ION INJECTION AND ACCELERATION IN THE POLAR CUSP

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ABSTRACT

This paper discusses cusp ion observations and their relationship to the morphology and dynamics of the polar cusp. Ion mass spectrometer data are used to illustrate the mixing of solar wind, ionospheric, and magnetospheric plasmas that occurs in the cusp.

INTRODUCTION

The existence of the magnetospheric cusp was suggested by magnetometer data from early satellites. The first high resolution ion and electron measurements made in the dayside auroral region confirmed the existence of the cusp (see Winningham and Heelis, 1983 for a historical review). Cusp ion observations, in particular the observation of predicted energy-latitude ion dispersion signatures, provided key insights into the structure of the magnetosphere as well as the morphology and dynamics of the cusp. In the past few years a new generation of high sensitivity and high temporal resolution instruments have returned data from the cusp region. In particular ion mass spectrometer data over the thermal energy range of magnetosheath plasma from the S3-3, Dynamics Explorer, and Prognoz satellites and both ion mass spectrometer and three dimensional total ion measurements from Dynamics Explorer -1 satellite are now available. The S3-3 and Dynamics explorer data (Shelley, 1979, Shelley et al. 1982, Gurgiolo and Burch 1982) have shown that the escape of ionospheric plasma from the polar cap and cusp region is very much larger than that predicted by early polar wind models. Data from the Prognoz satellites (Lundin et al. 1982, Lundin, 1984 and 1985, and Lundin and Dubinin, 1984) show the complicated interaction of this ionospheric plasma in the entry layer and how it relates to the generation of field aligned currents.

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In this paper we will discuss the entry and subsequent drift of solar wind ions, acceleration of ionospheric ions in the cusp, and the observations of magnetospheric ions in the cusp. Since the subject of plasma and field observations in the external cusp, entry layer, and mantle regions are discussed earlier in this volume (Lundin, 1985, Sckopke, 1984) we will emphasize the low to mid altitude region (i. e. below about 5 earth radii).

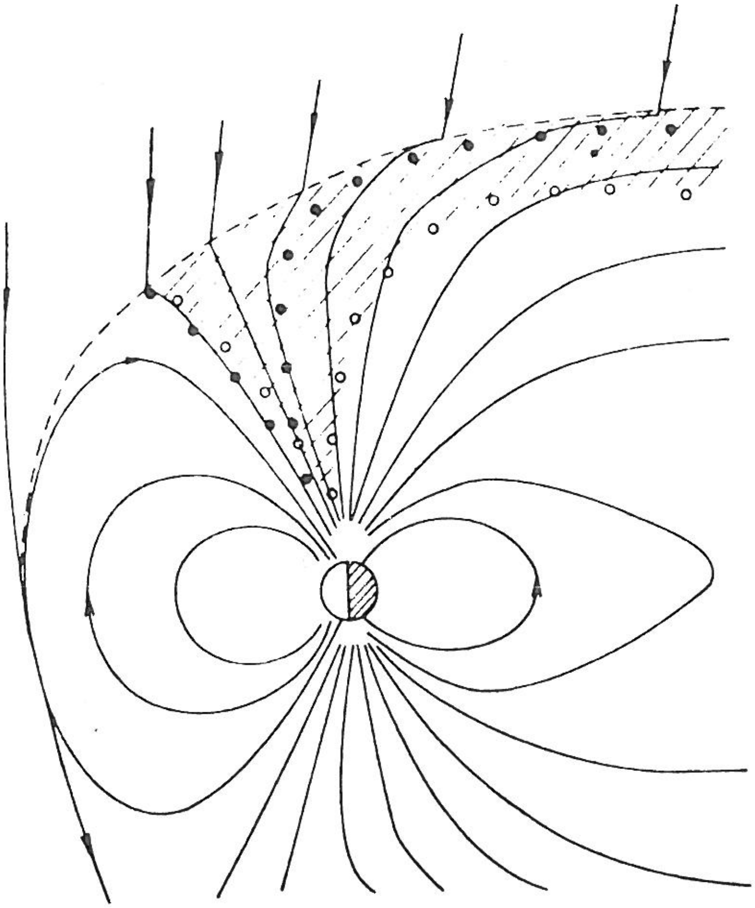

Figure 1. Model of entry of magnetosheath ions into the magnetosphere and subsequent antisunward drift. Lines with arrows represent magnetic field lines. Open circles represent particles with relatively slow velocities parallel to the magnetic field and solid circles represent faster particles. From Rosenbauer et al. (1975).

ENTRY AND SUBSEQUENT DRIFT OF SOLAR WIND IONS

The general behavior of ions in the low and mid altitude cusp (i. e. below about ~5 earth radii, geocentric) is most often discussed using a model that was introduced by Rosenbauer et al. (1975) to explain the observed spatial distribution of the plasma mantle or entry layer. Figure 1 is reproduced from their paper. It shows the combined effects of of localized entry of magnetosheath plasma and subsequent antisunward drift. Magnetosheath plasma, including ions with a wide energy distribution, simultaneously gain access to the cusp along newly interconnected field lines which are then convected antisunward. In this figure the solid circles show the trajectory of ions with higher field aligned velocities and the open circles represent the trajectories of ions with lower field aligned velocities. The differences in field aligned velocities follow from the velocity spread in magnetosheath plasma and the different path lengths traversed by ions with various injection pitch angles. The key features of this model are the entry being restricted spatially, temporally or both, and the convection electric field. This model leads to the prediction of a latitude-energy dispersion for ions in the cusp (Shelley et al. 1976, Reiff et al. 1977), and an energy-pitch angle dispersion for ions above the mirror altitude and below the injection point on field lines connected to the cusp (Burch et al., 1982). The illustration in Figure 1, is based on the assumption that the cusp injection occurs at high latitudes as suggested by Harendel et al. (1978) and others. It must be pointed out that Figure 1 needs only slight modifications to be consistent with impulsive injection (Lemaire, 1977, Heikkila, 1980), flux transfer events (Russell and Elphic, 1979), or reconnection at low latitudes (Paschmann et al. 1979).

Shelley et al. (1976) and Reiff et al. (1977) reported observing the latitude-energy dispersion predicted by this 'time of flight' model from satellites at altitudes of less than 1000 km in the polar cusp. Figure 2, which is reproduced from Shelley et al. (1976), shows the low-latitude limits of observation for particles of different masses and energies as a function of the inverse velocity in units of $(amu / keV)^{1/2}$. The horizontal bars represent the six second time resolution of the measurements. The solid line is a fit to the observed points but is identical to one calculated assuming impulsive injection at a distance of 10 (or 18) Re (earth radii) and convection in a dawn-dusk electric field of 60 (or 33) mV/m if the convection was constant in time and approximately parallel to the satellite track.

In addition to observing the energy-latitude ion dispersion, Reiff et al. (1977) had available simultaneous ion drift measurements from the AE - C spacecraft and were able to infer an injection distances in two cases (18 +30/-7 Re and 26 +/- 2 Re).

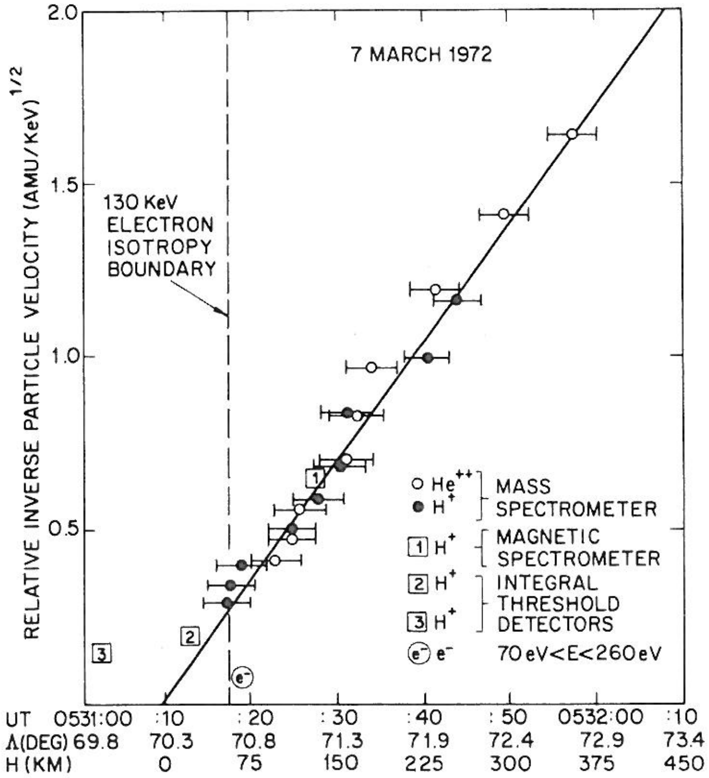

Figure 2. Lowest latitude of detection of particles of different mass and energy vs. inverse velocity for a poleward cusp crossing by the satellite 1971-089A. The horizontal bars represent the time resolution of the measurements. The satellite position at various times (UT) is given in both invariant latitude (λ) and relative displacement (H). The diagonal solid line represents the dependence of inverse velocity on latitude for antisunward convection in the cusp. From Shelley et al. (1976).

Carlson and Torbert (1980) were able to make more precise estimates of the injection distance using data from a rocket between 300 and 600 km. Figure 3 is reproduced from their paper. The format is similar to that used by Shelley et al. (Figure 2) with three important differences: 1) Since the rocket was not moving rapidly with respect to magnetic field lines, the dispersion in ion time of arrival arises from motions of the solar wind entry point or temporal variations in the entry process; 2) There was no mass analysis of the ions and there is a separate velocity dispersion curve for each ion species observed in the electrostatic analyzer used; and 3) The observed ion drifts are sunward in this case. Carlson and Torbert inferred that the injections occurred at a distance of 12 +/- 1 Re from the data in Figure 3

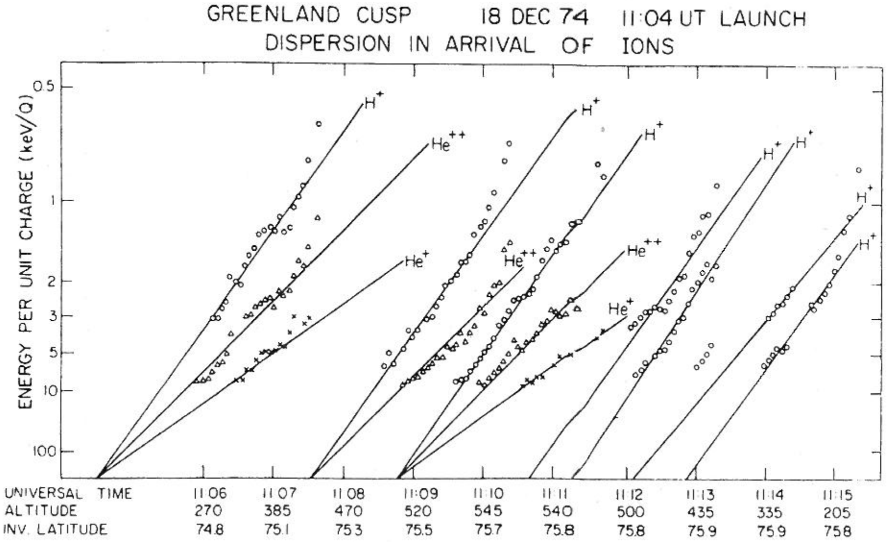

Figure 3. Inverse velocity vs. arrival times of ions observed by a rocket borne ion spectrometer. From Carlson and Torbert (1980).

and 7 and 19 Re from data obtained in another rocket flight. They also used the time width of the individual injections (~ 20 seconds) and the 100 second difference in arrival time of the 10 keV and 1 keV ions to infer that injection occurred nearly simultaneously over a flux tube with a diameter greater than 1000 km at the source. They explained the sunward drift by noting that the measurements were probably made equatorward of the flow reversal boundary. We will discuss below the relationship of the polar cap convection patterns to the observed energetic ion measurements.

Burch et al. (1982) have shown that in addition to the energy-latitude dispersion of particles in the polar cusp there is also a energy-pitch angle dispersion at higher altitudes. This effect is illustrated in Figure 4 using ion mass spectrometer data from the Dynamics Explorer -1 Satellite (Shelley et al. 1981). Seven minutes of data acquired on October 15, 1981 are presented in the form of modified energy-time spectrograms (from top to bottom) for H^+, He^{++}, and a channel sensitive to all ions. The Energetic Ion Composition Spectrometer (EICS) has several operating modes with varying cycle times, energy ranges, and masses sampled. During this period the instrument cycle time was 24 seconds or approximately four spin periods. In each instrumental cycle the EICS samples 15 logarithmically spaced energies covering the energy per charge range 10 eV/e to 17 keV/e at 24

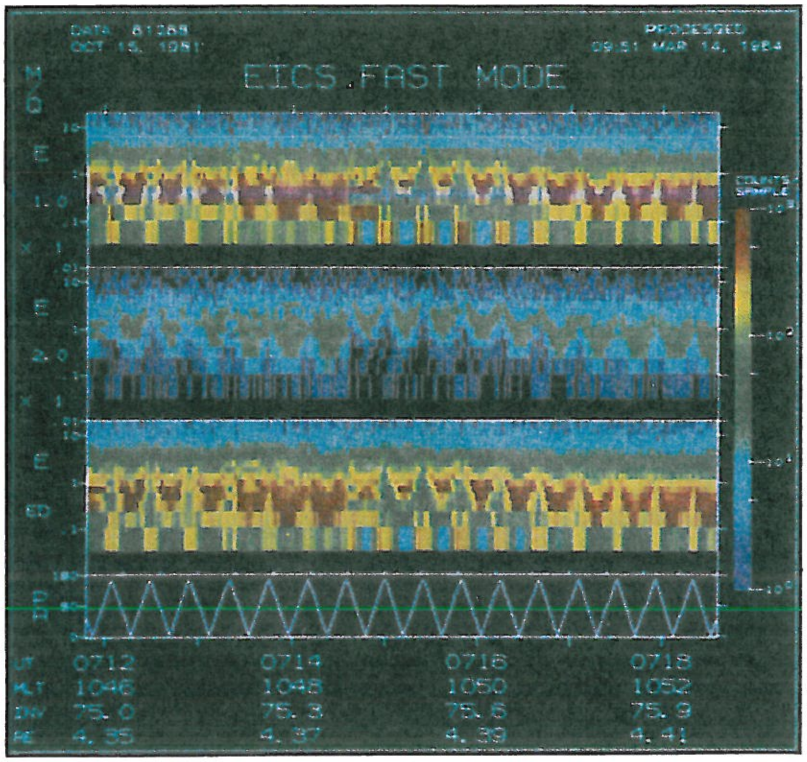

Figure 4. Energy-time spectrogram of ions observed in the cusp from Dynamics Explorer -1. The top three panels are H^+, He^{++} and non mass analyzed data respectively. See text for a description of the format.

angles for both H^+ and He^{++} in one channel and a separate detector sensitive to all ions in another channel. Since the instrument samples only one mass species at a time, the abscissa in Figure 4 has been modified to present the 24 energy spectra for each species in angle order (rather than time order) for each instrument cycle. Pitch angle is indicated in the bottom panel. Note that this display convention results in an apparent satellite spin period equal to the instrumental cycle time. The instrumental counting rate, which is nearly proportional to number flux is encoded using the color bar on the right. The universal time (UT) and orbital parameters geocentric distance in earth radii (Re), invariant latitude (INV) and magnetic local time (MLT) are also indicated.

Both the energy-time and energy-pitch angle dispersion signatures are clearly discernable in all three energy-time spectrograms. In fact two injection events are shown overlapping during the period from ~ 0712 to ~ 0715 in Figure 4. Detailed examination of the relative He^{++} and H^+ energy-pitch angle data show that the high energy He^{++} and H^{+} data from the same instrument cycle have similar distributions in particle velocity, not energy, consistent with the predictions of the time-of-flight model. The low energy data for the two species are, however, dissimilar throughout the interval presented in Figure 4.

The EICS H^{+} and He^{++} data from one instrument cycle centered on 0715 UT are presented in Figure 5 as phase space density contour plots. The contours of constant phase space density are displayed in a coordinate system fixed with respect to the satellite velocity direction. The origin and the 500 km/sec grids in this system, as well as the direction of the magnetic field (B) are indicated. The labels are the log$_{10}$ of the phase space density in units of sec^3/km^6. The energy-pitch angle distributions of the high energy H^{+} and He^{++} ions coming down magnetic field lines are similar as noted above. It is also apparent from Figure 5 that the difference between the low energy H^{+} and He^{++} data is the low energy H^{+} ions flowing up the magnetic field line from the ionosphere below. We defer discussion of upward accelerated ionospheric ions in the cusp to the next section.

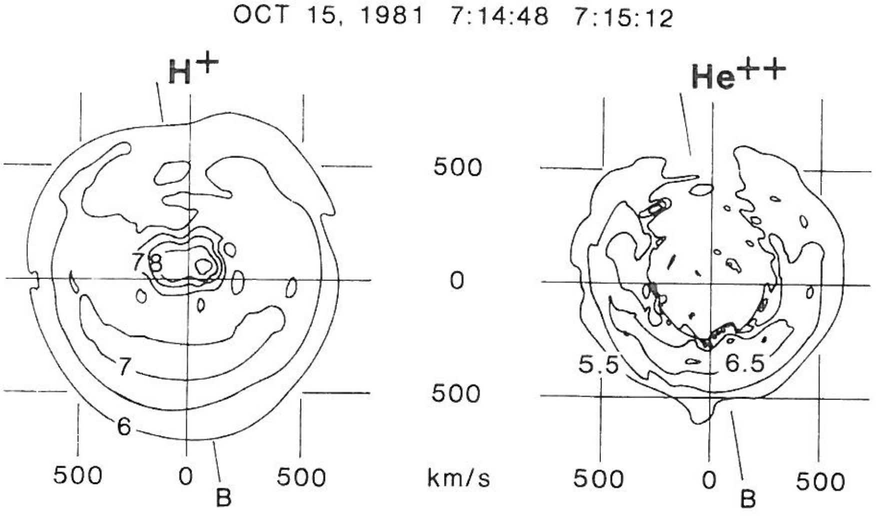

Figure 5. Contours of constant phase space density for a 24 second interval from the period shown in Figure 4. The coordinate system and contour units are indicated in the text. The direction of the local magnetic field is indicated by the lines labeled 'B'.

As with all geophysical models, the steady drift of plasma after a localized injection model discussed above is not consistent with all of the experimental observations. Reiff et al. (1977 and 1980) and Burch et al. (1980) have identified and discussed in detail events with ' V ' shaped ion energy-latitude dependences. Injection followed by drift in a constant direction leads to a steady increase or decrease of ion energy with latitude. The ' V ' type signatures have both an energy decrease and increase with latitude and a minimum in the observed ion energy in the middle. These events are not rare and occur during periods of weak or northward interplanetary magnetic field (Reiff et al., 1980).

Reiff et al. (1977 and 1980) proposed a very high rate of 'cross field diffusion' to explain these events. Burch et al. (1980) introduced a model of the polar ionospheric electric potential distribution and showed that the observed low altitude Atmosphere Explorer ion energy-latitude dependance of both the normal and ' V ' type could be qualitatively explained by injection followed by drift under the influence of the electric fields that were included in their model.

The relationship between convection direction, altitude, and assumed magnetic topology in the dayside magnetosphere is complex as pointed out by Paschmann et al. (1976), Crooker (1979), Heelis et al. (1980), Winningham and Heelis (1983), Heelis (1985) and others. Measurements of cusp ion composition, energy and angular distributions under various geophysical conditions continue to provide both insights and limitations on global models of the magnetosphere. In particular the dependence of observed plasma flows, and Birkeland currents on the 'y' component of the interplanetary magnetic field as reported by Burch et al. (1984) have lead Reiff and Burch (1984) to propose a modified gobal model of the magnetosphere.

ENTRY OF MINOR SOLAR WIND IONS

There are only a few reports of solar wind ions other than H^+ and He^{++} being observed in the magnetosphere. The third most abundant solar wind species, oxygen, is a few percent of the solar wind helium. As with helium, solar wind oxygen is identified by its charge state. Solar wind oxygen is typically 6 or 7 times ionized. For a discussion of minor ions in the solar wind see Bame et al. 1983, Schmidt et al., 1980, Kunz et al. 1983 and references therin.

Detection of minor solar wind ion species in the earth's magnetosphere at the level of a few parts in 10,000 is experimentally challenging. Lynch et al. (1976) observed that solar wind oxygen was less than 20% of the observed He^{++} or 0.15% of the H^+ in the evening auroral zone. Hovestadt et al. (1978) have reported observing solar wind helium, oxygen, carbon, and heavier ions at extremely high energies in the earth's radiation belts. Peterson et al. (1983) have reported some preliminary correlated observations of thermal oxygen ions in the solar wind and cusp. The planned releases of lithium at the subsolar point by AMPTE (Active Magnetospheric Particle Tracer Explorers) in the fall of 1984 (Krimigis et al, 1982) will provide a unique opportunity to study the transfer of mass from the solar wind to the magnetosphere and its further transport and energization within the magnetosphere.

ACCELERATION OF IONOSPHERIC IONS IN THE CUSP

The first direct observation of upward accelerated ions in the cusp was reported by Sharp et al. (1977). Torbert and Carlson (1980) reported electron and ion spectra at low altitudes in the cusp that are best explained by an electrostatic acceleration parallel to the magnetic field at an altitude of several thousand kilometers. Recently several statistical studies of the magnetic local time dependence of upward accelerated ions have been made (Ghielmetti et al. 1978, Klumpar, 1979, Shelley, 1979, Gorney et al. 1981, and Yau et al. 1984). Only one of these studies (Shelley, 1979) was limited to the cusp region. All of these studies report high occurrence probabilities of upward accelerated ions in the cusp region.

Shelley (1979) in his study of 100 orbits of S3-3 ion mass spectrometer data acquired above 5000 km between 0900 and 1500 magnetic local time used simultaneous electron data to select 57 'clearly identified cusp crossings'. Upstreaming O^+ ions with energies greater than 500 eV were unambiguously observed on 33 of these crossings (58%). Shelley pointed out that this fraction is a lower limit because of instrumental sensitivity, the limited energy range, and limited temporal resolution. He suggested that ionospheric ions are being accelerated out of the mid-altitude cusp into to boundary layer regions of the magnetosphere on a nearly continuous basis. The later studies are consistent with this suggestion.

The cusp, then, contains a mixture of recently injected solar wind plasma and accelerated ionospheric plasma. We will show in the next section that it also contains some energetic magnetospheric plasma from the dayside magnetosphere. The mass spectrometer data from Dynamics Explorer -1 provide a clear picture of the relative importance of these three plasma sources.

Energetic ion composition data from a cusp crossing on October 8, 1981 are presented in Figure 6 and 7. Figure 6 is a set of energy-time spectrograms similar to Figure 4, except that the data have been averaged over all pitch angles and the time scale compressed. The instrumental cycle time during the period these measurements were made was 96 seconds which is the temporal resolution in Figure 6 and 7. The three color panels are, from top to bottom, H^+, He^{++}, and O^+. The color bar on the right indicates the average flux in units of $(cm^2 -sec - sr- keV/e)^{-1}$. The energy-latitude dispersion of the solar wind ions (H^+ and He^{++}) is the most prominent feature in this presentation. The origin of this dispersion was discussed above. Figure 7 is a set of three spin phase angle-time spectrograms for the same interval presented in Figure 6. This type of presentation is particularly useful for defining magnetospheric boundaries. To produce Figure 7 the fluxes were sorted into 24 spin phase angle bins (zero degrees corresponds to the spacecraft velocity direction) and then integrated from 10 eV/e to 1 keV/e. The flux units encoded by the color bar on the right are $(cm^2-sec-sr)^{-1}$. Over the polar cap the magnetic field makes an angle of about 90 degrees with the

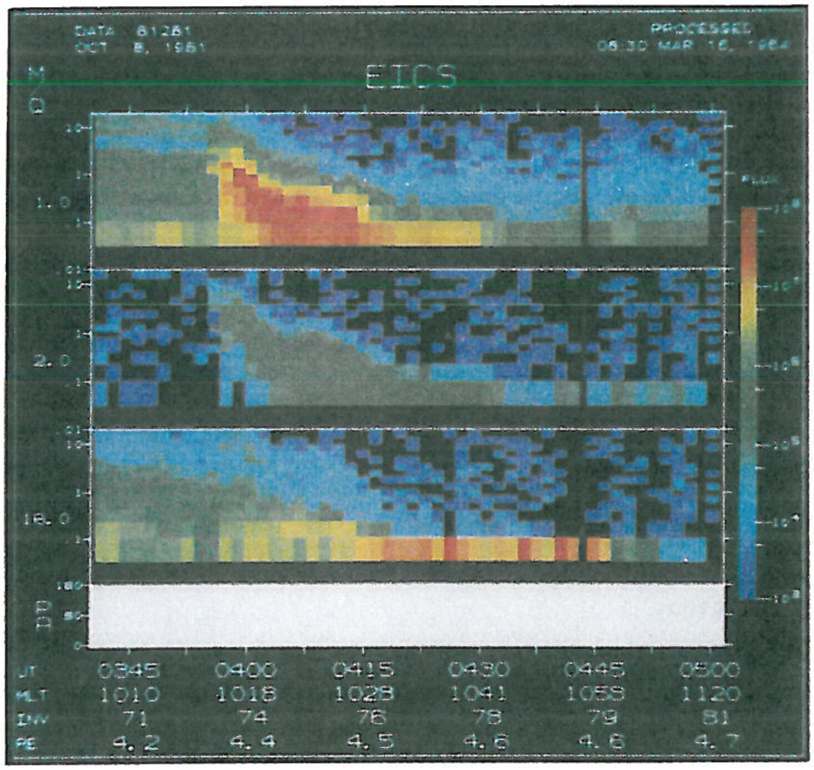

Figure 6. Energy-time spectrogram for a Dynamics Explorer cusp crossing on October 8, 1981. The three top panels are data for H^+, He^{++} and O^+ respectively. The data have been averaged over all pitch angles. The flux units encoded by the color bar on the right are $(cm^2-sec-sr-keV/e)^{-1}$.

satellite velocity direction, so ions flowing up magnetic field lines from the ionosphere are near 90 degrees in Figure 7. The equatorward boundary of solar wind ions (H^+ and He^{++}) is crossed in one 96 second instrumental cycle period. This instrument cycle is also the onset of a prominent feature in the O^+ panel.

The O^+ feature in Figure 7 starting at about 0355 is centered on the magnetic field direction. The low energy (less than 1 keV) ions that form it have been accelerated away from the ionosphere below. At the onset they are observed at pitch angles close to 90 degrees. This is the same type of velocity distribution as that shown for the low energy H^+ ions in Figures 4 and 5 above. It is commonly called a ′ conical ′ distribution. Ions must be accelerated normal to the magnetic field to produce such distributions (Sharp et al. 1977). Ion distributions that are narrowly collimated about the magnetic field direction are called ion ′ beams ′.

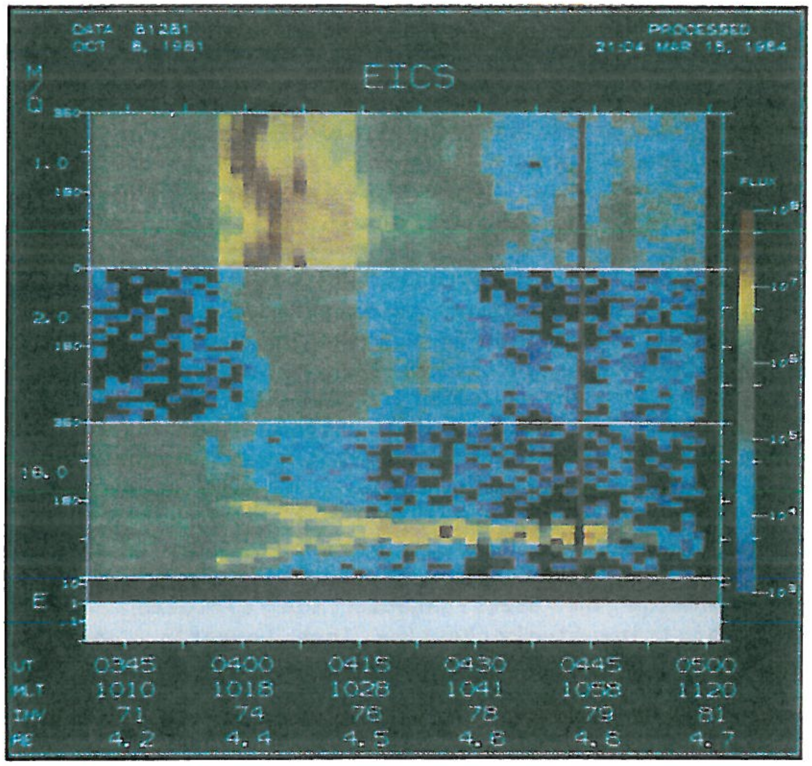

Figure 7. Spin phase angle-time spectrogram for the same period displayed in Figure 6. The data have been collected in 24 angular bins and integrated from 10 eV/e to 1 keV/e. The flux units encoded by the color bar on the right are $(cm^2\text{-sec-sr})^{-1}$. Low energy O^+ ions flowing up magnetic filed lines from the ionosphere below are visible from ~0415 to ~0450.

Ion beams can be formed in two ways: acceleration of ions parallel to the magnetic field direction; or as the result of the conservation of magnetic moment which will cause the 'cone' angle of conic distributions to become smaller than the instrumental resolution as they move upward into regions with weaker magnetic fields.

In the segment of data shown if Figures 6 and 7, the O^+ distribution changes from conical at the equatorward edge of the cusp region to beam-like over the polar cap. It must be noted that this is the only example found to date in the Dynamics Explorer data set of such a smooth transition between types of distribution. The more typical case has multiple variations between conical and beam-like distributions, sometimes on a time scale short compared to the instrumental cycle time. Beam and conical events are sometimes not experimentally distinguishable. Gorney et al. (1981), Yau et al. (1984), and Shelley (1979) have published relative occurrence frequencies of the two types of accelerated ion distributions in the cusp local time region. All of these reports show that beam like and conical distributions have roughly equal probabilities of occurrence in the cusp. Klumpar et al. (1984) have also shown that acceleration parallel and perpendicular to the magnetic field direction can occur on the same magnetic field lines.

As noted above, the reason for distinguishing between different types of ion distributions is that different acceleration mechanisms are thought responsible for them. Unfortunately identifying the acceleration as being perpendicular or parallel to the magnetic field direction is not enough information to uniquely identify the processes involved -- there are many more than two acceleration mechanisms to choose from. Lennartsson (1983) has provided a short introduction into types of acceleration mechanisms that have been considered relevant to the magnetosphere. It is not the intention here to survey the vast number of reports discussing the problem of acceleration of ionospheric ions. For cusp studies, however, the work of Ungstrup et al. (1979) and Gorney (1983) are particularly relevant. Ungstrup et al. (1979) focused attention on electrostatic ion cyclotron waves as a mechanism for transversely heating ions (creating conic distributions). Gorney (1983) pointed out that downflowing ion beams (i.e. the cusp type injection events discussed above and by Burch et al., 1982) form 'rings' of energetic ions similar to those shown in Figure 5, and that these rings have characteristics that make them unstable and are therefore a possible energy source for the waves that in turn cause particle acceleration.

Another possible source of very low energy upflowing ionospheric ions in the cusp region is the 'classic polar wind' described by Axford (1968), Banks and Holzer (1969) and others. Recent reports of the polar wind have been made by Chappell et al.

(1982), Gurgio and Burch (1982), and Sojka et al. (1983). The classic polar wind is made up of cold (1 eV or less) H^+ ions with a H^+ to O^+ flux ratio of about 100, although some recent work by Barakat and Schunk (1983) shows how the original models of the polar wind may be modified to get larger O^+ fluxes. Gurgiolo and Burch (1982) and Shelley et al. (1982) have noted that there is an additional component in the upward flowing low energy ion observations that was not predicted by models of polar wind. Shelley et al. (1982) observed O^+ to H^+ ratios of 10 and energies of 10's of eV. Gurgiolo and Burch (1982) noted a 'heated' component of the polar wind. The observations of Gurgiolo and Burch (1982), and those shown in Figures 6 and 7 above, show that at least some of the warm O^+ beams observed streaming up magnetic field lines in the polar cap can originate in the cusp. This is possible because the antisunward convection velocities are comparable with the upward O^+ flow velocities. For example, a 10 eV O^+ ion travels ~13 km/sec or ~8.5 minutes per earth radius. There are, however, other physical processes that can accelerate ionospheric ions over the polar cap and outside the cusp region, such as those responsible for polar cap aurora. Independent of source, cusp, polar wind, polar aurora, or a combination of these the flux of ionospheric ions out of the polar cap is considerable, and can make a non-negligible contribution to the plasma sheet (Shelley et al. 1982, Yau et al. 1984).

MAGNETOSPHERIC IONS IN THE CUSP

It is remarkable that energetic O^+ fluxes only gradually decrease in intensity poleward of the point where the satellite enters onto cusp field lines in the data presented in Figures 6 and 7. Equatorward of the cusp (i. e. prior to about 0355 UT), the dayside magnetosphere energy and mass composition is consistent with that reported at lower magnetic latitudes on dayside magnetic field lines (Young, 1980, Lennartsson et al. 1981, and Lennartsson and Sharp 1982). Poleward of the first observation of solar wind ions (i. e. after about 0355 UT), the flux of energetic (greater than 1000 eV) O^+ ions at ALL pitch angles only slowly decreases. This point is illustrated in Figure 8 which is a spin phase angle-time spectrogram similar to Figure 7 except that the integral fluxes displayed are from 1 keV/e to 17 keV/e. Significant fluxes of downcoming energetic O^+ are observed until almost 0415 UT. Evidence of energetic magnetospheric ions on cusp field lines has also been noted by Shelley et al. (1976).

There have been several recent reports in the literature that have called into question the meaning and detectability of 'closed' and 'open' magnetic field lines. McDiarmid et al. (1976) and others have noted 'trapped' electron distributions in the cusp region at low altitudes; Eastman and Frank (1982) have noted a similar situation on field lines where magnetic reconnection has been reported (Paschmann et al. 1979); Frank et al. (1982) have reported long lived, cross polar cap auroral structures (Theta Aurora); Peterson and Shelley (1984) have detected isotropic energetic O^+ on field lines over the polar cap; Foster and Burrows (1977) have reported trapped electron fluxes over the polar cap; and Huang et al. (1983) have reported isotropic keV ion distributions in the magnetotail lobes. In Figures 6, 7 and 8 above we see both freshly injected solar wind ions (H^+ and He^{++}) and energetic magnetospheric ions (greater than 1 keV isotropic O^+) simultaneously on the same magnetic field lines.

Several different physical explanations of these surprising observations have been offered. Daly and Fritz (1982) have noted that electrons can be reflected (i.e. trapped) at the minimum in magnetic field strength on 'open' magnetic field lines at the magnetopause and that ions are, at best, only partially reflected at such a minimum. Peterson and Shelley (1984) have noted that

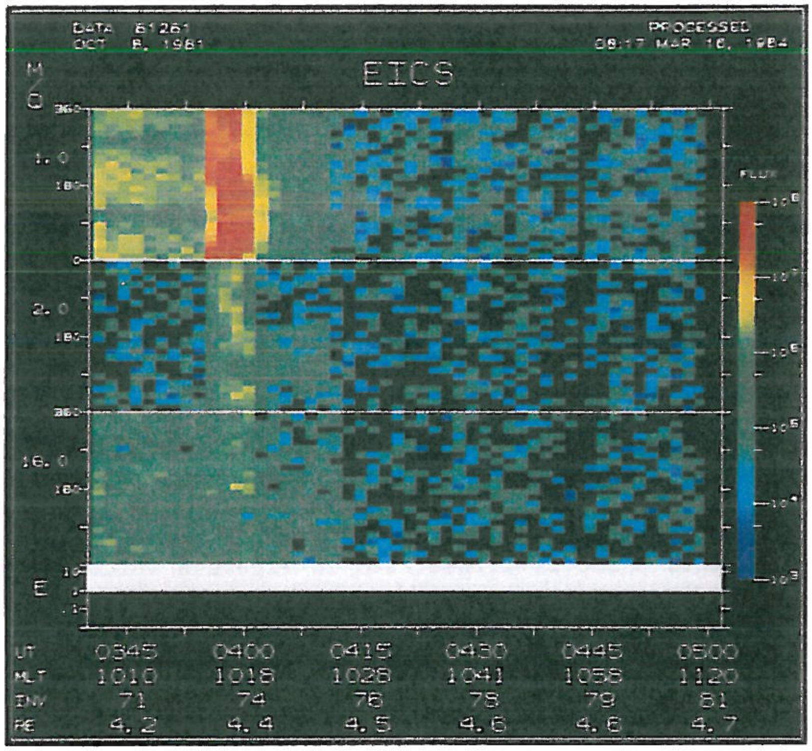

Figure 8. Spin phase angle-time spectrogram for the same interval presented in Figures 6 and 7. The data have been integrated from 1 keV/e to 17 keV/e in Figure 8. The flux units encoded by the color bar on the right are $(cm^2\text{-sec-sr})^{-1}$.

substantial pitch angle scattering of energetic O^+ from magnetospheric field lines that have been recently 'opened' (i. e. merged with solar wind magnetic field lines) and convected over the polar cap could account for their observations. Diffusion of ions out of the magnetosphere into the magnetosheath or boundary layers has also been discussed by several authors (e.g. Freeman et al. 1977, and Haerendel et al. 1978). Huang et al. (1983) explained their surprising observations in the magnetotail lobes as filaments of plasma sheet plasma convecting 'away' from the plasma sheet during times when the interplanetary field was northward. Foster and Burrows (1977) inferred the infrequent existence of a fluctuating potential barrier far down the magnetotail lobes to explain their observations. Frank et al. (1982a and 1982b) have explained the Theta Aurora as arising from bifurcation of the magnetotail lobes, a process that most certainly would involve cusp plasmas.

Not all of the phenomena listed above involve the cusp, but the proposed mechanisms can all occur on cusp field lines. Because the energetic O^+ ions do not immediately decrease in intensity after ~0355 in Figures 6,7 and 8, they may well arise from magnetospheric plasma that is on recently 'opened' field lines that are drifting through the cusp. They could also arise from a very strong diffusion process. In any case, the above discussion shows that particle signatures alone are not always an unambiguous indicator of 'open' or 'closed' field lines.

CONCLUDING REMARKS

The polar cusp was originally studied because it provided information and insights on solar wind plasma entering the magnetosphere. With the data from modern high sensitivity and high temporal resolution instruments it is now possible to separate ionospheric and magnetospheric components from the solar wind plasma on cusp field lines. We have briefly discussed the results so far obtained in the study of this mixture: ionospheric plasma is accelerated upwards into the cusp; ionospheric plasma accelerated in the cusp is observed over the polar caps; and this plasma could make a non-negligible contribution to the maintenance of the plasma sheet. We have also noted the numerous reports that show the difficulty in using particle pitch angle signatures alone as an indicator of 'open' or 'closed' magnetic field lines.

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