu, S. J. Bame, and S. Singer, Outflow of plasma from the magnetotail into magnetosheath, *J. Geophys. Res.*, **77**, 6688-6695, 1972.
27. Klassen, A., V. Bothmer, G. Mann, M. J. Reiner, S. Krucker, A. Vourlidas, and H. Kunow, Solar energetic electron events and coronal shocks, *Astron. Astrophys.*, **385**, 1078-1088, 2002.
28. Kremser, G., and R. Lundin, Average spatial distributions of energetic particles in the midaltitude cusp/cleft region observed by Viking, *J. Geophys. Res.*, **95**, 5753-5766, 1990.
29. Lin, R. P., Energetic solar electrons in the interplanetary medium, *Sol. Phys.*, **100**, 537, 1985.
30. Lundin, R., plasma composition and outflow characteristic in the magnetospheric boundary layers connected to the polar cusp, in *The polar Cusp*, edited by J. A. Holtet and A. Egeland, pp. 9-32, Kluwer Academic Publishers, Dordrecht, the Netherlands, 1985.
31. Lundin, R., and E. M. Dubinn, solar wind energy transfer regions inside the dayside magnetopause: accelerated heavy ions as tracers for mhd-processes in the dayside boundary layer, *Planet. Space Sci.*, **33**, 891-907, 1985.
32. Marklund, G. T., L. G. Blomberg, C.-G. Fälthammar, R. E. Erlandson, and T. A. Potemra, Signatures of the high-altitude polar cusp and dayside auroral regions as seen by the Viking electric field experiment, *J. Geophys. Res.*, **95**, 5767-5780, 1990.
33. Meng, C. I., and K. A. Anderson, A layer of energetic electrons ($> 40\text{keV}$) near the magnetopause, *J. Geophys. Res.*, **75**, 1827-1836, 1970.
34. Meng, C. I., and K. A. Anderson, Characteristics of the magnetopause energetic electrons layer, *J. Geophys. Res.*, **80**, 4237, 1975.
35. Meng, C. I., A. T. Y. Lui, S. M. Krimigis, S. Ismail, and D. J. Williams, Spatial distribution of energetic particles in the distant magnetotail, *J. Geophys. Res.*, **86**, 5682-5700, 1981.
36. Newell, P. T., and C. I. Meng, Cusp width and b_z : Observations and a conceptual model, *J. Geophys. Res.*, **92**, 13,673-13,678, 1987.
37. Newell, P. T., and C. I. Meng, The cusp and the cleft/boundary layer: Lower altitude identification and statistical local time variation, *J. Geophys. Res.*, **93**, 14,549-14,556, 1988.
38. Newell, P. T., and C. I. Meng, Open and closed low latitude boundary layer, in *Polar Cap Boundary Phenomena*, edited by J. Moen, A. Egeland, and M. Lockwood, pp. 91-101, Kluwer Academic Publishers, Dordrecht, the Netherlands, 1998.
39. Paschmann, G., G. Haerendel, N. Sckopke, and H. Rosenbauer, Plasma and field characteristics of the distant polar cusp near local noon: The entry layer, *J. Geophys. Res.*, **81**, 2883-2899, 1976.
40. Reiff, P. H., T. W. Hill, and J. L. Burch, Solar wind plasma injection at the dayside magnetospheric cusp, *J. Geophys. Res.*, **82**, 479, 1977.
41. Reme, H., et al., The Cluster ion spectrometry (CIS) experiment, *Space Sci. Rev.*, **79**, 303-350, 1997.
42. Roederer, J. G., *Dynamics of geomagnetically Trapped radiation*, Springer-Verlag, New York, 1970.
43. Roederer, J. G., Global problems in magnetospheric plasma physics and prospects for their solution, *Space Sci. Rev.*, **21**, 23, 1977.
44. Rosenbauer, H., A boundary layer model for magnetospheric substorms, *J. Geophys. Res.*, **80**, 2723, 1975.
45. Russell, C. T., M. M. Mellot, E. J. Smith and J. H. King, Multiple spacecraft observations of interplanetary shocks: four spacecraft determination of the shock normals, *J. Geophys. Res.*, **88**, 4739-4748, 1983.
46. Sckopke, N., G. Paschmann, H. Rosenbauer, and D. H. Fairfield, Influence of the interplanetary magnetic field on the occurrence and the thickness of the plasma mantle, *J. Geophys. Res.*, **81**, 2687-2691, 1976.
47. Sckopke, N., G. Paschmann, G. Haerendel, B. U. Sonnerup, S. J. Bame, T. G. Forbes, J. E. W. Hones, and C. T. Russell, Structure of the low latitude boundary layer, *J. Geophys. Res.*, **86**, 2099-2110, 1981.
48. Shabansky, V. P., Magnetospheric process and related geophysical phenomena, *Space Sci. Rev.*, **8**, 366-454, 1968.
49. Shabansky, V. P., Some processes in magnetosphere. *Space Science Review* **12** (3), 299, 1971.

50. Sheldon, R. B., H. E. Spence, J. D. Sullivan, T. A. Fritz, and J. Chen, The discovery of trapped energetic electrons in the outer cusp, *Geophys. Res. Lett.*, **25**, 1825-1828, 1998.
51. Sibeck, D. G., N. L. Borodkova, G. N. Zastenker, S. A. Romanov and J.-A. Sauvaud, Gross deformation of the dayside magnetopause, *Geophys. Res. Lett.*, **25**, 453--456, 1998.
52. Siscoe, G., N. Crooker, K. Siebert, N. Maynard, D. Weimer and W. White, Cusp geometry in MHD simulations, *Surveys in Geophysics*, **26**, 387-407, 2005
53. Song, P., and C. T. Russell, Model of the formation of low- latitude boundary layer for strongly northward interplanetary magneticfield, *J. Geophys. Res.*, **97**, 1411, 1992.
54. Spreiter, J. R., and S. S. Stahara, A new predictive model for determining solar wind -terrestrial planet interactions, *J. Geophys. Res.*, **85**, 6769-6777, 1980.
55. Spreiter, J. R., and A. L. Summers, On conditions near the neutral points on the magnetosphere boundary, *Planet. Space Sci.*, **15**, 787-798, 1967.
56. Stömer, C., Sur les trajectoires des corpuscules electrisés dans l'espace sous l'actions des magnetisme terrestreavec application aux avariores boreales, secondee memoire, *Arch. Sci Phys. Nat. Ser. 4*, **32**, 117-123, 1911.
57. Terasawa, T., et al., Solar wind control of density and temperature in the near-Earth plasma sheet: WIND/GEOTAIL collaboration, *Geophys. Res. Lett.*, **24**, 935-938, 1997.
58. Trattner, K. J., S. A. Fuselier, W. K. Peterson, S. W. Chang, R. Friedel, and M. R. Aellig, Origins of energetic ions in the cusp, *J. Geophys. Res.*, **106**, 5967-5976, 2001.
59. Tsyganenko, N. A., and D. P. Stern, Modeling the global magnetic _eld of the large-scale Birkeland current system, *J. Geophys. Res.*, **101**, 27,187-27,198, 1996.
60. West, H. I., and R. M. Buck, Observations of > 100 keV protons in the Earth's magnetosheath, *J. Geophys. Res.*, **81**, 569-584, 1976.
61. Wilken, B., et al., Rapid: The imaging energetic particle spectrometer on Cluster, *Space Sci. Rev.*, **79**, 399-473, 1997.
62. Yamauchi, M., and R. Lundin, Physical signatures of magnetospheric boundary layer processes, in *Physical Signatures of Magnetospheric Boundary Layer Processes*, edited by J. A. Holtet and A. Egeland, pp. 99-109, Kluwer Academic Publishers, Dordrecht, the Netherlands, 1998.
63. Zhang, H., T. A. Fritz, Q.-G. Zong and P. W. Daly, Stagnant exterior cusp region as viewed by energetic electrons and ions: A statistical study using Cluster Research with Adaptive Particle Imaging Detectors (RAPID) data, *J. Geophys. Res.*, **110**, A05211, doi:10.1029/2004JA010562.
64. Zhou, X.-W., C. T. Russell, G. Le, and N. Tsyganenko, Comparison of observed and model magnetic _elds at high altitudes above the polar cap: Polar initial results, *Geophys. Res. Lett.*, **24**, 1451-1454, 1997.
65. Zong, Q.-G., and B. Wilken, Layered structure of energetic oxygen ions in the magnetosheath, *Geophys. Res. Lett.*, **25**, 4121-4124, 1998.
66. Zong, Q.-G., B. Wilken, S.-Y. Fu, T. A. Fritz, Z.-Y. Pu, N. Hasebe, and D. J. Williams, Ring current oxygen ions in the magnetosheath caused by magnetic storm, *J. Geophys. Res.*, **106**, 25,541-25,556, 2001.
67. Zong, Q.-G., T. A. Fritz, B. Wilken, and P. W. Daly, Energetic ions in the high latitude boundary layer of the magnetosphere - rapid/CLUSTER observation, in *The Lower- Latitude Boundary Layer*, edited by P. T. Newell and T. G. Onsager, p. 101-110, AGU, AGU, Washington, D.C., 2002.
68. Zong, Q.-G., T. A. Fritz, H. Zhang, A. Korth, P. W. Daly, M. W. Dunlop, K.-H. Glassmeier, H. Reme and A. Balogh, Triple cusps observed by Cluster—Temporal or spatial effect?, *Geophys. Res. Lett.*, **31**, L09810, doi:10.1029/2003GL019128, 2004
69. Zong, Q.-G. , T. A. Fritz, H. Spence, A. Korth, P. W. Daly, M. Dunlop, A. Balogh, J. Fennell, Z. Y. Pu and H. Reme, Energetic electrons as a field line topology tracer in the high latitude boundary / cusp region: Cluster RAPID observations, *Surveys in Geophysics*, **26**, 215-240, 2005