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Overlapping ion populations in the cusp: Polar/TIMAS results

K.J. Trattner,[1,5] A.J. Coates,[1] A.N. Fazakerley,[1] A.D. Johnstone,[1] H. Balsiger,[2] J.L. Burch,[3] S.A. Fuselier,[5] W.K. Peterson,[5] H. Rosenbauer,[4] and E.G. Shelley[5]

Abstract. The 90 degree inclined orbit of the Polar satellite crosses the cusp at intermediate altitudes ($4R_E$-$6R_E$). The Toroidal Imaging Mass-Angle Spectrograph (TIMAS) on the Polar spacecraft can obtain full energy/pitch angle distributions for four masses simultaneously. Many examples of magnetosheath particle injections with velocity dispersion, sometimes overlapping, have been observed.

We report on two crossings of the cusp where TIMAS observed several overlapping cusp ion injections. These injections showed simultaneous onset of cusp ion precipitation at two different energies as well as the brief occurrence of ion precipitation above and below the energy of a preexisting population. Existing models of cusp precipitation do not provide an adequate explanation of these observations.

1. Introduction

The polar cusps are the only regions through which the topside terrestrial ionosphere can have continuous contact with solar wind plasma. It is believed that the solar wind plasma in the high latitude cusp was plasma injected across the Earth's magnetopause during magnetic reconnection [see *Smith and Lockwood*, 1996].

The observed dispersion of these precipitating particles on open field lines is usually interpreted as a velocity filter effect which occurs due to the finite extent in space and/or time of the reconnection region. For a southward interplanetary magnetic field (IMF), newly opened field lines are convected polewards under the joint action of magnetic tension and the solar wind flow, causing lower energy particles from the reconnection site to arrive at successively higher latitudes [*Rosenbauer et al.*, 1975; *Reiff et al.*, 1977; *Burch et al.*, 1982; *Peterson*, 1985]. The velocity filter effect also causes an energy-pitch angle dispersion. Ions with larger pitch angles need to have higher energies to arrive at the observing satellite at the same time as ions travelling with lower pitch angles. For a steady rate of reconnection at the magnetopause, the ion energy should show a continuous latitudinal dispersion. In contrast, a pulsating cusp model predicts that the ion signature shows discontinuities, sudden steps in the energy-latitude profile. These steps occur for periods of little or no reconnection between the pulses and are also convected polewards [e.g., *Cowley et al.*, 1991; *Newell and Meng*, 1991; *Escoubet et al.*, 1992; *Lockwood and Smith*, 1992].

The scenario is somewhat different for a northward IMF. Ion energies increase with latitude because of magnetic reconnection at the tail lobes and equatorward convection of field lines [e.g., *Woch and Lundin*, 1992]. For both southward and northward IMF, there are deviations from this relativly simple picture. In particular southward IMF conditions show cusp ion signatures which sometimes overlap [*Woch und Lundin*, 1991; *Yamauchi and Lundin*, 1994; *Norberg et al.*, 1994, *Xue et al.*, 1997]. Both overlapping traces show energy-latitude and energy-pitch angle dispersions which indicate that ions are precipitating downwards on convecting field lines. This feature has been interpreted as evidence for pulsed reconnection at the magnetopause [*Lockwood and Smith*, 1994]. However, it was also stressed that zero pitch angle ions at different energies, observed simultaneously on convecting field lines, must have been injected at different points on the magnetopause [e.g., *Onsager et al.*, 1994].

The overlapping cusp ion signatures discussed above have been reproduced quite well by a model due to *Lockwood* [1995]. The mechanism in his model is based on continuous particle entry along the newly opened field line as predicted by the reconnection model. The overlapping is caused by the variation of the ion acceleration on crossing the magnetopause combined with the ion time-of-flight effect.

In this paper we report on cusp crossings observed by TIMAS onboard the Polar spacecraft which show a different type of signature. The proton observations reported here will be compared with previous observations and the model by *Lockwood* [1995].

2. Observations

Figures 1 and 2 each show 8 panels of colorcoded proton flux (particles/cm^2 s sr keV/e) in an energy versus pitch angle representation for events observed on March 22 and April 7, 1996, respectively. The data are averaged over 12 seconds (two spins). The specific start and stop times of the averaged interval (HH:MM:SS) are indicated on top of the individual panels. Note that all times used later in the text refer to the centers of these time windows. For the first panel in each row additional information about universal time (UT), distance in Earth radii (R), L-shell (L), eccentric dipole magnetic

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[1] Mullard Space Sci. Lab., Holmbury St. Mary, England.
[2] Physikalisches Inst., University of Bern, Switzerland
[3] Southwest Research Inst., San Antonio, TX 78228, USA
[4] Max Planck Institut für Aeronomie, Lindau, Germany
[5] Lockheed-Martin Palo Alto Res. Lab., CA 94304, USA

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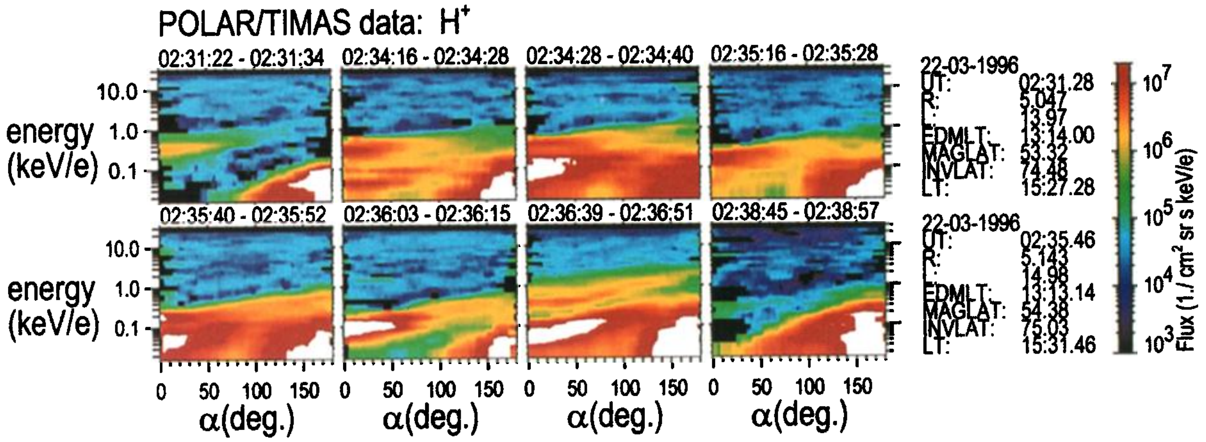

Figure 1. 8 panels of colorcoded proton flux (particles/cm^2 s sr keV/e) in an energy versus pitch angle representation. Plotted are data from a Polar cusp crossing observed by TIMAS on March 22. White areas represent data greater than the maximum flux.

local time (EDMLT), magnetic latitude (MAGLAT), invariant latitude (INVLAT) and local time sector (LT) are given on the right hand side of the plot. Both events were observed arount 13:00 EDMLT.

To assist in the interpretation of our observations we used data from the solar wind experiment [*Ogilvie et al.*, 1995] and the magnetic field investigation [*Lepping et al.*, 1995] on the Wind spacecraft. Those data were obtained from the ISTP key parameter data base. Wind observations for the March 22 event were made at about $X = 55\,R_E$, $Y = 57\,R_E$ and $Z = 3.5\,R_E$ (GSE) and were lagged by 9 minutes to account for plasma travel time to the subsolar point. For the April 7 event solar wind observations took place at $X = 84\,R_E$, $Y = 21\,R_E$ and $Z = -2\,R_E$ and were lagged by 27 minutes. Note that both observations are far upstream of the Earth's magnetopause, which could introduce additional complications in interpreting the event timing.

3. Results

The solar wind magnetic field observation at Wind for the entire period of interest on March 22 showed a magnetic field direction almost along the Earth-Sun line with a B_x=4.3nT, B_y=1.3nT and B_z=0.1nT (GSM).

Ions with pitch angles less than 90° represent particles streaming towards the ionosphere. The Polar spacecraft crossed poleward into the cusp and encountered downward precipitating protons on open field lines at an invariant latitude of about 74° (first panel in Figure 1). These protons have a characteristic signature in energy vs. pitch angle, typical for cusp precipitating particles due to the time-of-flight effect. The energy of zero degree pitch angle particles is about 0.35 keV. Also seen is a low energy component below 0.1 keV streaming upwards from the ionosphere, with the highest flux at pitch angles near 180°. The onset of the downward streaming protons occurred at about 02:30 UT, increased steadily in intensity but stayed constant in energy till 02:34:22 UT (second panel). At 02:34:22 there is a sudden onset of downward streaming protons at energies of about 0.05 keV (second panel). Those ions also show a characteristic energy-pitch angle dispersion. The new component starts to increase in intensity (third panel) then switches off suddenly one minute later at 02:35:22 UT (fourth panel). The original upper trace was not affected by this lower energy component and moved only slightly to lower energies. While the original trace continues to move to lower energies (fifth panel at 02:35:46) another low energy component sud-

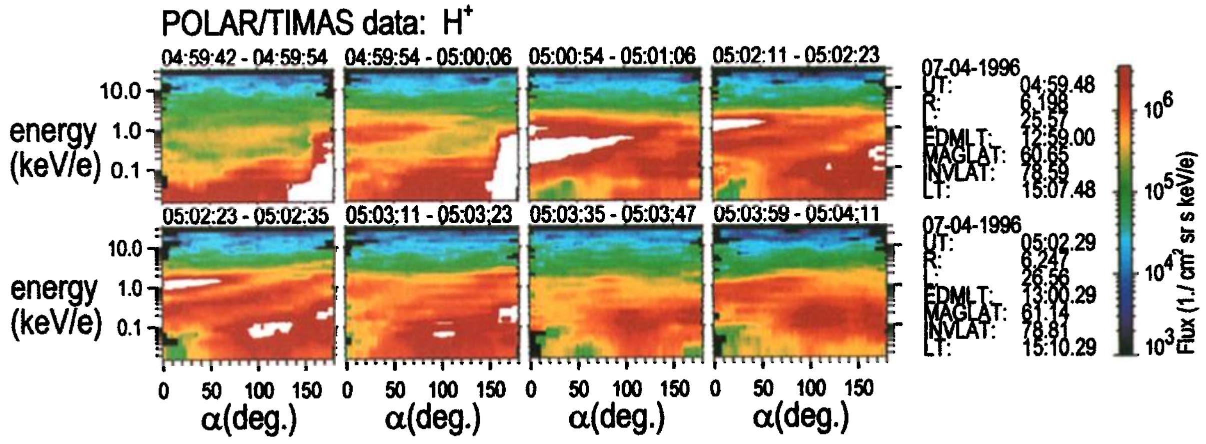

Figure 2. 8 panels of colorcoded proton flux (particles/cm^2 s sr keV/e) in an energy versus pitch angle representation. Plotted are data from a Polar cusp crossing observed by TIMAS on April 7.

denly appears at about 0.04 keV but disappears again about 20 seconds later (sixth panel). At 02:36:45 the original trace has reached 0.05 keV (seventh panel) as another trace appears at about the energy where the original trace started. This trace also shows the well known energy-pitch angle dispersion. While the original trace decreases further in energy and finally falls below the TIMAS energy window, the new curve also starts to decrease in energy but shows strong variations in intensity. Further sudden appearances of energy-pitch angle dispersion at energies below a preexisting trace occurred at 02:44 and 02:45 (not shown in Figure 1).

Another Polar cusp crossing from April 7 is shown in Figure 2. The solar wind magnetic field observed at Wind pointed towards the Earth with B_x=-1.2nT, B_y=2.6nT and B_z=-0.8nT (GSM). The first panel in Figure 2 shows proton flux at 04:59:48. As before, the upward flowing low energy component is again present near 180°. Polar encountered downward precipitating protons at 05:00 at an invariant latitude of about 78° (second panel). These protons arrived at Polar at two different energies, about 1 keV and 0.1 keV, showing the typical energy-pitch angle dispersion. Both traces increased in intensity (05:01) and the lower energy trace also increased in energy. Both traces suddenly switched off at 05:03:41 (panels six and seven). A single trace of 1 keV protons reappeared again at 05:04:05.

Together with the overlapping proton traces we also observed intense overlapping He^{++} traces (not shown here) which indicates that these ions are magnetosheath ions.

4. Discussion

Overlapping signatures of cusp precipitating particles are not new. *Yamauchi and Lundin* [1994] showed meso-scale ion injections of upward steps in energy superimposed on the typical downward ramp of an energy-latitude dispersion. They classified their observations with respect to the north-south direction of the IMF and poleward or equatorward bound satellite passes. Those observations were interpreted as evidence for multiple access of magnetosheath plasma to the same flux tube at different times, generating independent plasma clouds injected towards the ionosphere. However, *Lockwood* [1995] pointed out that these observations could be also interpreted as a single pulsed reconnection together with a finite gyroradius effect. The overlap in the data occurred only for non field-aligned ions due to their finite gyro radii. Downward precipitating field-aligned ions showed only an upward step and no overlap. This is caused by a reconnection rate which goes to zero between two pulses and switches off field-aligned ions, while higher pitch angle ions are still seen due to their different times-of-flight.

The model by *Lockwood* [1995] mentioned above would generate overlapping signatures for all pitch angles including field aligned. The onset of the overlap would appear as a bifurcation of a preexisting cusp signature. The bifurcated ion traces would merge again into one trace at higher latitudes. Such a bifurcation was observed by *Woch and Lundin* [1991] and can be explained as a steady reconnection and steady magnetosheath conditions while the bifurcation is caused by the variation of the ion acceleration on crossing the magnetopause, combined with the ion time-of-flight effect. Simultanously observed precipitating ions would therefore arrive from different points of the magnetopause with different parallel velocities which is consistent with our observations. The model can also be used for pulsed reconnection when the high energy trace is, even at onset, detached in energy from the low energy trace. A patch of newly opened flux could suddenly restore conditions for the bifurcated stage. In this case also the low energy trace should show a step in energy. Where this was not observed the *Lockwood* [1995] model offered an alternative. The appearance of overlapping signatures could be explained by a rapid fall of the Alfvén velocity at the magnetopause.

The March 22 event, however, does not satisfy all of the above described conditions. There are overlapping traces at lower energies followed by a trace at higher energies. The original trace was unaffected by these onsets, indicating that steady reconnection conditions applied to the magnetopause. The traces are well separated in energy and also overlap for field-aligned ions, in contrast to the observations reported by *Yamauchi and Lundin* [1994]. The overlapping traces do not bifurcate from a preexisting cusp signature and also do not merge at higher latitudes as described in the model by *Lockwood* [1995]. They rather disappear within seconds, leaving the original trace unaffected.

In contrast to the first example, the second example shows no original trace and additional traces appearing at higher and lower energies. Both traces in the second event appeared simultaneously at separated energies within the 12 seconds of our time resolution and showed no sudden upward or downward steps in energy during their existence. That again would be consistent with steady reconnection conditions. Both traces also overlap for field-aligned ions but do not develop out of a preexisting cusp signature. In addition, the solar wind conditions before the rotation of the magnetic field were again stable.

Yamauchi and Lundin [1994] argued that flux tubes with downward precipitating ions could be reopened by the solar wind, leading to the injection of another magnetosheath cloud towards the ionosphere. The reconnection of an opened magnetic field line was also discussed by *Fuselier et al.* [1997]. The observation made by TIMAS might support such a model. However, it is not obvious how an already open convecting field line, where magnetosheath ions continuously stream across the boundary gets reopened or closed again without affecting the preexisting trace.

An alternative would be an adaption of Lockwoods model. Polar may cross on to non-convecting field lines away from the reconnection region, eventually reaching convecting field lines. It would therefore move into the bifurcated ion precipitation region without seeing the preexisting trace. *Luhmann et al.* [1984] and *Crooker et al.* [1985] suggested that magnetic reconnection will occur preferentialy for antiparallel IMF and terrestrial magnetic field. They also showed preferred reconnection sites on the magnetopause according to the direction of the IMF. The first case described above is particularly difficult because the IMF was almost radial. It would be draped around the magnetopause and small fluctuations in the direction could have a large effect on the location of the reconnection region. We will discuss these scenarios together with additional events from our survey in a subsequent paper.

5. Summary

We have shown data for two cusp crossings from March 22 and April 7, 1996, observed with the TIMAS instrument on Polar. The comparison of the observations with previous observations from other missions [e.g., *Woch and Lundin*, 1991; *Yamauchi and Lundin*, 1994] and with an ion precipitation model by *Lockwood* [1995] has revealed features previously neither observed nor explained.

- Sudden appearance of overlapping energy versus pitch angle traces.
- Overlapping traces do not fall/rise together in energy.
- Traces overlap also for field-aligned particles, precipitating downward along the same field line but have not developed out of a preexisting trace as suggested in the model by *Lockwood* [1995].
- Overlapping traces are sometimes short lived (half a minute) while a preexisting trace is unaffected, consistent with steady reconnection.
- Sudden onset of downward precipitating ions at two different energies. Those ions should have arrived from different points on the magnetopause. The agreement in arrival time of these protons is no coincidence. Several other events in our survey, showing the same feature, have been identified.

Models of cusp ion precipitation have reached a reasonable state of maturity for relative simple conditions such as strongly southward IMF. However, it is clear form the TIMAS observations presented here that more complicated conditions such as radial IMF tend to complex cusp ion precipitation signatures that are not easily understood with current models. It is hoped that as more events like these are identified, their properties may lead to the extension of cusp models.

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H. Balsiger, Physikalisches Institut, University of Bern, Bern, Switzerland

J.L. Burch, Southwest Research Institut, San Antonio, TX 78228, USA

H. Rosenbauer, Max Planck Institut für Aeronomie, Lindau, Germany

S.A. Fuselier, W.K. Peterson, K.J. Trattner, E.G. Shelley, Lockheed-Martin Palo Alto Research Laboratory, Palo Alto, CA 94304, USA (e-mail: trattner@aspen.spasci.com)

A.J. Coates, A.N. Fazakerley, A.D. Johnstone, Mullard Space Science Laboratory, University Collegè London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, England

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