Cusp energetic ions as tracers for particle transport into the magnetosphere

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Abstract

The magnetospheric cusps are focal points in studies of both magnetic reconnection at the magnetopause and plasma entry into the magnetosphere. Contrary to a well-understood precipitating thermal magnetosheath ion population, the origins of energetic ions in the cusp regions are still a matter of controversy. It has been suggested that these Cusp Energetic Particles (CEP) with significant fluxes from magnetosheath energies up to several hundred keV/e are accelerated locally in the cusp. A recent paper has suggested local plasma conditions conducive to CEP acceleration in the Cusp Diamagnetic Cavity (CDC). An alternative source region for CEP events is the quasi-parallel bow shock, which is a well known particle accelerator. Energetic ions accelerated at the bow shock can be transported downstream and enter the cusp along newly reconnected field lines. Composition and energy spectra of these CEP events resemble those of bow shock energetic diffuse ions.

We use recently developed techniques to determine the location of the reconnection site at the magnetopause, draping interplanetary magnetic field (IMF) lines over the magnetopause and mapping those field lines back into the solar wind to show the magnetic connection between the cusp regions, the Earth bow shock, and the upstream region. Several cusp crossings by the Polar satellite during variable IMF conditions are analyzed for patterns between the cusp, their connection to the upstream region and the appearance of energetic ions in the cusp. Local plasma conditions in the cusp are also documented. This analysis reveals that the occurrence of CEP events is not uniquely determined by local plasma conditions. The flux of CEP ions depends on the location of the quasi-parallel bow shock and the magnetic topology in the magnetosheath. Our analysis allows us to use CEP ions as tracers for plasma transport into the cusp and to better understand the magnetic topology between the solar wind and the ionosphere.

Introduction

The observation of energetic particles in the magnetospheric cusp region by *Chen et al.* [1997, 1998] and *Chen and Fritz* [1998] led to a controversy about the origin of these particles. It has been surmised by these authors that Cusp Energetic Particles (CEP) are penetrating magnetosheath ions accelerated locally by the reduced and turbulent magnetic field inside Cusp Diamagnetic Cavities (CDC), which are present in the high altitude cusp [e.g., *Fritz et al.,* 1999; *Niehof et al.,* 2005; *Whitaker et al*., 2006, 2007]. Within these cavities, observations by the Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) and the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) instruments [*Blake et al.,* 1995] onboard the Polar spacecraft showed ion composition measurements similar to the solar wind composition, particle energies above the typical solar wind energies up to several hundred keV/e, and CEP fluxes substantially higher than those in the solar wind. *Niehof et al.* [2008] have recently suggested plasma conditions in the cusp that they believe are necessary and sufficient for the generation of CEP fluxes in the Cusp Diamagnetic Cavity (CDC). These criteria are (1) a plasma density at least 10 times greater than in adjacent regions outside the cusp (but inside the magnetosphere), (2) a bulk plasma flow slower than 75 km/s antisunward, (3) a $\Delta B/B$ greater than 20% on time scales of under a minute (turbulent field) and (4) a 20% decrease in the average field.

The local acceleration interpretation was challenged by *Chang et al.* [1998, 2000] who presented a conceptual model showing how the quasi-parallel bow shock maps along draped, reconnected, interplanetary magnetic field lines (IMF) into the cusp. Analyzing a 6-month database of Polar and Wind data for the northern cusp, *Chang et al.* [1998] found that CEP events occurred mainly for $\Theta_{Bn} < 45°$ and that ion spectra upstream/downstream from the quasi-parallel bow shock are similar to CEP spectra.

A similar conclusion was reached by Trattner et al. [1999], who compared two CEP events with simultaneous observations by Geotail upstream and downstream of the quasi-parallel bow shock. They found a remarkably good agreement between the CEP cusp spectrum and the bow shock spectrum up to 200 keV/e and concluded that bow shock accelerated ions can account for the CEPs observed by the Polar satellite.

In a subsequent study, *Trattner et al.* [2001] compared a number of well established characteristics of bow shock accelerated ions with CEP ions. They showed that characteristic spectral breaks in the CEP spectra are consistent with spectral breaks of bow shock accelerated ions. The density ratio of energetic to thermal protons and temperatures of the energetic proton and helium distributions for CEP and bow shock accelerated ions are similar. In addition, the exponential spectral slope of CEP ions increases with increasing solar wind velocity, as predicted by various shock acceleration models [e.g., *Ellison,* 1981; *Lee*, 1982; *Forman and Drury*, 1983] and confirmed by upstream observations from AMPTE/IRM [*Trattner et al.*, 1994]. Finally, the helium to proton acceleration efficiency ratio is similar to that predicted by shock acceleration theory. The observed CEP spectra can be simply explained by transporting bow shock accelerated particles along connected magnetic field lines into the cusp.

A third source region for CEP ions discussed in the literature is the magnetosphere itself [e.g., *Sibeck et al.,* 1987; *Fuselier et al.,* 1991]. Magnetospheric ions may also enter the cusp along field lines which connect the cusp with the magnetopause (especially on the duskside) and contribute to the observed energetic cusp ions for the energy range >150 keV/e usually not covered by bow shock accelerated ions. Magnetospheric ions may also drift directly into the cusp from the magnetosphere as shown in particle simulations by *Blake* [1999]. Thus the entire CEP spectrum can be readily explained by contributions from outside sources with little or no local acceleration required.

In this study we use recently developed techniques to determine the location of the reconnection site at the magnetopause together with draping the IMF over the magnetopause. The reconnected field lines are mapped back into the solar wind to show the magnetic connection between the cusp regions, the Earth bow shock and the upstream region. Four Polar cusp crossings during variable IMF conditions are analyzed for the occurrence of CDCs, enhanced fluxes of CEP ions, and the magnetic connection of these ions to the upstream region. We document local plasma conditions in the CDC and compare them with the criteria for local acceleration recently suggested by Niehoff et al. [2008]. The study reveals that while CEP ions do occasionally occur within CDCs, their presence is not limited to CDCs and their reported magnetic turbulence. The presence and intensity of CEP ions in the cusp depends strongly on the location of the quasi-parallel bow shock and the magnetic topology in the magnetosheath.

2. Instrumentation and Methodology

In this study we analyze ion distributions observed during 4 northern hemisphere cusp crossings by the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) [*Shelley et al.,* 1995] and the CEPPAD [*Blake et al.,* 1995] instruments onboard the Polar spacecraft.

Polar/TIMAS proton measurements cover the energy range from 15 eV/e to 33 keV/e in 28 energy steps and provide 98% coverage of the unit sphere during a 6-sec spin period. The Polar/CEPPAD sensor package consists of three sensors from which only the Imaging Proton Sensor (IPS) is used in this study. The IPS measures protons over the energy range from ~10 keV to 1 MeV in 16 energy steps.

The Polar spacecraft was launched on February 24, 1996, into a nearly 90° inclination orbit with a perigee of about 2 R_E and an apogee of about 9 R_E. Polar crosses the cusp regions during two periods each year, with each period lasting several months. The cusp ion distributions are observed at altitudes between 3.5 and 9 R_E and up to 90° invariant latitude (ILAT).

In addition to Polar ion data, solar wind context measurements observed by the Wind Magnetic Field Instrument (MFI) [*Lepping et al*., 1995] and the Wind Solar Wind Experiment (SWE) [*Ogilvie et al*., 1995] are used. These data are provided by the ISTP key parameter web page. Solar wind observations are convected to the magnetopause.

To determine the magnetic connection between the cusp and the bow shock we use the *Cooling et al.* [2001] analytical model at the magnetopause as the external (magnetosheath) magnetic field that is draped against the magnetopause. The *Cooling et al.* [2001] magnetic field model is a restricted version of the more general *Kobel and Flückiger* [1994] model (which is an analytic representation of the magnetic field throughout the magnetosheath).

Somewhere along the draped IMF field lines at the magnetopause, reconnection will connect the IMF field lines to geomagnetic field lines. This process magnetically connects the cusp regions to the upstream solar wind. To highlight the connection of the cusp to the bow shock, the dayside draped IMF field lines are traced back to the *Farris and Russell* [1994] bow shock, where their contact points are marked with respect to the shock region.

3. Observations

The first Polar cusp event discussed in this study occurred on 18 September 1996, and is characterized by several strong and rapid variations in the CEP ion flux. Figure 1 (bottom panel) shows the H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument onboard the Polar satellite. Polar was located in the dusk sector around 14:00 magnetic local time (MLT) moving towards the equator. It encountered magnetosheath ions on open geomagnetic field lines at about 06:45 UT before leaving the cusp at about 12:08 UT (marked by the rightmost white line in the bottom panel). The magnetosheath ions during this extended cusp crossing exhibit a multitude of structures, both in intensity and sudden changes in the energy of the precipitating particles. These so-called “transient cusp steps” on open magnetic field lines are convected under the joint action of magnetic tension and momentum transfer from shocked solar wind flow, creating, for the instruments onboard the Polar satellite, an ever-changing precipitating ion profile. This interpretation is based on the pulsating cusp model where cusp steps are the result of changes in the reconnection rate at the magnetopause. Variable reconnection creates neighboring convecting flux tubes in the cusp with different time histories since reconnection [e.g., *Cowley and Lockwood,* 1992; *Lockwood and Smith*, 1994]. Observations of cusp steps as shown in Figure 1 (bottom panel) are generally interpreted as temporal rather than spatial variations; however, the existence of spatially separated flux tubes as a consequence of multiple reconnection lines was also confirmed in earlier studies [e.g., *Newell and Meng*, 1991; *Onsager et al.*, 1995; *Weiss et al*., 1995; *Wing et al.*, 2001; *Trattner et al*., 2002, 2003, 2005].

The high energy range depicted in the color spectrogram in Figure 1 (>10 keV/e), is also known to represent the peak in the flux distribution of CEP ions; i.e., the energy range where the cusp ion spectral slope contains a break and diverges from the shocked solar wind spectra [e.g., *Trattner et al*., 2001]. The changes in particle flux above 10 keV/e for the 18 September 1996 Polar cusp crossing are significant and clearly visible in the bottom panel of Figure 1. The regions with high CEP flux (R1 and R2) are separated from regions with low CEP flux (R2 and R4) by white vertical lines located at about 08:31 UT, 09:10 UT and 10:02 UT.

The top panels in Figure 1 show solar wind conditions for the 18 September 1996 cusp crossing. The data from the Wind SWE and MFI experiments have been convected by about 14 minutes to account for the travel time between the Wind satellite and the magnetopause. The average solar wind density, N, for this event was about 6 cm^{-3} (top panel) and the average solar wind velocity, V, was about 545 km/s (second panel). The IMF components in GSM coordinates, B_X (black line), B_Y (green line), and B_Z (colored area) are shown in the third panel of Figure 1. The IMF components are highly variable throughout the Polar cusp event and probably cause the structured/dynamic behavior of the cusp particle flux. The B_Y component was mostly positive, reaching a maximum of about 6 nT with one brief negative value of about -4 nT at about 10:00 UT. The B_Z component was mostly southward with several brief northward interruptions. The B_X component showed the most dramatic changes, switching from a maximum of about -6 nT to 6 nT at 08:29 UT, back to -8 nT at 09:03 UT and again to 6 nT at 09:58 UT (marked with vertical black lines). These times for the B_X field reversals are in excellent agreement with the boundaries between regions of high and low CEP flux, which lag the IMF B_X field reversals by a couple of minutes, with a slightly longer delay for the return of the CEP flux to the cusp (R2 to R3 in Figure 1, bottom panel).

Figure 2 shows the magnetic field magnitude B [nT], the proton density N [cm^{-3}] and the plasma beta (ratio of the thermal energy density to the magnetic energy density) as observed by the Polar satellite during the 18 September 1996 cusp crossing. The magnetic field magnitude B in the top panel also shows dashed lines indicating the boundaries between high and low CEP flux regions from Figure 1. The cusp magnetic field is characterized by several depressed and turbulent field regions around 08:00, 09:30 UT and 11:30 UT. These field regions are in agreement with CDC regions as described in *Niehof et al.* [2008], which are suspected to be where local acceleration of precipitating magnetosheath ions occurs [e.g., *Chen and Fritz*, 1998].

The middle panel of Figure 2 shows the highly variable proton density N, reaching maxima of about 18 cm^{-3}. The highest proton density peaks are consistent with the appearance of the CDCs. A very good indicator for the presence of CDCs is the plasma beta in the cusp as shown in Figure 2. Beta rises sharply in a CDC, reaching about 10 during the Polar cusp crossing on 18 September 1996. While the appearance and disappearance of CEP ions correlates very well with the changes in the IMF (see Figure 1), it is important to note that boundaries of high CEP flux regions are not in agreement with the position of the CDCs. The first CDC was encountered from 07:10 UT to 08:31 UT, with the second from 09:10 UT to 10:15 UT. Only the inner edges of these CDCs (08:31 UT and 09:10 UT) agree with the boundaries observed for high fluxes of CEP ions (R1 and R3). For the first CDC, the CEP ions are also present outside the cavity (before 07:10 UT, Figure 1), while the second CDC was observed for another 15 minutes after the CEP ions suddenly disappeared.

A third beta enhancement encountered from 11:12 UT to 12:08 UT indicates the position of another CDC next to the open-closed field line boundary which was weaker and less developed than the previously encountered structures due to the stronger geomagnetic field magnitude at lower altitudes. No significant CEP flux was observed during that encounter.

Figure 3 illustrates changes in CEP flux during the 18 September 1996 Polar cusp crossings. Plotted are 5 minute averaged proton flux spectra (1/(cm^2 s sr keV/e)) observed by the TIMAS and CEPPAD instruments, starting at 08:00 UT (R1), 08:40 UT (R2) and 09:20 UT (R3). The cusp proton spectra below 10 keV show all the characteristics of shocked solar wind. The spectra consist of a cold dense core distribution which has been slowed, deflected, compressed and heated by the shock in addition to a shell of hotter ions, containing some 10%-20% of the downstream distribution, which has been initially reflected at the shock but subsequently transmitted downstream [e.g, *Gosling et al.,* 1989].

At about 10 keV the cusp spectra exhibit distinctive breaks. For the cusp spectra in region R1 and R2, these breaks are caused by the presence of CEP ions whose spectral characteristics agree with energetic ions accelerated at the quasi-parallel bow shock [e.g., *Fuselier,* 1994; *Trattner et al*., 1994]. A similar break in the cusp spectrum of region R2 (no CEP ions present) is caused by the remnants of the ring current distribution. These ions, originally located on closed field lines at the magnetopause, are able to enter the cusp once those field lines have been reconnected at low latitudes. A detailed comparison of the spectral evolution in this energy range, from closed field lines throughout the cusp region into the lobes, supported by 3D distributions provided by the TIMAS instrument, has demonstrated this connection to ring current ions. However, this investigation is beyond the scope of this paper.

A detailed analysis of the cusp ion spectra and the range of densities and temperatures can be found in *Trattner et al.* [2001]. For the present study, we are only interested in the changes of the CEP flux during a cusp crossing. In particular, while the flux of the shocked solar wind core distribution is about the same for all four cusp regions on 18 September 1996, the energetic particle distributions are dramatically different.

Within the same cusp crossing, the energetic particle flux at 100 keV for regions with CEP ions compared to regions with no CEP ions changes suddenly by up to four orders of magnitude.

3.1 Magnetic topology and the occurrence of CEP ions

The energetic particle flux in the cusp is highly variable. It is the purpose of this study to investigate and understand what influences the appearance and variability of CEP ions. Figure 4 shows the magnetopause shear angle at the magnetopause and the most likely location of the reconnection line (dashed white line) for region R1 during the 18 September 1996 cusp crossing. The dayside magnetopause magnetic shear angle was determined by using the *Cooling et al.* [2001] analytical model as the external (magnetosheath) magnetic field and the T96 model at the *Sibeck et al.* [1991] ellipsoidal magnetopause as the internal (magnetosphere) magnetic field. Differences in the magnetopause shapes between the two models are corrected by mapping of the draped magnetosheath field conditions along the boundary normal onto the *Sibeck et al*. [1991] magnetopause.

Red areas in Figure 4 represent regions where the geomagnetic fields and the draped IMF are anti-parallel while blue and black areas represent regions where the merging fields become parallel. The anti-parallel reconnection regions for the Polar cusp crossing are bifurcated and located in the southern dawn and northern dusk region (IMF clock angle of 141°). The black circle represents the location of the terminator plane as it intersects the magnetopause.

The dashed white line represents a continuous line of maximum magnetic shear across the magnetopause for the solar wind and IMF conditions at about 08:22 UT on 18 September 1996. This line of maximum magnetic shear was documented as the most likely location for the location of the reconnection line in a study by *Trattner et al.* [2007] based on 130 Polar cusp crossings. Along this tilted X-line, the geomagnetic field lines open, magnetically connecting the northern cusp regions along the merged IMF to the ion distributions in the northern hemisphere magnetosheath region. At the same time, the tilted X-line cuts off ion distributions from the southern hemisphere magnetosheath region, keeping them from accessing the northern cusp. This provides an easily testable model where the location of the quasi-parallel shock, a well known particle accelerator, would have a direct influence on the energetic particle distributions observed in the cusp. For southward IMF conditions and a satellite located in the northern cusp, CEP ions can only be observed if a quasi-parallel shock is located in the northern hemisphere and draped, reconnected IMF field lines exit the bow shock at this location.

Figure 5 demonstrates this connection for the 18 September 1996 Polar cusp crossing. Shown is the bow shock as seen from the Sun for the four cusp regions defined in Figure 1. Color-coded is Θ_{Bn}, the angle between the shock normal and the upstream IMF direction for the respective time intervals. Red regions represent the location of the quasi-perpendicular shock region while green and blue region represent the quasi-parallel shock region. The black circle depicts the terminator plane projected to the bow shock. The black line shows the bow shock exit points of the IMF as it convects through the magnetosheath along the sub-solar line from the shock to the magnetopause. The convecting IMF that encounters the quasi-parallel bow shock threads the magnetosheath, and moves towards the magnetopause, allowing shock accelerated ions to populate that field line.

The clusters of points at the end of the black lines represent the crossing points of the fully draped IMF (along the dayside magnetopause) at the bow shock. In all four cases the crossing points are in the quasi-parallel bow shock region. For the time intervals with high CEP fluxes in the northern cusp (regions R1 and R3, left panels in Figure 5), the crossing points of the quasi-parallel shock region are also located in the northern hemisphere, supporting the model description above and providing a direct magnetic connection from the bow shock to the northern cusp. In contrast, the IMF crossing points for regions R2 and R4 (right panels), with no CEP fluxes, are located in the quasi-parallel shock region in the southern hemisphere. This location is disconnected from the northern cusp region and the Polar satellite by the tilted reconnection line. The change in the direction of the IMF B_X component for regions R2 and R4 caused the location of the quasi-parallel bow shock to shift to the opposing hemisphere, drastically changing the observed energetic particle population in the northern cusp. During the time intervals for region R2 and R4 the CEP ions should be present in the southern cusp. The appearance and disappearance of CEP ions in the northern cusp is in agreement with these changes in the IMF and not with the locations of the CDCs.

Figure 6 illustrates the magnetic connection further. Plotted are the magnetopause and the bow shock as seen from the dusk and rotated into the IMF plane. The location of these two boundaries have been determined by using the solar wind and IMF conditions observed during the time interval of the high CEP flux region R3. Also shown are draped field lines (dashed curves) and the location of the quasi-parallel bow shock (thick line) which is, in this representation, extending almost to the sub-solar location of the bow shock. An IMF line convecting through the bow shock encounters the particle acceleration region at the quasi-parallel bow shock long before it is fully draped around the magnetopause. Shock accelerated ions are already present on this field line when reconnection commences.

The second event discussed in this study occurred on 11 August 1996. Figure 7 shows the H^+ omni-directional flux measurements ($1/(cm^2$ s sr keV/e)) observed by the TIMAS instrument (top panel) and the cusp magnetic field magnitude B (nT) (bottom panel). The Polar satellite encountered magnetosheath particle flux in the cusp at about 04:00 UT and was travelling equatorward from about local noon to 15:00 MLT before crossing the open-closed field line boundary at about 08:27 UT.

The solar wind density during this cusp crossing was about 14 cm^{-3} with a solar wind speed of about 370 km/s. The IMF conditions (GSM coordinates) were variable throughout the cusp crossing with the components changing from (-2.4, 1.2. -1.5) to (-0.07, -3.4, 0.7) nT for the two time periods selected (R1 and R2). The solar wind and IMF observations have been convected by about 30 minutes to account for the travel time from the Wind satellite to the magnetopause.

As in the previous event, the magnetosheath particle flux in the cusp is highly structured with a plasma density reaching about 27 cm^{-3} (not shown). Such a high plasma density at altitudes of about 9 R_E created an extended CDC as shown in the cusp magnetic field magnitude in the bottom panel of Figure 7. The CDC was observed for about 4 hours due to the slow motion of the Polar satellite at these altitudes and covers almost the entire cusp crossing. The CDC is marked in the bottom panel of Figure 7 with two vertical black lines. Two time periods have been selected and marked with white vertical lines (top panel) and black bars (bottom panels) to illustrate the variability of CEP ions even within a CDC. The first interval R1 from 06:15 UT to 06:45 UT is characterized by a high CEP flux while the second period from 07:13 UT to 07:44 UT exhibits the absence of high energy ions even at the TIMAS upper energies.

The sudden flux change within the same CDC is documented in Figure 8, which shows the particle flux at 10 keV, 50 keV and 100 keV versus latitude for the 11 August 1996 Polar cusp crossing. Note that due to the orbit path of Polar, time in Figure 8 advances with decreasing latitude. The periods of interest are marked with black bars. While the 10 keV flux only changes slightly, the flux for 50 keV and 100 keV ions is about three orders of magnitude lower for region R2 compared to region R1. After reaching a new maximum at about 81°, the energetic particle flux continues to slowly decrease again towards higher latitudes. This is not unexpected since high latitude field lines are stretched into lobe field lines and make contact with the flanks of the bow shock where the shock is weaker.

Figure 9 shows the location of the quasi-parallel bow shock at the bow shock as seen from the Sun for the two intervals selected in Figure 7. The layout is the same as in Figure 5. During time interval R1 the cusp has a good connection to the quasi-parallel bow shock, located at the dayside and covering the sub-solar region (left panel). During time interval R2, the cusp has a connection to the quasi-parallel bow shock, however, the shock acceleration region is located downstream in the night side sector of the bow shock. Convection of the IMF with the solar wind and magnetic connection to the downstream flanks of the weakened quasi-parallel bow shock make it increasingly difficult for energetic ions to reach the northern cusp region. Hence there is a three orders of magnitude decrease of the CEP flux within the same CDC.

The CDC observed during the 11 August 1996 Polar cusp crossing satisfies the conditions defined in *Niehof et al.* [2008] for the generation of CEP ions. If the turbulence within the CDC is responsible for the generation of CEP ions as suggested by, e.g., *Chen and Fritz* [1998], the flux of CEP ions should be high throughout the cusp crossing on 11 August 1996 due to the extended CDC. However, such behavior was not observed. The CEP ion population changed suddenly by orders of magnitude in agreement with changes in the location of, and the connection to, the quasi-parallel shock. These changes are ultimately due to variations in the IMF direction.

The third event is an example of a Polar cusp crossing with an extended CDC but no CEP ions in the entire interval. The Polar cusp crossing occurred on 8 September 1996. Figure 10 shows the H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument (top panel) and the magnetic field magnitude B (nT) during the cusp crossing (bottom panel). The Polar satellite encountered magnetosheath particle flux in the cusp at about 02:00 UT and was travelling equatorward from about local noon to 13:30 MLT before crossing the open-closed field line boundary at about 04:30 UT.

The solar wind density during this cusp crossing was about 5.5 cm^{-3} with a solar wind speed of about 410 km/s. The IMF was dominated by a southward field with average IMF components of (2.5, -0.35, -2.6) nT in GSM coordinates. The field conditions were stable throughout the period of interest discussed below (marked by a black bar in the bottom panel). The solar wind and IMF observations were convected by about 17 minutes to account for the travel time from the Wind spacecraft to the magnetopause.

The magnetosheath particle flux streaming into the northern cusp reached plasma densities of about 12 cm^{-3} at Polar altitudes of about 9 R_E, which gave rise to a CDC observed for about 2 hours. The CDC is marked with two vertical black lines in the bottom panel of Figure 10. The equatorward boundary of the CDC was detected at 04:50 UT when the IMF changed to a slightly northward but mainly radial direction. This shift reconfigured the location of the reconnection line and the associated plasma entry. The magnetosheath particle flux in the cusp dropped to a variable density between 2 and 6 cm^{-3}, terminating the existence of a CDC. Only subsequent density spikes to 6 cm^{-3} resulted in a brief and small drop in the cusp magnetic field magnitude together with some turbulence around 04:15 UT; the signatures associated with CDCs.

The CDC for the 8 September 1996 cusp event is very uniform, and a one hour segment from 02:30 UT to 03:30 UT was selected to investigate the appearance of CEP ions and the connection to the quasi-parallel shock. The combined spectra of TIMAS and CEPPAD observations within the one hour segment showed the absence of CEP ions. The spectra resemble in form and intensity the spectra labeled R2 in Figure 3 that also depicted the absence of CEP ions.

Figure 11 shows Θ_{Bn} at the bow shock, as seen from the Sun. The layout is the same as in Figure 5. During the 02:30 UT to 03:30 UT encounter of the Polar satellite with the CDC, the quasi-parallel bow shock is located in the southern hemisphere. While the fully draped IMF is connected with the quasi-parallel shock location, this source will be cut off from the northern hemisphere cusp by the reconnection line at the equator. No shock accelerated ions are able to reach the northern cusp - which is indeed the case. As in the previous examples, the presence of a CDC has not contributed to the generation of CEP ions.

The fourth event is an example of a Polar cusp crossing without a CDC but with the presence of CEP ions. The Polar cusp crossing occurred on 15 September 1997. Figure 12 shows the H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument (top panel) and the magnetic field magnitude B (nT) during the cusp crossing (bottom panel). The Polar satellite encountered magnetosheath particle flux in the cusp at about 01:30 UT and was travelling equatorward from about 11:00 to 13:00 MLT before crossing the open-closed field line boundary at about 04:05 UT. Two time intervals from 01:30 to 02:00 UT (R1) and from 02:30 to 03:00 UT (R2) have been selected during this cusp crossing to investigate the influence of the IMF direction on the particle entry into the cusp. The intervals are marked with horizontal black bars in the bottom panel of Figure 12. The CEP flux levels for this event are very low in comparison to earlier events, and can be attributed to the unique position of the Polar satellite in the high latitude cusp. As discussed in Figure 8, geomagnetic field lines at these latitudes are stretched out into the lobes, encountering the quasi-parallel shock at the flanks, downstream in the night sector. From that location it will not only be increasingly more difficult for energetic ions to reach the northern cusp region, but also at these latitudes, the magnetic field lines are connected to a much weaker shock, reducing the overall flux levels. This latitude dependence is documented in Figure 8 and can be also observed in Figure 1, where the flux levels before 07:30 UT continuously decrease towards higher latitudes.

The solar wind density during this cusp crossing was about 6.7 cm^{-3} with a solar wind speed of about 430 km/s. The average IMF conditions for the two time intervals R1 and R2 are (-4.1, 2.7, -2.6) and (1.9, 3., -5.4) nT in GSM coordinates. The solar wind and IMF observations were convected by about 18 minutes to account for the travel time from the Wind spacecraft to the magnetopause.

The magnetosheath particle flux at the high latitude boundary of the northern cusp reached plasma densities of only about 2 to 7 cm^{-3}, which was too small to create a CDC at Polar altitudes of about 8 R_E. The magnetosheath plasma density spiked to 18 cm^{-3} at the open-closed field line boundary of the cusp. However, that caused only a moderate depression of the cusp magnetic field around 03:50 UT at a Polar altitude of about 6.5 R_E. No clearly defined CDC was present during this Polar cusp crossing. Despite the absence of a CDC, the top panel of Figure 12 reveals a sharp change in the energetic particle flux at 02:19 UT, in conjunction with a change in the IMF B_X component from negative to positive.

Figure 13 shows Θ_{Bn} at the bow shock, as seen from the Sun, for the two time intervals defined above. The layout is the same as in Figure 5. During time interval R1 (left side) the quasi-parallel shock is in the northern hemisphere, covering a sizeable part of the dayside bow shock including the sub-solar point. During time interval R2 the IMF rotation caused the quasi-parallel shock to move to the southern hemisphere, repeating the scenario described before. While in both cases the fully draped IMF crossed into the solar wind and connected magnetically with the quasi-parallel shock location, the southern hemisphere bow shock source was cut off from the northern hemisphere cusp by the equatorial reconnection line. Despite the reduced fluxes in the 15 September 1997 cusp crossing, the dramatic sensitivity of the CEP flux levels for IMF direction and the subsequent change of location of the quasi-parallel shock can still be observed.

4. Summary and Conclusions

The discovery of CDCs in the high altitude cusp region and the alleged association to CEP distributions has caused a long standing controversy about a possible new acceleration region in the magnetosphere. The diamagnetic effect of plasma in the high altitude cusp was parameterized by *Tsyganenko and Russell* [1999], who also noted turbulence in the depressed field region. A direct correlation between the appearance of CDCs, the turbulence within the CDC and the generation of CEP ions to MeV energies was discussed by *Chen et al.* [1997, 1998] and *Fritz et al*. [1999]. More recent work reported on an energy dependent enhancement process for ions and electrons with stronger flux enhancement for lower energies [*Whitaker et al*., 2006] and a strong anti-correlation between magnetic field strength and plasma pressure within a CDC [e.g., *Niehof et al*., 2005]. The concept of a new acceleration region in the high altitude cusp region was greeted with strong opposition by various groups who pointed out strong similarities between the characteristics of CEP and bow shock accelerated ions [e.g., *Chang et al.* 1998, 2000; *Trattner et al*., 1999, 2001; *Fuselier et al*., 2002]. The similarities between the two distributions include spectral shape, spectral breaks, temperatures, species-dependent acceleration efficiencies, ion composition, a solar wind velocity dependent spectral slope, and the fact that CEP ions only seem to be present when there is a magnetic connection from the cusp to the quasi-parallel bow shock.

In addition, a direct magnetospheric source along magnetic field lines that connect the cusp with the magnetopause was discussed for the CEP energy range > 150 keV/e [e.g., *Sibeck et al*., 1987; *Fuselier et al.*, 1991]. Magnetospheric ions may also drift directly into the cusp from the magnetosphere as shown in particle simulations by *Blake* [1999].

The idea that CEP ions are accelerated locally in the cusp was promoted because of a correlation between the appearance of CEP ions within CDCs. Recently Niehof et al. [2008] have suggested necessary and sufficient plasma conditions for the creation of CEP fluxes in the CDC. In this study we have investigated four Polar cusp crossings for such a correlation, showing events that have the CDC plasma conditions suggested by Niehof et al. [2008] and associated CEPs, CDC with the Niehof et al. plasma conditions without CEPs, and an event with a change in the energetic particle population but no CDC.

The first Polar cusp crossing on 18 September 1996 was characterized by several isolated CDCs along the path of the satellite. In a similar manner the CEP ion population showed sudden and dramatic flux changes by four orders of magnitudes. However, the boundaries for CDCs and CEPs did not match. One of the CDCs did not show any CEP ions; in another the CEP ions would suddenly disappear while the satellite was still immersed within a CDC. In contrast, CEP ions for the third CDC were also present outside the cavity.

The changes in the CEP ion distributions matched perfectly with sudden changes in the IMF B_X component. These changes caused a dramatic shift in the location of the quasi-parallel bow shock from the northern to the southern hemisphere. CEP ions at Polar were only observed when there was a direct magnetic connection from the northern cusp to the northern hemisphere quasi-parallel bow shock. If the draped IMF was magnetically connected to the quasi-parallel bow shock in the southern hemisphere, those shock accelerated ions where cut off from reaching the northern cusp by the tilted X-line in the sub-solar region.

The second event occurred on 11 August 1996 and consisted of a Polar cusp pass that covered 4.5 hours. About 4 hours of this cusp pass were dominated by an extended CDC. An analysis of the behavior of CEP ions revealed again a sudden three orders of magnitude change in the flux of these energetic ions. This flux change occurred while Polar was still in the same extended CDC but during a time when the IMF shifted, moving the quasi-parallel shock region from a dayside location to a far-downstream location. Due to the convection with the solar wind and a magnetic connection to a much weaker shock at the night side flank region, bow shock energetic ions have less access to the cusp region; which accounts for the sudden drop of the CEP flux in the CDC.

The third event occurred on 8 September 1996. Polar crossed the cusp region in the equatorward direction in about 2.5 hours of which almost 2 hours were an extended CDC. This CDC showed no CEP ion flux throughout the entire period and the investigation of the solar wind condition revealed a quasi-parallel shock location in the southern hemisphere. As in the previous event, these bow shock accelerated ions are separated from the northern hemisphere cusp by the equatorial reconnection line. The presence of a CDC during this cusp crossing did not contribute to the energetic ions.

The fourth Polar cusp event on 15 September 1997 was characterized by the absence of a CDC. Despite the absence, there was a change in the flux of the energetic particles which was again attributed to a shift in the location of the quasi-parallel shock from the northern to the southern hemisphere. This shift occurred during the high latitude section of the Polar cusp crossing. In this location, cusp field lines are stretched out into the lobes, which caused as in the previous example only weak fluxes in the cusp. However, even under these conditions a clear change in the flux level of the energetic ions with the shift in the location of the quasi-parallel shock could be observed.

This study emphasizes again a strong dependency of CEP ions on a magnetic connection to the quasi-parallel shock. The appearance of CDCs is only related to the density of the magnetosheath plasma and the altitude in the cusp. A correlation between CDCs and CEP ions could not be established; which makes it highly unlikely that the magnetic turbulence within a CDC has any significant influence on the ion energy. The magnetic turbulence reported in CDCs believed to be responsible for the acceleration of magnetosheath ions to MeV energies [e.g., *Chen et al*., 1997, 1998] is, to a large percentage, just multiple encounters of the satellite with the boundary of the CDC (Nykyri, private communication, 2008).

This study also showed that a systematic usage of this method, to magnetically connect cusp field lines with the bow shock, considering the location of the quasi-parallel bow shock and the appearance of CEP ions in the cusp can be used as tracers for plasma transport into the magnetosphere and better understand the magnetic topology between the solar wind and the ionosphere.

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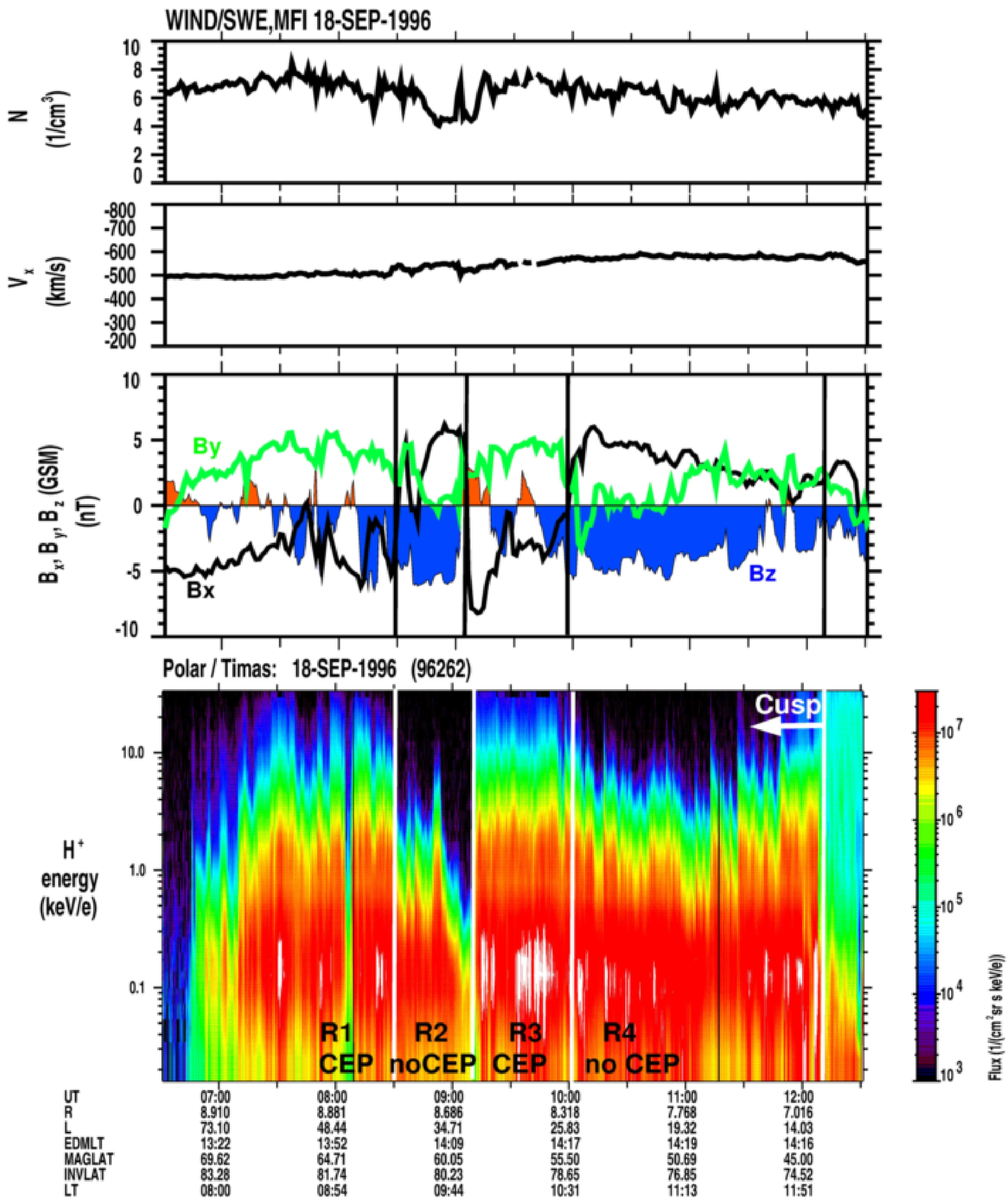

Figure 1: The solar wind density N and solar wind velocity V (top panels) observed by Wind/SWE for the Polar cusp crossing on 18 September 1996. The third panel shows the IMF conditions in GSM coordinates (B_X, B_Y, B_Z) observed by Wind/MFI. The solar wind and IMF data have been convected by about 14 minutes to account for the travel time from the satellite to the magnetopause. Vertical black lines in the magnetic field panel separate regions with high or low CEP flux levels (see below). The bottom panel shows H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument onboard the Polar satellite during a northern hemisphere cusp crossing on 18 September 1996. Polar was moving towards the equator and encountered magnetosheath ions on open geomagnetic field lines at about 06:45 UT before leaving the cusp at 12:10 UT. The periods of interest separating regions with high CEP flux from regions with low CEP flux are marked by white lines.

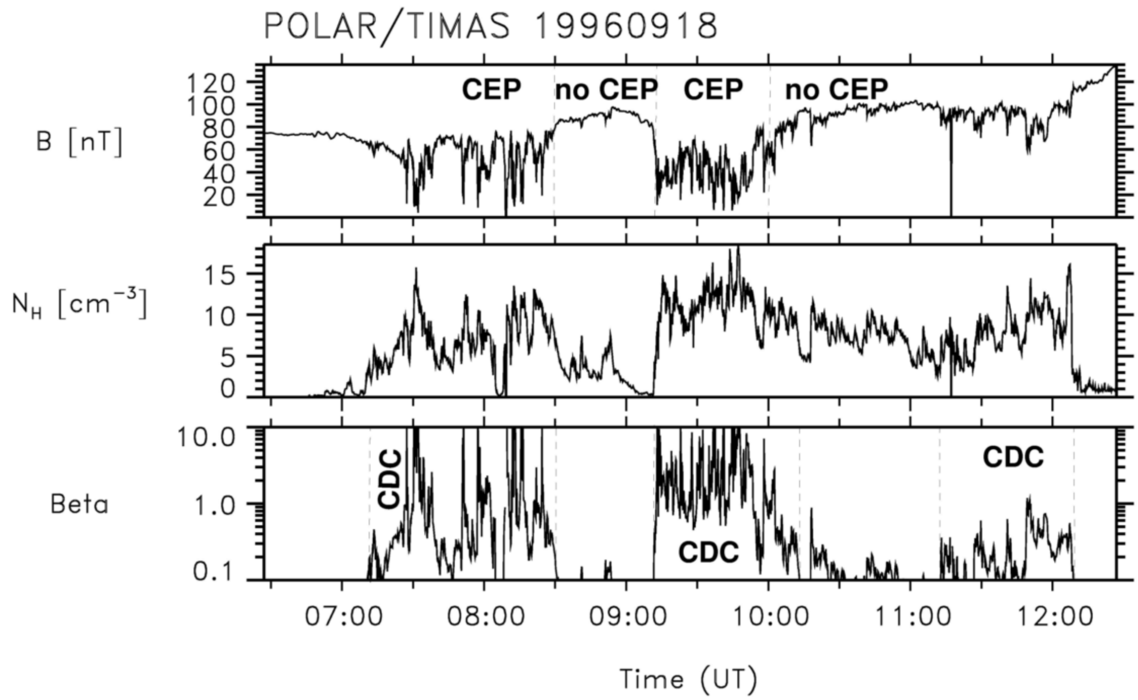

Figure 2: Local magnetic field intensity B (nT), hydrogen density N_H (cm^{-3}) and the plasma beta observed by the Polar satellite during the September 18, 1996, cusp crossing. The appearance of a cusp diamagnetic cavity (CDC) [*Chen et al.,* 1998; *Niehof et al*., 2008] is caused by high plasma density at high altitudes in the Polar orbit and is characterized by a depressed and turbulent magnetic field. This effect also causes the local plasma beta to spike, reaching factors of 10 within the CDC during this cusp crossing. The appearance of CEP ions is only partially in agreement with the CDC's. CEP distributions are also present outside CDC's as well as missing inside CDC's.

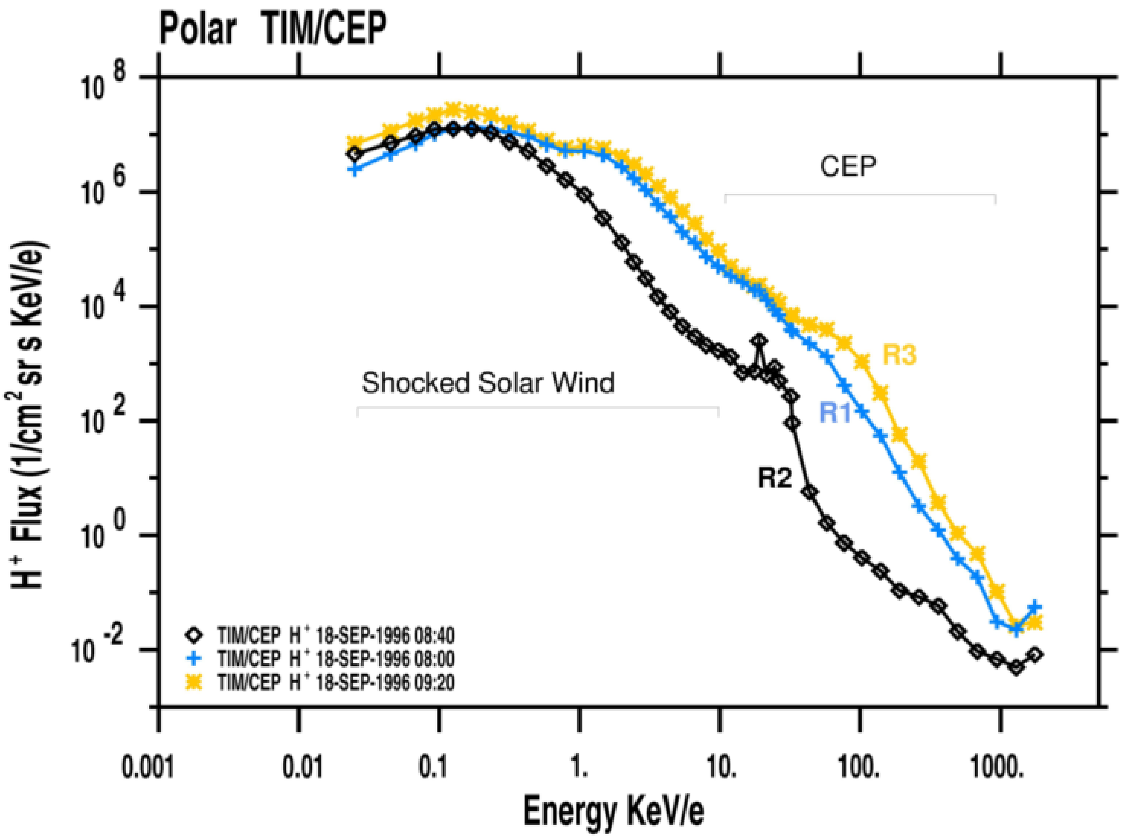

Figure 3: Proton flux line spectra (1/(cm^2 s sr keV/e)) from the TIMAS and CEPPAD instruments for three different time intervals in Figure 1. The spectra are averaged over 5 minutes starting at the time indicated in the time labels. The change in the CEP flux levels during the 18 September 1996 Polar cusp crossing reached about 4 orders of magnitude for 100 keV particles.

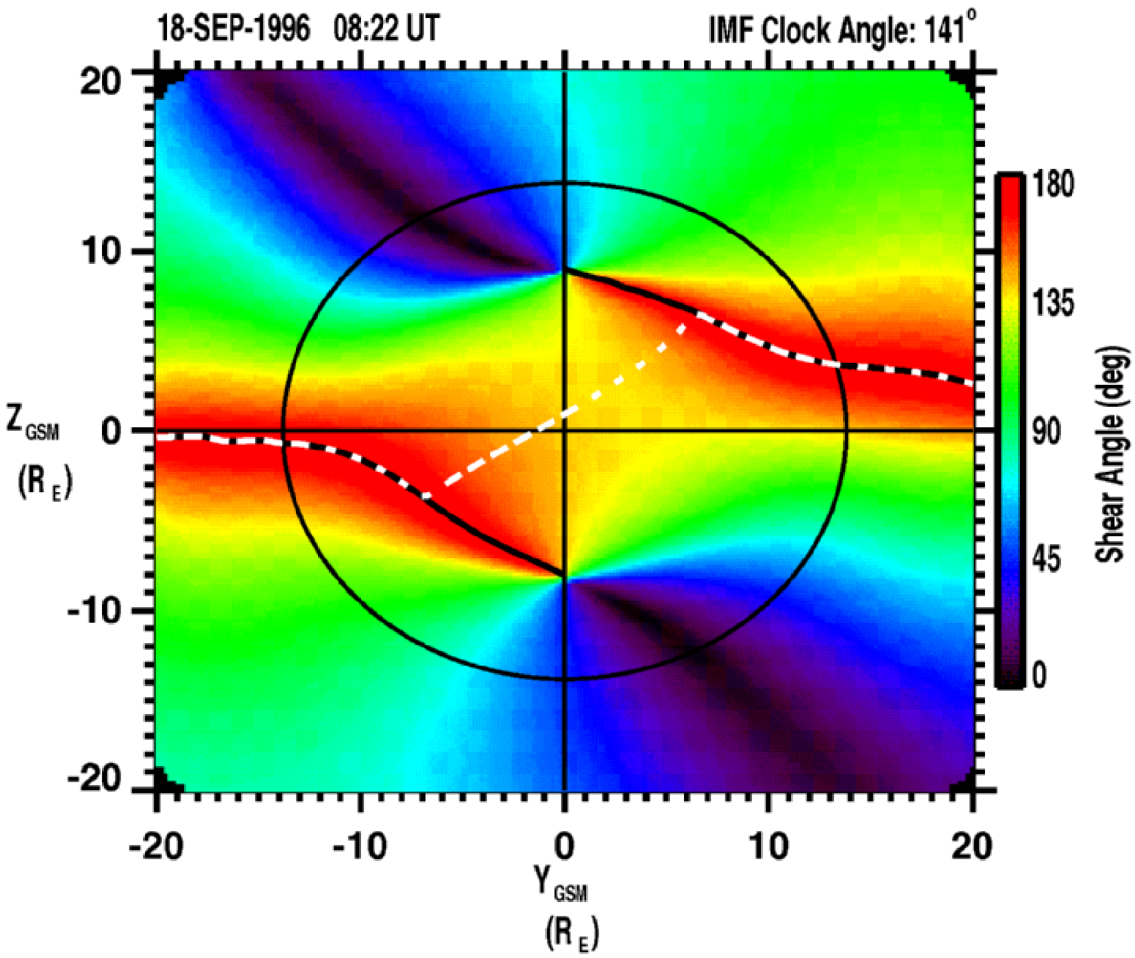

Figure 4: The magnetopause shear angle for region R1 in Figure 1, as seen from the Sun. The magnetopause shear angle was calculated using the magnetic field direction of the T96 model combined with the fully draped IMF conditions at the magnetopause [*Cooling et al.* 2001] for the 18 September 1996, Polar cusp crossing. The circle represents the magnetopause shape at the terminator plane. The dashed white line represents the location of the line of maximum magnetic shear across the magnetopause as the most likely location of the reconnection line [*Trattner et al.*, 2007].

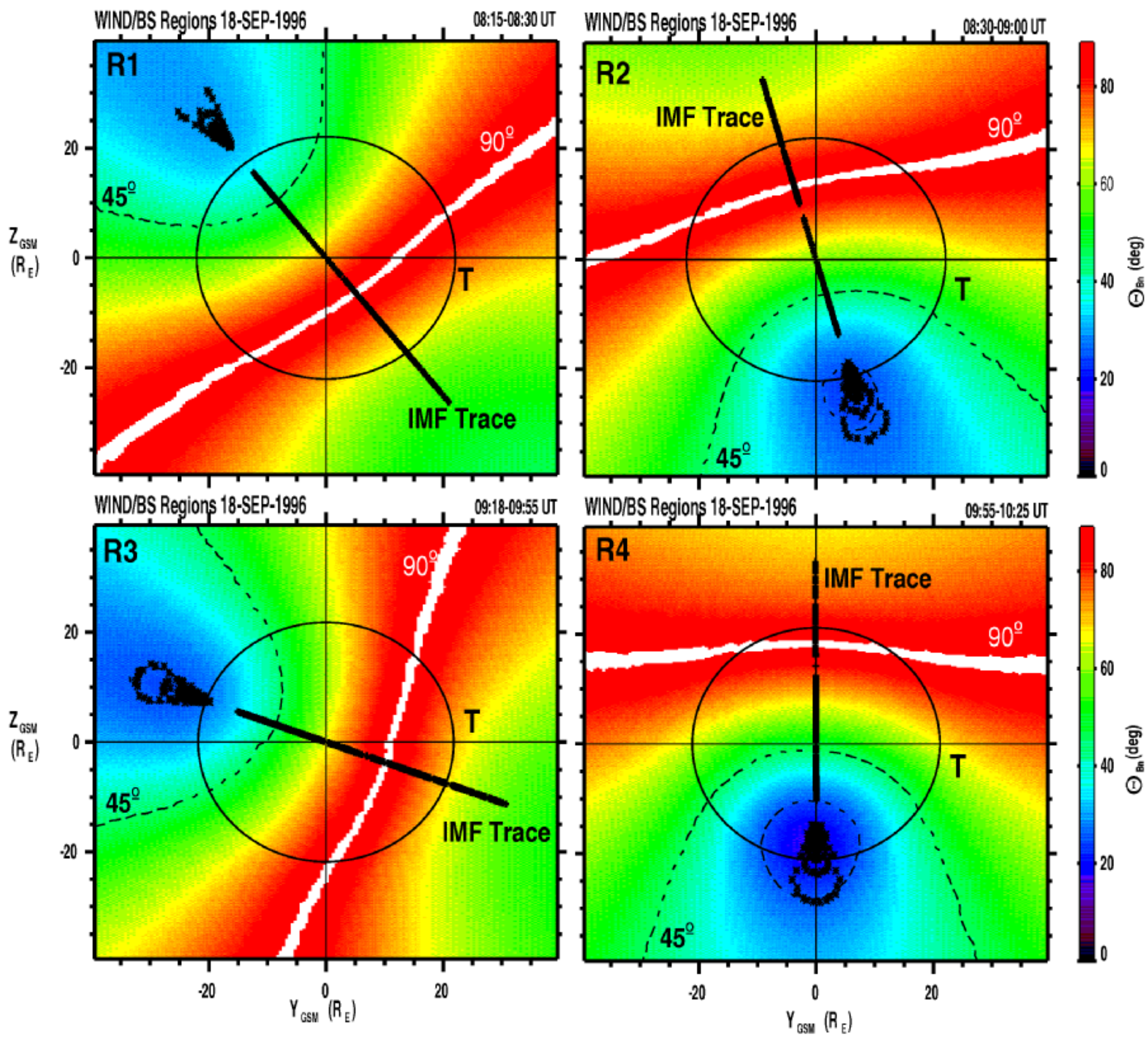

Figure 5: The bow shock as seen from the sun. Color coded is Θ_{Bn}, the angle between the shock normal and the IMF for the respective time intervals. Red regions represent the quasi-perpendicular shock region while green and blue region represent the quasi-parallel shock region, a well known particle accelerator. The black circle depicts the terminator plane projected to the bow shock. The black line shows the bow shock exit points of the sub-solar IMF field line on its way through the magnetosheath. The cluster of points are the exit points of the fully draped IMF at the bow shock. For the time intervals with high CEP flux (regions R1 and R3), the exit points are within the quasi-parallel shock in the northern hemisphere, providing a direct magnetic connection from the bow shock to the northern cusp. In contrast, the IMF exit points for regions R2 and R4, with significant lower CEP flux levels, are located in the quasi-parallel shock region in the southern hemisphere. This location is disconnected from the northern cusp region and the Polar satellite by the tilted reconnection line.

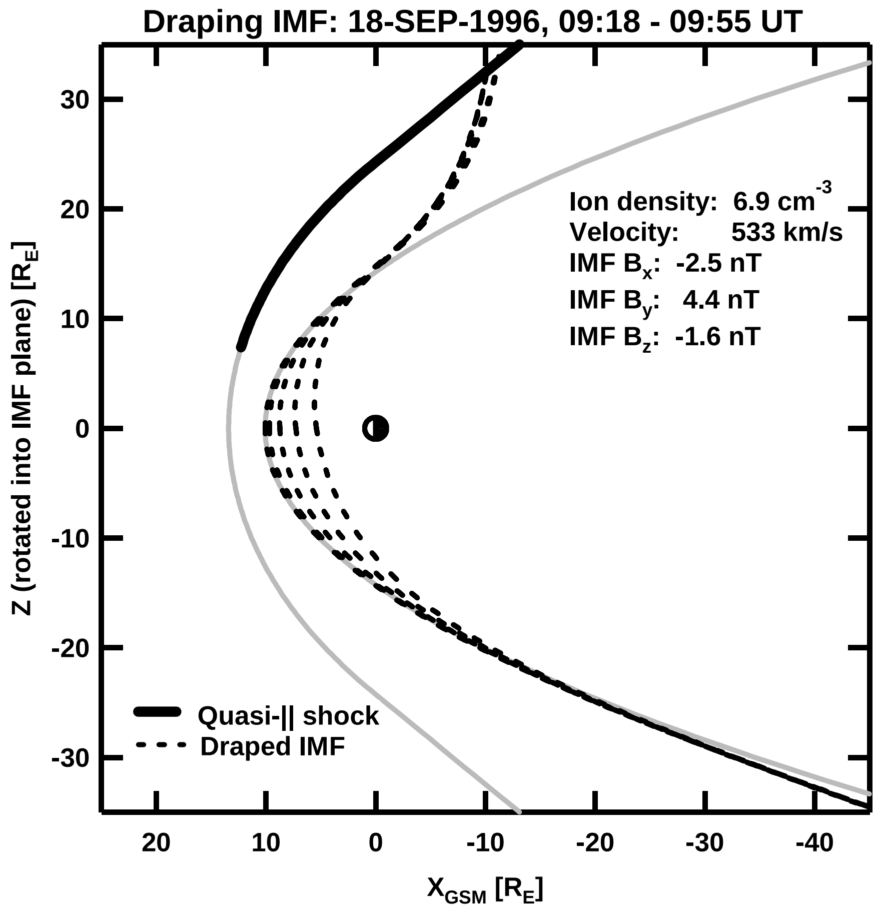

Figure 6: The location of the quasi-parallel bow shock region (thick line) and the fully draped IMF field line (dashed lines), rotated into the plane of the IMF and seen from the dusk side. The quasi-parallel bow shock stretches almost to the sub-solar point, allowing IMF field lines convecting through the magnetosheath to have access to the shock acceleration region.

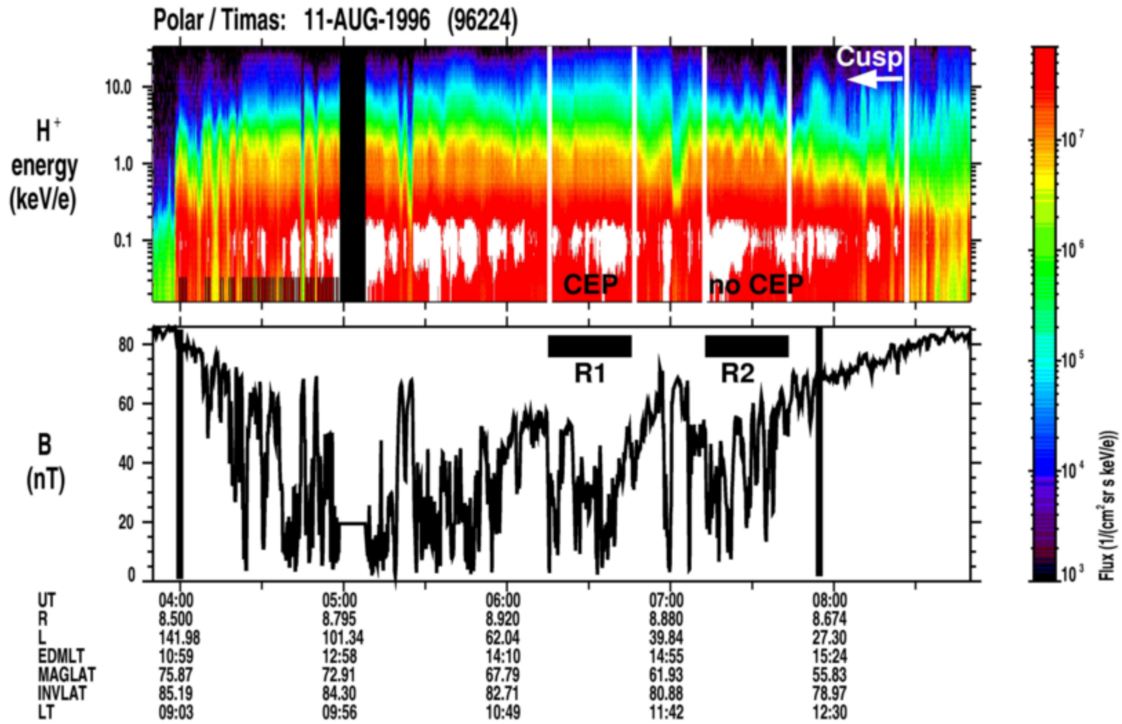

Figure 7: The top panel shows H^+ omni-directional flux measurements ($1/(cm^2$ s sr keV/e)) observed by the TIMAS instrument onboard the Polar satellite during a northern hemisphere cusp crossing on 11 August 1996. Polar was moving towards the equator region and encountered magnetosheath ions on open geomagnetic field lines at about 04:00 UT. The cusp crossing is dominated by high flux levels which together with the high Polar altitude, causes an extended CDC (marked by vertical black lines n the bottom panel), covering almost the entire cusp crossing. Two periods of interest within the CDC are marked with white lines (top panel) and black bars (bottom panels), R1 with a high CEP flux and R2 with no CEP flux.

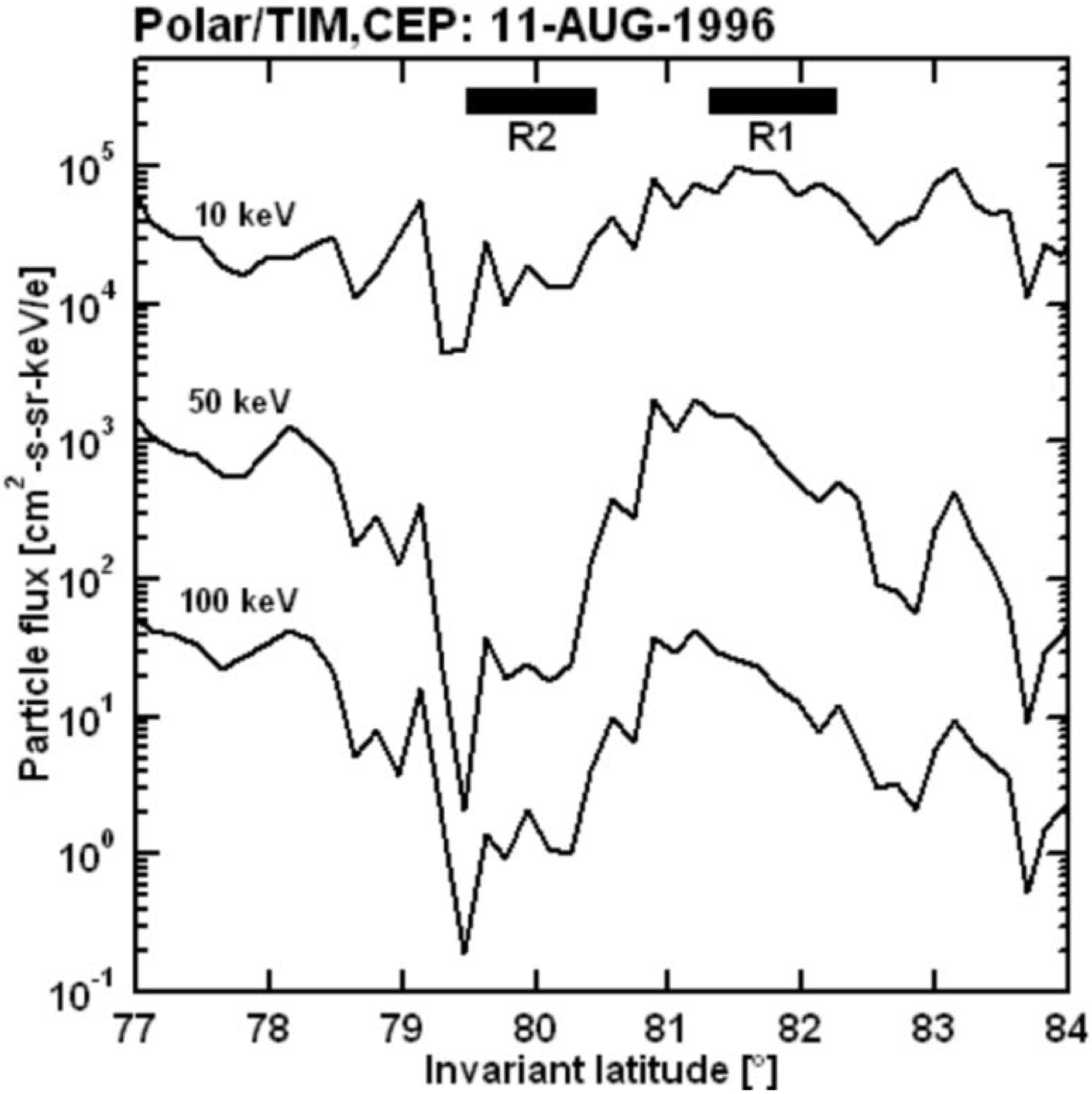

Figure 8: The hydrogen flux (1/(cm^2 s sr keV/e)) at 10 keV, 50 keV and 100 keV versus invariant latitude as observed by TIMAS and CEPPAD during the 11 August 1996, Polar cusp crossing. The period of interests R1 and R2 are marked with black bars. A comparison of the flux level for R1 and R2 reveals a significant change, reaching about three orders of magnitude for the higher energies. There is also a distinctive flux decrease for the high energy proton distribution with increasing latitude while the lower energies are only marginally affected.

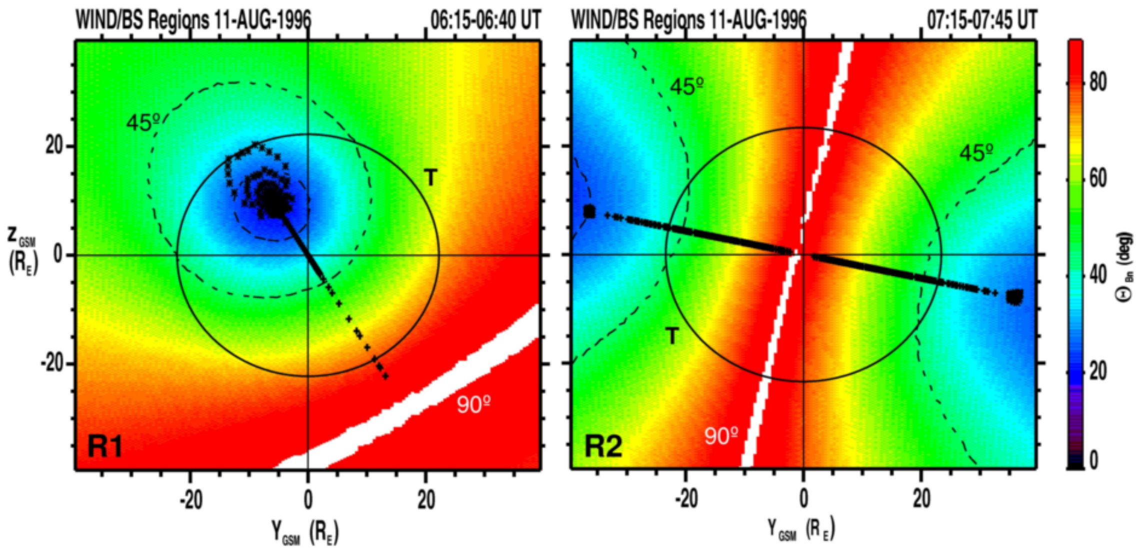

Figure 9: The bow shock as seen from the sun. The layout of this Figure is the same as in Figure 5, using the two time intervals marked in Figure 7. Time interval R1 with a high CEP flux has a direct magnetic connection to the quasi-parallel bow shock region, located at the dayside northern hemisphere. Time interval R2 with no significant CEP flux has a connection to the quasi-parallel bow shock located far down the magnetospheric tail. From such a distance no significant energetic particle fluxes can reach the northern cusp region.

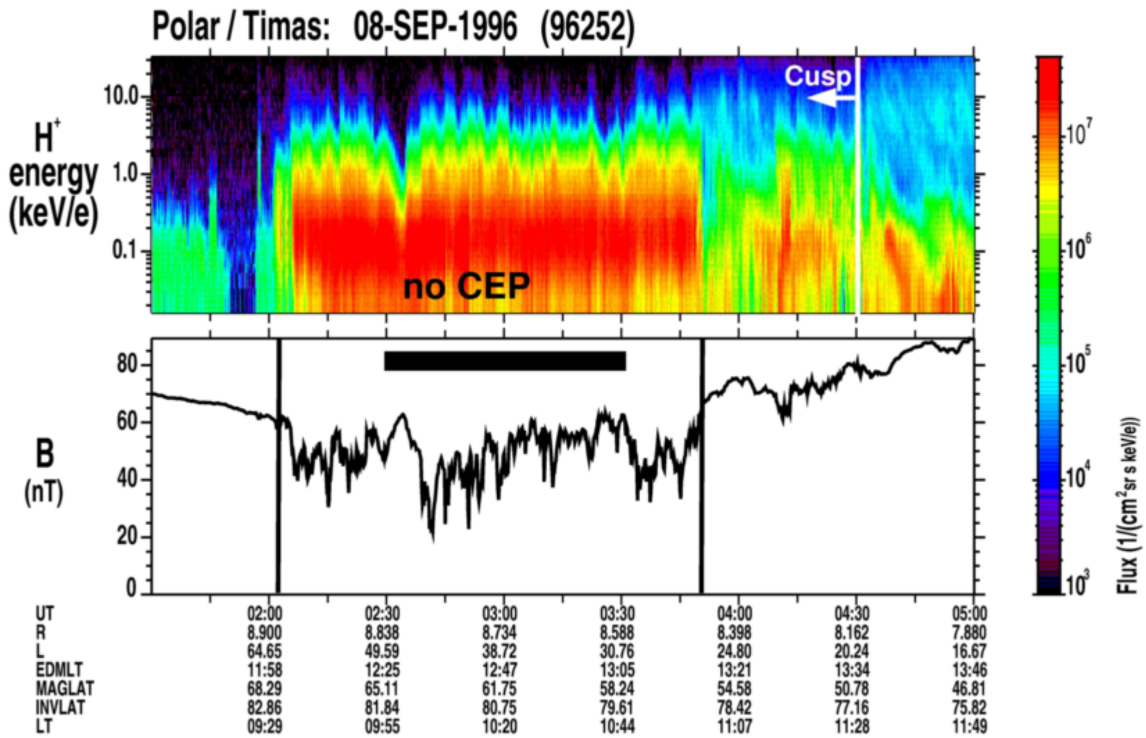

Figure 10: The top panel shows H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument onboard the Polar satellite during a northern hemisphere cusp crossing on 8 September 1996. Polar was moving towards the equator region and encountered magnetosheath ions on open geomagnetic field lines at about 02:00 UT. The cusp crossing is dominated by high flux levels which together with the high Polar altitude, causes an extended CDC (marked by vertical black lines in the bottom panel), covering almost the entire cusp crossing. In contrast to the previous events, this CDC shows no significant flux in the higher energies.

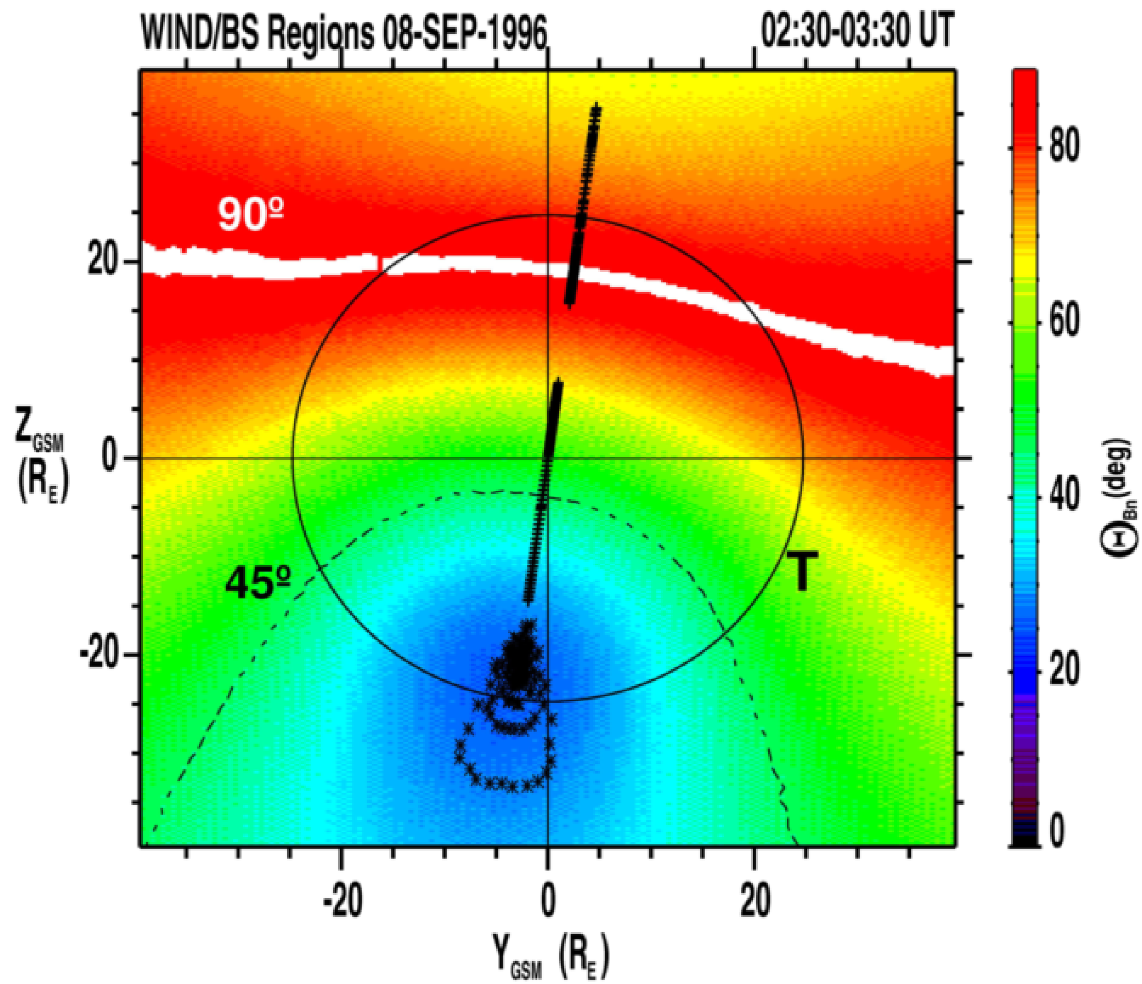

Figure 11: Θ_{Bn} at the bow shock, as seen from the sun, during the Polar CDC encounter on 8 September 1996. The layout of this Figure is the same as in Figure 5. The magnetic field conditions for the time interval marked in Figure 9 lead to a quasi-parallel bow shock location in the southern hemisphere. While there is a direct magnetic connection of the draped IMF field lines to the quasi-parallel bow shock region in the southern hemisphere, this source of energetic ions is cut of by the reconnection line. No energetic ions can reach the northern cusp to be observed in the CDC.

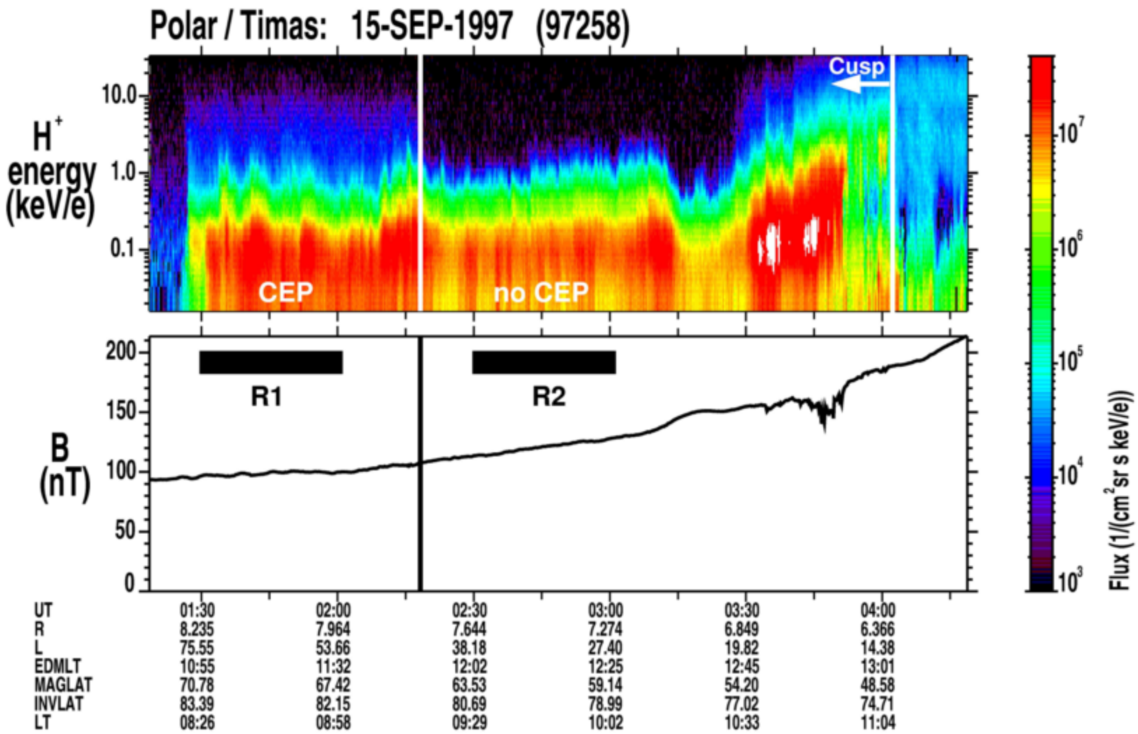

Figure 12: The top panel shows H^+ omni-directional flux measurements (1/(cm^2 s sr keV/e)) observed by the TIMAS instrument onboard the Polar satellite during a northern hemisphere cusp crossing on 15 September 1997. Polar was moving towards the equator region and encountered magnetosheath ions on open geomagnetic field lines at about 01:30 UT. Due to the lower altitude of the Polar satellite (and stronger local geomagnetic field), combined with a lower plasma density in the cusp, no CDC is formed. Despite the absence of a CDC there is a substantial change in the flux at higher energies caused by changing IMF conditions.

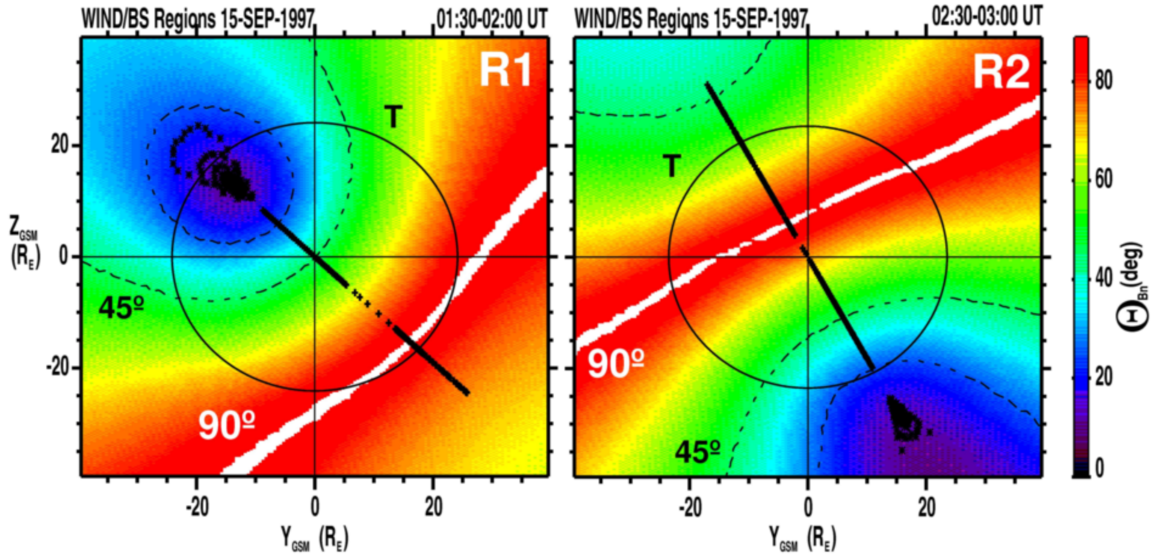

Figure 13: The bow shock as seen from the sun for the 15 September 1997 Polar cusp event. The layout of this Figure is the same as in Figure 5, using the two time intervals marked in Figure 11. Time interval R1 with a high CEP flux has a direct magnetic connection to the quasi-parallel bow shock region, located at the dayside northern hemisphere. Time interval R2 with no significant CEP flux has a connection to the quasi-parallel bow shock located in the southern hemisphere. This source of energetic particles will be again cut off by the reconnection site and energetic ions will be prevented from reaching the northern cusp region.