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First polar and 1995-034 observations of the midaltitude cusp during a persistent northward IMF condition

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Abstract. We present the first observations by Polar and 1995-034 of the mid-altitude cusp. On May 29, 1996, the Polar and 1995-034 spacecraft crossed into an extended cusp region. The region was characterized by intense fluxes of solar wind like ions in the energy range 1-10 keV that had angular distributions that showed evidence of flows and trapping. The ion composition data are combined with energetic proton observations from Polar and plasma observations from 1995-034 and DMSP satellites to examine the spatial and temporal extent and plasma characteristics of the cusp during a persistent northward IMF condition. The composition data is consistent with expected solar wind composition with a source temperature of $\sim 1.25 \times 10^6$ K. The combined spacecraft observations show an extended cusp-like region, probably produced by northward IMF.

Introduction

The dayside magnetosheath plasma is dominated by an ion population with charge states and composition characteristic of the solar wind (Gloeckler et al., 1986). The magnetosheath plasma accesses magnetic field lines that penetrate or are adjacent to the magnetopause. The plasma near the magnetopause boundary is classified by the energy flux and density of its components (Newell and Meng, 1988). In the high latitude dayside magnetosphere, the different plasma regimes have been identified using both high and low altitude data (Haerendal and Paschmann, 1982; Newell and Meng, 1988). The cusp proper is usually defined by the existence of high density soft electron precipitation combined with intense ~keV ion precipitation and is found close to local noon. Away from noon the energies and densities of the ions and electrons become generally hotter and less dense and are classified variously as mantle, cleft/LLBL, etc. (Newell and Meng, 1988; Smith and Lockwood, 1996). Satellites entering the magnetosheath observe highly ionized ions with composition ratios and charge states that were frozen in the solar wind stream near the sun (Gloeckler et al., 1986; Gloecker and Geiss, 1989). The high charge state and intensity of higher mass ions makes them easily distinguishable from ionospheric and magnetospheric ions. Near the dayside cusp and cleft regions, the

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plasma is dominated by these high charge state ions. This fact is used to help identify the plasma regions traversed by Polar.

In this paper, we present the first cusp observations by the 1995-034 and Polar satellites. These observations provide a unique, simultaneous, two point perspective of the middle altitude cusp. Polar is in a ~2×9 Re orbit at ~86° inclination (Acuña et al., 1995) while 1995-034 is in a ~1.2×7.2 Re orbit at ~63° inclination (Fennell et al., 1996). We use data from the CAMMICE MICS (Magnetospheric Ion Composition Sensor) and CEPPAD IPS (Imaging Proton Spectrometer) on the Polar satellite. We compare the MICS results with observations by IPS on Polar and with simultaneous plasma observations from 1995-034 and low altitude DMSP F12 and F13 satellites.

MICS measured the ion flux, mass, and charge state for ions with energies of 1-200 keV/q (Wilken et al., 1992). MICS views perpendicular to the Polar spin axis which was ~50° from the sun line towards dawn. MICS provided the ion charge state data that identifies the source of the plasma. If the plasma is solar wind in nature, the data can be used to estimate its source temperature. IPS measured protons ≥18 keV and provided 4π sr coverage (Blake et al., 1995). 1995-034 measured the plasma electrons and protons with energies of 0.2-30 keV and 0.04-25 keV respectively plus energetic electrons ≥130 keV and protons ≥80 keV. DMSP measured plasma electrons and protons with energies of 0.03-30 keV (Hardy, et al., 1984). For this paper we used the IGRF95 field model for magnetic coordinates. Attempts to perform accurate high-to-low altitude field line mappings with more complex field models are beyond the scope of the present work.

Observations

On May 29, 1996, the Wind satellite was ~155 Re upstream of Earth while Geotail and IMP-8 were in the near Earth solar wind. Their data showed that the solar wind speed was relatively constant (~350-370 km/sec). The interplanetary magnetic field (IMF) was northward for several hours. The near earth GSM IMF values show B_Y and B_Z were comparable from 0000 UT to 0238 UT except for short intervals near 0135 UT and 0207 UT where $B_Y > B_Z$. For 0238-0730 UT $B_Z > B_Y$ and B_Z approached B_{TOTAL} at times. Near 0230-0235 UT at Wind, the IMF rotated sunward and the density increased by ~20% indicating an IMF sector boundary passage which arrived at Earth near 0319 UT. We report on an interval beginning at ~0100 UT on May 29, 1996. Polar and 1995-034 were in the prenoon sector heading poleward, as shown in Figure 1a. The DMSP satellite positions, for the early hours on May 29, are shown in Figure 1b where tick marks on some of the DMSP trajectories mark cusp or cusp-like encounters. The shading of Polar and 1995-034 trajectories mark the extent of dayside soft particle fluxes observed.

1995-034 entered into the structured LLBL/cusp like plasma near 0135 UT. This was evidenced by a rapid decrease in the

energy of the plasma electrons and ions (see Figure 2) and occurred well poleward of the >130 keV electron trapping boundary (not shown). Figure 2 shows that the LLBL/cusp plasma consisted of soft, intense, structured electron fluxes and hot ions with peak energy flux near 500-600 eV. However, sporadic fluxes of >80 protons (not shown) were present until ~0317 UT, an indicator that 1995-034 was near the LLBL/cusp boundary. At 0317 UT the mean energy of the soft electrons decreased and the ion average energy increased to ~1 keV, indicative of entry into the cusp proper. (Coincident with arrival of IMF sector boundary. IMF B_Z increased dramatically, B_X increased toward positive values, B_Y decreased and $B_Z > B_Y$ since ~0250 UT.) Finally, 1995-034 crossed into the post noon PSBL near 0420 UT, as evidenced by an order of magnitude increase in the mean ion energy and a return of the keV electrons, and continued to lower latitudes near 15.4 MLT. Tick marks are shown on the Polar and 1995-034 trajectories at ~0316 UT and 0420 UT for comparison.

The MICS data, summarized in Figure 3, show that Polar left the dayside plasma sheet and entered a plasma region characterized by low-energy high charge state ions near 0300 UT. Polar remained in this population until ~0710 UT when it entered the polar cap. The Hydra plasma data (R. Freidel, personal communication, 1996) showed that Polar entered the cleft/LLBL plasma, simultaneous with the plasma changes observed by 1995-034, near 0317 UT. Figure 3e displays spin-averaged proton intensity and shows that the ring current ion energy decreased ($\propto 1/L^3$) as Polar moved outward from L~3.2. Figure 3f shows the energy integrated proton angular distributions. Clear loss cones were seen between 0100 and 0305 UT in the inner magnetosphere, as expected. [The magnetic field direction in Fig. 3f corresponds to the center of the loss cone near 225-255° until 0300 UT. Thereafter, it was centered between the flux peaks, until 0635 UT, when the field direction changed rapidly multiple times.]

Figure 3 shows that O^+, He^{++} and He^+ fluxes were present in the inner magnetosphere. After ~0300 UT only He^{++} and $O^{>2+}$ were observed, with the He^{++} intensity peaking around 3 keV. Heavier high charge state ions were also seen after 0300 UT (not shown). Such composition changes would be expected upon entering the LLBL/cusp. The initial >1 keV LLBL/cusp H^+ population was nearly isotropic, however, by ~0317 UT (approximate IMF sector boundary arrival time) the angular distributions exhibited trapped signatures interspersed with periods of beam-like distributions. This new proton population had a complex angular distribution perpendicular to Polar's spin axis. As Polar was leaving the magnetosheath plasma, near 0638 UT, two intervals of beam-like H^+ distributions were observed by MICS (ref. Fig. 3f). Near 0700 UT, the beams showed "flow" direction reversals that were consistent with a change in sign of the IMF B_X and B_Z components. Thus, based on the MICS data, Polar appears to have traversed a much extended cusp-like region with the low latitude entry at invariant latitude, Λ~77.3° and poleward exit at Λ~85° during this period of northward IMF. The simultaneous Polar and 1995-034 cusp observations near 0420 UT (See tick marks on their trajectories in Fig. 1) shows that the cusp was extended ($\Delta\Lambda$~4.8°) and spanned their relative positions.

The IPS proton angular distributions, shown in Figure 4, exhibited features similar to those observed by MICS. The IPS proton data are presented in a polar angle versus azimuthal angle format where Det-0 views roughly along the Polar spin axis, Det-9 views nearly along the anti-spin direction and the rotation about the spin axis is divided into 32 angular sectors.

(Note, sector angles of Figs. 3 and 4 are in instrument reference frame.) IPS Det-0, -2 and -3 viewed sunward during sector-0. The magnetic field direction is indicated by a white dot, when it was stable during the data sample interval (~1.6 min.). At ~0359 UT IPS observed a nearly "pancake" angular distribution, as did MICS (see Fig. 3f). Such distributions indicate the existence of a particle trapping field geometry. At ~0418 UT IPS detected an earthward directed particle flux. By ~0456 UT the pancake distributions returned (Fig. 3f and Fig 4 at ~0624 UT) and persisted until ~0644 UT, when an earthward beam-like distribution was observed by both MICS and IPS. By ~0703 the direction of the beam had rapidly shifted anti-sunward and became less pronounced at IPS but still strong at the lower energies measured by MICS.

Examination of Figure 1 (and Table 1) shows that 1995-034 and Polar entered the structured soft particle region at essentially the same Λ but separated by ~1.5 hrs in UT and ~1 hr in MLT. This hints that the low latitude edge of the LLBL/cusp was stable for the 1.5 hour interval. This is borne out by the DMSP data, especially those from DMSP F12, as shown in Table 1. (Note: DMSP F13 reached the cusp-like region only near 0108 UT; labeled "LLBL below cusp" in Table 1.) Up through 0428 UT DMSP observed that the lower edge of the LLBL/cusp changed only slightly in latitude. The position ranged from Λ~77.0-77.7 at DMSP altitudes and Λ~77.3-77.4 at Polar/1995-034 altitudes. The DMSP data, on the whole, show good agreement with the 1995-034 and Polar determinations of the position of the low latitude boundary of the LLBL/cusp. The small differences are probably well within the errors of the model field used (IGRF95), the IMF conditions, and the separation of the satellites. Most of the DMSP F13 observations were taken in the plasma sheet and could not be used to define the LLBL/cusp boundary, however, they do constrain the cusp to be above the latitudes shown and are presented in Table 1 for completeness.

Composition Results

MICS post accelerates ions by 22.5 kV/q to increase the delectability of the higher masses. High charge state ions, such as solar wind O^{+3}-O^{+6}, have their energies increased by 67-135 keV and are easily detected. A detailed analysis was made of the charge state of the LLBL/cusp ion population. The analysis process is described in Grande et al. (1996). The multi-parameter data (DE's) were recorded for the highest mass ions detected in each 184 msec data accumulation period. This includes measurements of the ion's energy per charge (E/q),

Table 1. Boundaries of Soft Plasma Region

Satellite	UT	Λ (deg)	λ (deg)	MLT (Hr)	Comment
Polar	0316	77.3	57.1	10.0	LLBL/cusp entry
	0710	85.0	75.2	16.6	exit to polar cap
1995-034	0135	77.4	54.3	11.1	LLBL/cusp entry
	0420	76.1	51.3	13.8	exit to PSBL
DMSP F12	0105	82.9	82.7	13.3	polar cap to cusp
	0108	77.1	76.3	11.4	cusp to LLBL
	0247	81.0	80.4	15.0	polar cap to cusp
	0249	77.7	77.1	12.5	cusp to LLBL
	0428	77.0	76.9	15.8	LLBL to cusp
	0610	74.4	73.4	16.5	PSBL to LLBL
DMSP F13	0108	77.1	76.2	11.4	LLBL below cusp
	0250	75.3 max	74.3	11.9	PSB*
	0432	74.7 max	73.3	12.5	PSB*
	0614	75.0 max	72.1	13.4	PSB*

where Λ is invariant latitude and λ is magnetic latitude
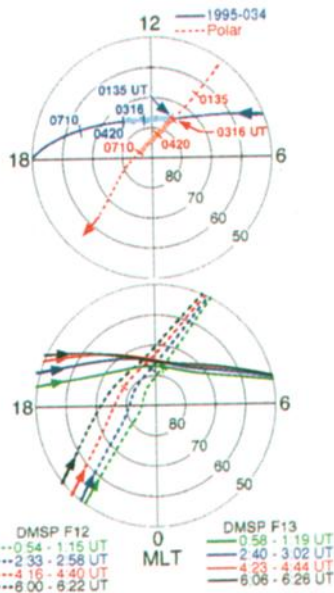* did not get into LLBL

Figure 1. Trajectories of Polar and 1995-034 satellites (top) and of DMSP F12 and F13 satellites (bottom) in invariant latitude (Λ) and MLT.

velocity (via time of flight (TOF)), and total energy (E). The low energy of the magnetosheath ions complicates their detection because they are heavily scattered and straggle in the TOF foil and thus provide less than MICS best resolution.

The results of the analysis of the DE's are shown in Figure 5. Figure 5a is a plot of ion E vs. E/q for the period 03:00 to 07:00 UT and shows loci that are lines of constant charge state. The expected positions of charge states 1 and 2 are shown. For this study, only DE's with charge states >+2 were used. These DE's fall within the bounded area, top left of Figure 5a. The selected DE's were used to generate Figure 5b, which shows the ion E vs. TOF. Since these are non relativistic ions, different masses should have different loci. (The expected loci for some masses are shown.) Figure 5b shows that the high charge state ions produced a spread of particle masses that centered predominantly on the CNO group. Figure 5c shows a plot of E/q vs. TOF for these ions and a few different mass per charge (M/q) loci. The majority of the ions grouped where high charge state oxygen and carbon are expected to be. (It should be emphasized, however, that with MICS it is not
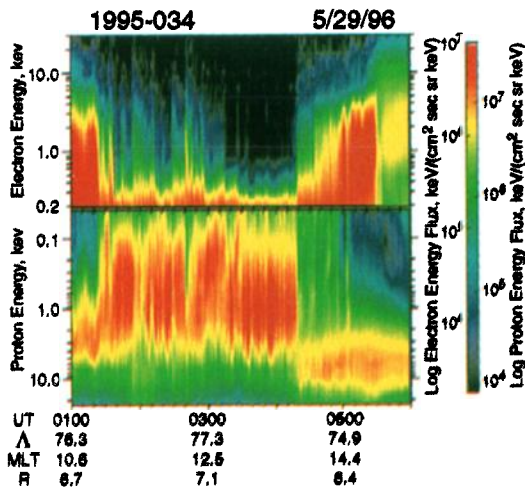
possible to actually distinguish the loci of the individual species, at these energies and limited DE statistics, as would be possible at higher energies or better DE statistics.)

Figure 5 shows that there is a consistent interpretation for all the high charge species in terms of a unified solar wind source. The high charge M/q combinations in Figure 5c correspond to a frozen-in coronal source temperature, derived from the ionization fractions calculated by Arnaud and Rothenflug (1985), of ~1.25 x 10^6 degrees. This temperature represents a best fit to these data, as shown in Figure 5d. Division of the DE's into subgroups (not shown) produces ion subgroups with different and relatively well defined M/q ratios. This gives confidence that the procedure used is valid. For example, the carbon group showed an M/q centered on 2, corresponding to a carbon charge state of +6. For oxygen we obtained a broadened distribution centered on M/q of 2.5 to 3, for a mean charge of +6. For iron a mean charge state of 10 was obtained. Magnesium and silicon could not be unequivocally separated from the oxygen (which probably indicates our DE's identified as oxygen contain traces of Si^{+8}, Mg^{+10}, and possibly some C^{+5}). These observations are not unique. There have been many similar cusp encounters by the Polar satellite. These will be the subject of a future extended study with emphasis on what can be learned from the cusp composition measurements and how the solar wind source temperature derived from them compares to other estimates.

Summary

We conclude that, during the May 29, 1996 northward IMF period, the Polar, 1995-034 and DMSP spacecraft observed a spatially extended cusp region. The region was characterized by magnetosheath plasma with typical solar wind charge states and mass composition profiles. The composition re-
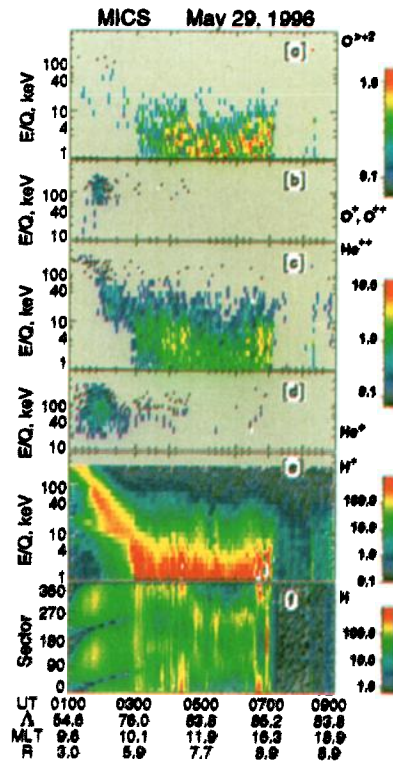

Figure 2. Spectrograms of plasma electron (top) and ion (bottom) energy fluxes observed by 1995-034 for 0100-0700 UT on May 29, 1996.

Figure 3. MICS plasma ion intensities: (a) $O^{>+2}$, (b) O^+, (c) He^{++}, (d) He^+, and (e) H^+. (f) shows the >1 keV proton angular distributions measured perpendicular to the Polar spin axis (sunward is ~125°).
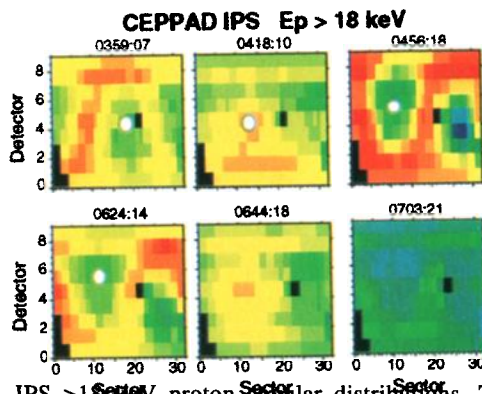
Figure 4. IPS >18 keV proton angular distributions. The black rectangles near center are from earth light and the black region near sector 0 is from sun light. The white dots show direction of B.

sults for this cusp observation are similar to the CCE magnetosheath observations of Gloeckler et al. (1986). The cusp's poleward boundary was extended to very high invariant latitudes ($\Lambda\sim85°$) and at least 4.8° wide, based on the simultaneous 1995-034 and Polar observations at 0420 UT. This extension of the cusp to high latitudes is probably related to the persistent northward IMF condition, especially after 0300 UT on May 29, 1996, and may be caused by merging on northern tail lobe field lines. The angular distributions of 1 to ~30 keV protons showed trapping signatures and flows. The trapping requires that the field intensity be greater at higher altitudes
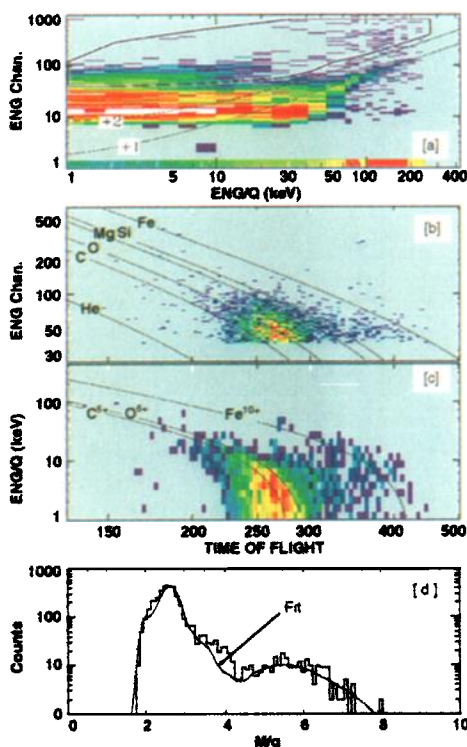

Figure 5. MICS ion multi-parameter (DE) data: (a) ion charge state identification.; (b) ion mass identification for ions in the upper bounded region of panel (a); (c) ion M/q identification; (d) best fit to the M/q distribution (after Arnaud and Rothenflug, 1985; see text).

away from Polar. This may be another indication of high latitude merging or at least a 'twisting' of the magnetic field. Finally, we have determined, using the composition data, that the temperature of the cusp plasma at its solar source was ~1.25 X 10^6 K.

This observation of the extended cusp is, so far, unique and required the high altitude observations provided by Polar plus the monitoring of the cusp's lower latitude edge by 1995-034 and DMSP. Detailed analysis of this and other simultaneous Polar, 1995-034 and DMSP encounters with the cusp will be the focus of a future study.

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