Temporal versus spatial interpretation of cusp ion structures observed by two spacecraft

K. J. Trattner,[1,2] S. A. Fuselier,[1] W. K. Peterson,[1] M. Boehm,[1] D. Klumpar,[3] C. W. Carlson,[4] and T. K. Yeoman,[5]

Received 20 June 2001; revised 13 December 2001; accepted 13 December 2001; published 10 October 2002.

[1] A series of nearly simultaneous cusp crossings by the Polar and Fast Auroral Snapshot (FAST) spacecraft are used to investigate the development of cusp structures such as sudden changes in the energy of cusp precipitating ions. While such changes are generally interpreted as temporal signatures, recent investigations show evidence that such features can also be interpreted as spatial structures. Our analysis of four events during stable solar wind conditions confirms that cusp structures observed by one satellite are remarkably similar to cusp features observed up to several hours later by a second satellite. Using the spatial separation of the Polar and FAST spacecraft, the cusp features could also be traced over several hours in magnetic local time. These similarities led to the conclusion that large-scale cusp structures are spatial structures related to global ionospheric convection pattern set up by magnetic merging and not the result of temporal variations in reconnection parameters. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2455 Ionosphere: Particle precipitation; 2463 Ionosphere: Plasma convection; *KEYWORDS:* cusp, cusp structures, magnetic reconnection, reconnection rate, ion precipitation

Citation: Trattner, K. J., S. A. Fuselier, W. K. Peterson, M. Boehm, D. Klumpar, C. W. Carlson, and T. K. Yeoman, Temporal versus spatial interpretation of cusp ion structures observed by two spacecraft, *J. Geophys. Res.*, *107*(A10), 1287, doi:10.1029/2001JA000181, 2002.

1. Introduction

[2] Reconnection of Earth's magnetic field lines with interplanetary magnetic field (IMF) lines at the magnetopause allows ions to stream continuously from the magnetosheath into the magnetosphere [e.g., *Lockwood and Smith*, 1993, 1994; *Onsager et al.*, 1993]. This incoming magnetosheath distribution is truncated as it crosses the magnetopause, forming a characteristic D-shape distribution. This type of distribution was predicted by *Cowley* [1982] and observed by many satellites [*Gosling et al.*, 1990; *Fuselier et al.*, 1991]. While the characteristics of the injected distribution change with time as the field line is convected, the spectra of precipitating particles observed in the cusp are further complicated by the fact that different energy ions have different flight times from the magnetopause to the observing satellite in the cusp. For a southward IMF, newly opened field lines convect poleward under the joint action of magnetic tension and shocked solar wind flow, causing lower-energy particles to arrive at successively higher latitudes [e.g., *Rosenbauer et al.*, 1975; *Shelley et al.*, 1976] which gives rise to a distinctive energy-latitude dispersion [e.g., *Reiff et al.*, 1977; *Smith and Lockwood*, 1996]. For a steady rate of reconnection at the magnetopause, the ion energy of downward precipitating ions should show a smooth and continuous latitudinal dispersion on these open field lines. However, satellite observations show that the energy of precipitating ions is rarely a smooth continuous variation with invariant latitude. These dispersions instead show complicated structures with variations in flux levels and sudden changes in the energy of the precipitating ions [e.g., *Newell and Meng*, 1991; *Escoubet et al.*, 1992].

[3] Structured cusp ion energy dispersions, also known as "stepped" or "staircase" cusp ion signatures, are often interpreted as temporal variations caused by periods of little or no reconnection that are interspersed with periods of continuous reconnection. The existence of steps has been predicted and is very well described in the pulsating cusp model [e.g., *Cowley et al.*, 1991; *Smith et al.*, 1992; *Lockwood and Smith*, 1989, 1990, 1994]. Figure 1 shows a schematic representation of how such steps in the cusp ion energy dispersion should appear for two spacecraft crossing the cusp at the same altitude at different times. The dashed line represents the equatorward edge of the cusp where downward precipitating ions are first encountered. For southward IMF, magnetic tension and shocked solar wind

[1]Lockheed-Martin Advanced Technology Center, Palo Alto, California, USA.
[2]Max Planck Institut für Aeronomie, Katlenburg-Lindau, Germany.
[3]Physics Department, Montana State University, Bozeman, Montana, USA.
[4]Space Science Laboratory, University of California, Berkeley, California, USA.
[4]Department of Physics and Astronomy, University of Leicester, Leicester, UK.

0148-0227/02/2001JA000181$09.00

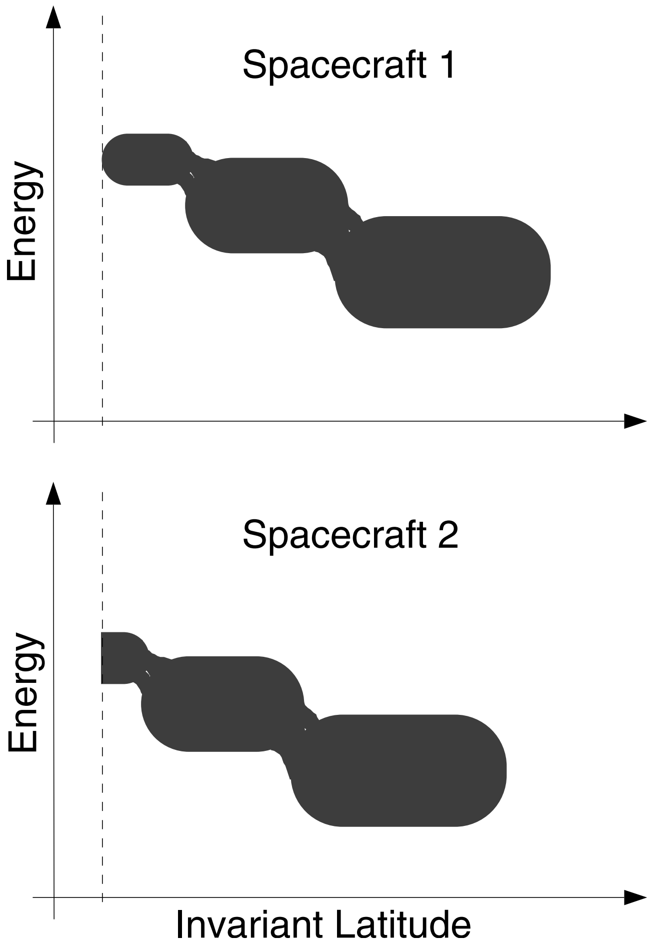

Figure 1. Schematic representation of cusp structures as observed by two spacecraft crossing the cusp at the same altitude but different times. If the cusp structures are caused by reconnection pulses, the spacecraft will encounter them at different latitudes. Cusp structures would be a temporal feature.

flow would convect these steps poleward. Spacecraft 1, crossing the cusp later than spacecraft 2, would observe the same sequence of steps at different latitudes. The convection of these transient cusp structures would create an ever-changing structural profile of cusp ions.

[4] Although single-satellite observations are unable to reveal whether steps in the cusp ion distribution signatures are moving, observations of steps have been interpreted as temporal rather than spatial variations. The observation of poleward moving events by the European Incoherent Scatter (EISCAT) radar [see *Lockwood*, 1995, 1996; *Lockwood et al.*, 1995], a natural consequence of a temporal feature and not predicted by a spatial interpretation, supports this view. In addition, *Lockwood et al.* [1998] compared Polar/Hydra data with a simulation model based on pulsed reconnection. As in the observations, the simulation showed that sudden steps in the ion energy occurred for upgoing and downgoing ions at the same time (without any delay). The ions are on field lines that have unique time histories since reconnection and upward/downward steps are caused by moving the effective location of the spacecraft to field lines which were reconnected more/less recently.

[5] It was also noted by *Lockwood and Smith* [1992] that variations in the reconnection rate are not the only way to introduce ion energy steps in the cusp. Solar wind parameters may vary, causing the magnetosheath ion populations to change. Variations in the IMF orientation may alter the degree of acceleration of the ions as they cross the dayside magnetopause. A satellite could also pass from flow stream lines emanating from one X-line to stream lines from a second X-line. This crossing into a different flux tube would appear as a step in the ion energy dispersion due to the different time history since reconnection for the two flux tubes [*Lockwood et al.*, 1995]. This step would not be convected with the solar wind but would appear as a standing feature in the cusp. Figure 2 shows a schematic representation of how such spatial cusp structures should appear for two spacecraft crossing the cusp at different times. Independent of the time delay between the cusp crossings, the satellites should encounter the cusp structures at the same latitude, observing a spatial feature.

[6] There is evidence that cusp ion steps can be produced in steady state by spatial variations [e.g., *Newell and Meng*,

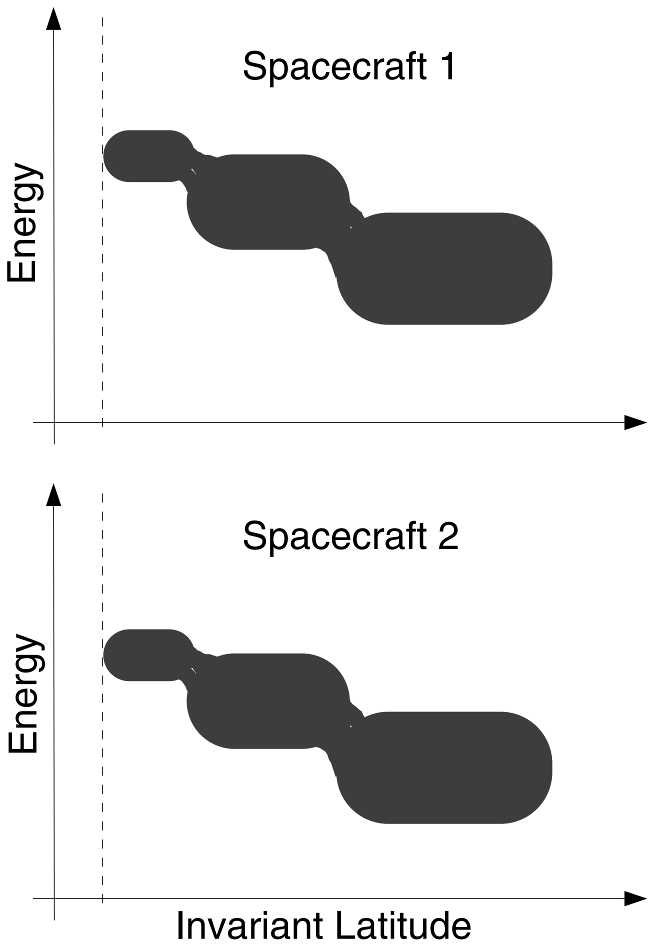

Figure 2. Schematic representation of cusp structures as observed by two spacecraft crossing the cusp at the same altitude but different times. If the cusp structures are caused by, for example, multiple X-lines, the spacecraft will encounter them at the same latitudes. Cusp structures would be a spatial feature.

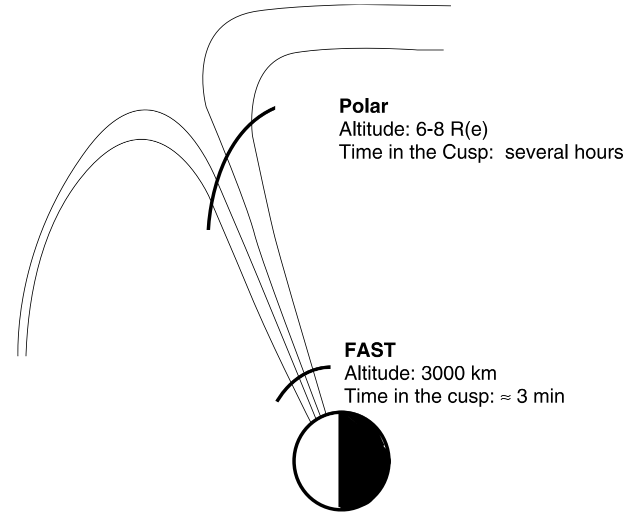

Figure 3. Schematic representation of the altitude separation of Polar and Fast Auroral Snapshot (FAST) as they cross the cusp. The comparison of FAST and Polar cusp crossings provides large temporal and spatial separations but makes direct comparision of flux levels difficult.

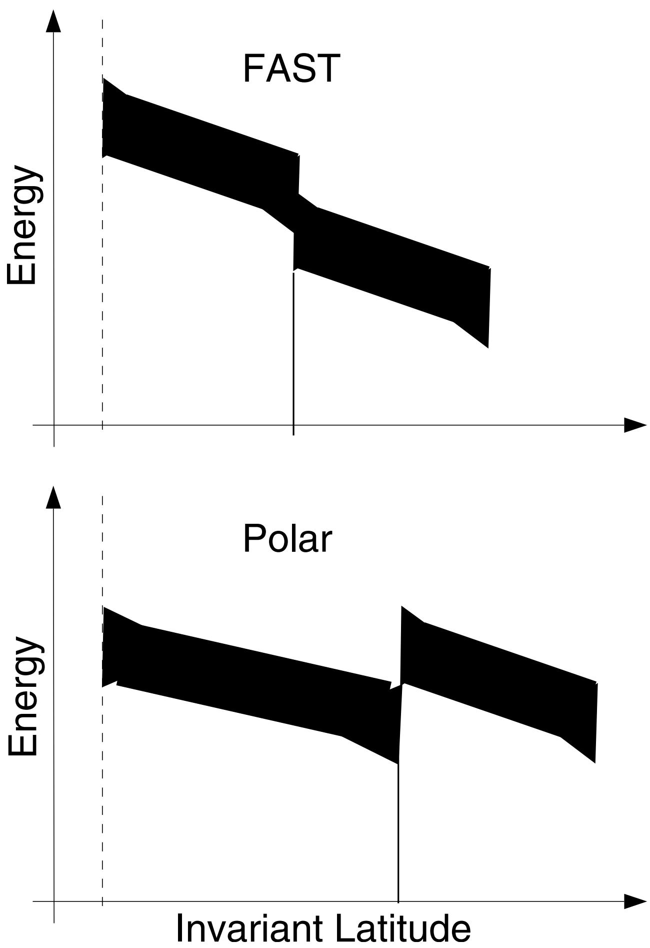

Figure 4. Schematic representation of one temporal step in the cusp ion energy dispersion as observed by FAST and Polar at different altitudes in the cusp.

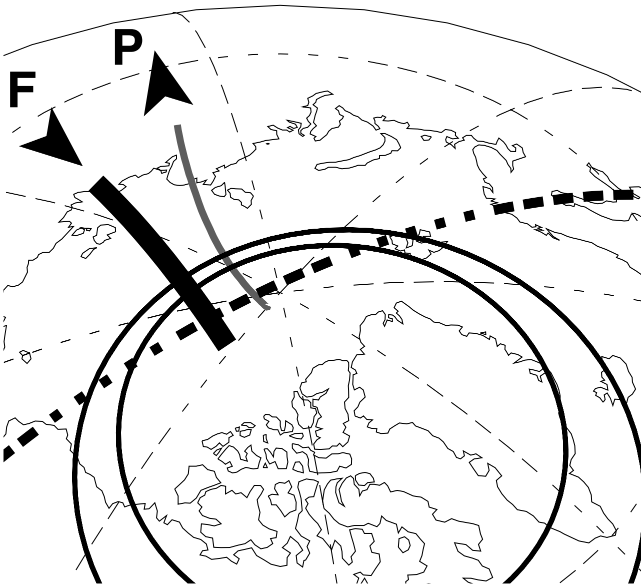

Figure 5. Magnetic foot points of the Polar (thin line) and FAST (thick line) orbits in the northern polar region for cusp passes on 25 September 1998. Their temporal and spatial separations are: ΔUT = 1 hour, ΔMLT = 0 hour. Also indicated is an average location of the auroral oval and the terminator (dashed line).

1991; *Weiss et al.*, 1995]. Using ISEE 2 observations, *Phillips et al.* [1993] interpreted cusp structures in terms of a quasi-steady spatial structure which did not appear to be consistent with a brief, localized merging event. *Ohtani et al.* [1996] examined multi-instrument measurements from Viking and DMSP F7 and concluded that field-aligned current systems appeared to be quasi-stationary. *Onsager et al.* [1995] used two near-conjugate passes of the high-altitude Dynamic Explorer 1 (DE 1) and low-altitude DE 2

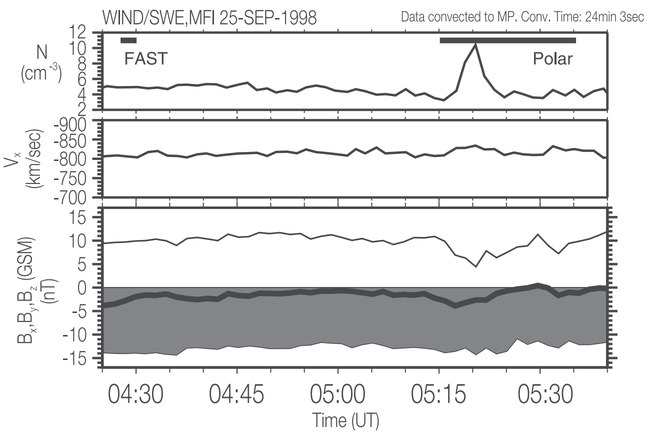

Figure 6. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 25 September 1998. The data have been propagated by ~24 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density N, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line), and B_z (shaded area). Solid bars indicate the times when Polar and FAST crossed the cusp to illustrate the temporal separation of the spacecraft.

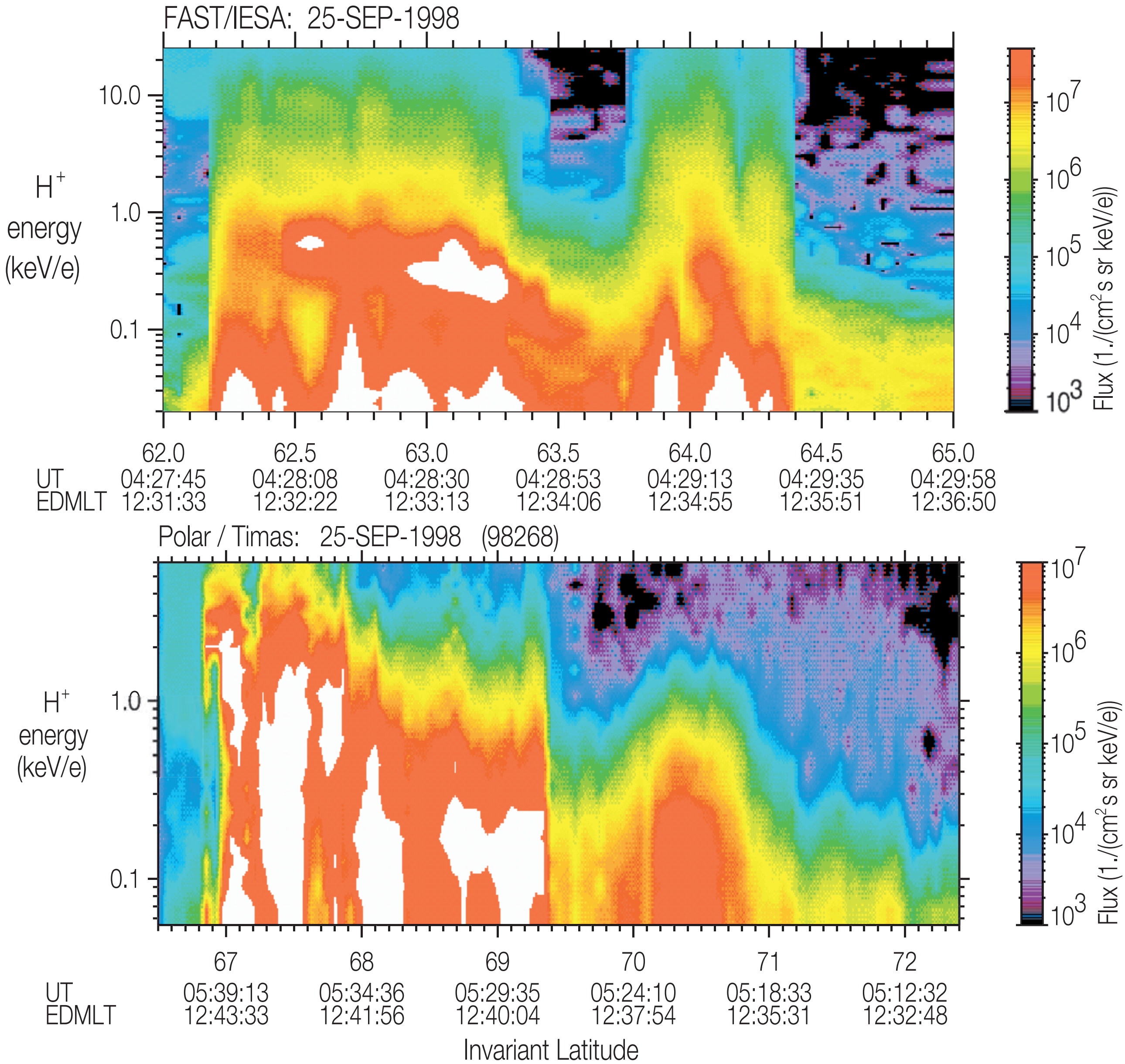

Figure 7. Comparison of FAST/IESA and Polar/Toroidal Imaging Mass-Angle Spectrograph (TIMAS) omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 25 September 1998. The observations occurred at about the same MLT but separated in time by ~1 hour. The similarities in the ion dispersion signatures are interpreted as spatial structures rather than temporal variability in the reconnection rate.

spacecraft in the dayside cusp to investigate spatial versus temporal structures. A similar step in the ion dispersion signature was detected at both the high- and low-altitude spacecraft but separated in universal time by ~20 min. This suggests that the discontinuity in the ion dispersion was due to a spatial structure rather than a temporal variation of the reconnection rate and that reconnection was occurring continuously for at least 20 min. The same conclusion was reached by *Trattner et al.* [1999], who compared two conjugated cusp crossings from Interball and Polar. For stable solar wind conditions, complicated cusp structures appeared to be stable and unchanged for 1.5 hours. This clearly indicates that the cusp structures were spatial features. The authors suggested that cusp structures are caused by either multiple X-lines forming neighboring flux tubes with different time histories or an evolutionary process of the field line while it is convected with the solar wind. The convected field lines each repeating this evolutionary process would create a standing feature in the cusp.

[7] Because of the conflicting observational evidence, this paper compares observations from two spacecraft in the cusp that have unprecedented temporal and spatial separation in order to determine to what degree cusp structures are temporal or spatial phenomenon. Following earlier work, we use combined observations from two spacecraft, Polar and Fast Auroral Snapshot (FAST), to

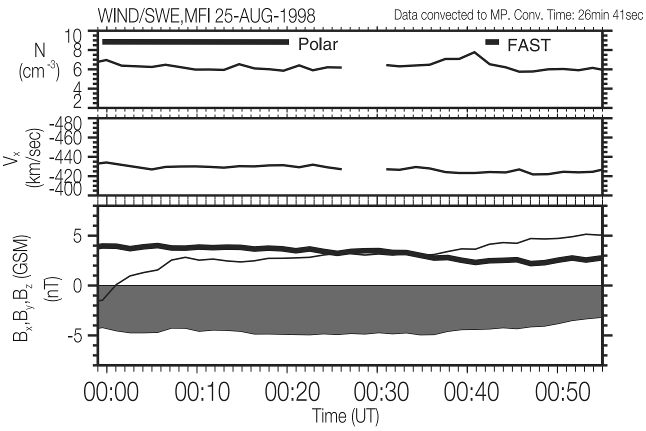

Figure 8. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 25 August 1998. The data have been propagated by $\sim$27 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density N, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line), and B_z (shaded area). Solid bars indicate the times when Polar and FAST crossed the cusp to illustrate the temporal separation of the spacecraft.

avoid the ambiguity of single-point measurements in distinguishing temporal and spatial effects. We investigate four dayside cusp passes by Polar and FAST with spacecraft separations in space and time of several hours (up to 5 hours in time and up to 3 hours in magnetic local time (MLT)). A comparison of cusp ion dispersion signatures observed during these intervals revealed that while individual cusp passes are quite different, cusp passes of two satellites during stable solar wind conditions show remarkable similarities. This suggests that major steps in the cusp ion energy dispersion are the result of spatial structures and not temporal variation in reconnection parameters. However, variations and smaller structures indicate that there are also temporal process involved in the creation of cusp structures.

2. Instrumentation and Data Selection

[8] In this paper we present ion observations from the dayside cusp using the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) on Polar [*Shelley et al.*, 1995] and the Ion Electrostatic Analyzer (IESA) on the FAST Small Explorer [*Carlson et al.*, 2001].

[9] Polar/TIMAS measurements cover the energy range from 16 eV e^{-1} to 33 keV e^{-1} and provide a 98% coverage of the unit sphere during a 6-s spin period. The ion distributions are observed at altitudes between 3.5 and 6 R_E in the cusp and up to 90° invariant latitude (ILAT).

[10] FAST/IESA measurements cover the energy range from 3 eV e^{-1} to 25 keV e^{-1} and provide coverage of all pitch angles with subsecond time resolution. The ion distributions are observed at altitudes of $\sim$3000 km in the cusp with an orbit inclination of 83°.

[11] In addition, Wind (Magnetic Fields Investigation (MFI) and Solar Wind Experiment (SWE)) data are used as solar wind context measurements [*Lepping et al.*, 1995; *Ogilvie et al.*, 1995]. These data are provided by the International Solar Terrestrial Physics (ISTP) key parameter Web page. The comparison of cusp crossings in this study requires events with stable solar wind conditions, especially stable IMF conditions. This requirement avoids changes in cusp structures due to changes in the location of the X-line.

[12] Figure 3 shows a schematic representation of the Polar and FAST spacecraft crossing the northern cusp. Their large altitude separation (up to 8 R_E) has several advantages over satellite crossings of the cusp at about the same altitude:

1. The different orbit periods of $\sim$18 hours and 2 hours for Polar and FAST, respectively, cause temporal separation between respective cusp crossings from 0 hours up to several hours. This is ideal for studying the lifetime and development of cusp structures.

2. Their different orbital planes also cause large spatial separations from 0 hours to several hours in MLT. This separation can be used to probe the longitudinal width of cusp structures.

3. While FAST spends an average 3 min in the cusp, Polar cusp crossings can last up to 5 hours. If cusp structures are temporal features and are convected poleward, their motion should clearly show up by comparing cusp crossings from Polar and FAST. Spacecraft at the same altitude which cross the cusp at about the same time might encounter quasiperiodic pulsations which could be mistaken for a spatial structure.

4. Polar and FAST cross the cusp with vastly different velocities. This velocity difference has direct consequences of how cusp structure appear at observing spacecraft. Figure 4 illustrates how one convecting cusp structure caused by variation in the reconnection rate will be observed by Polar and FAST. The slow moving Polar spacecraft should be overtaken by the convecting structures and move from an "old" flux tube to a "newer" flux tube with less time since reconnection. As shown in Figure 4 (bottom), Polar will encounter a step-up in the cusp ion energy dispersion. In contrast, the rapidly moving low-altitude FAST spacecraft would overtake the convecting cusp structures [*Lockwood and Davis*, 1996]. FAST would cross from an "new" flux tube into an "older" one, encountering a step-down in the cusp ion energy dispersion (Figure 4, top). By using Polar and FAST cusp crossings, temporal structures should not only be convected with the solar wind but also should appear different at the two spacecraft used in this study.

5. Another characteristic to be considered in the observation of temporal structures in the cusp is the number of structures encountered by Polar and FAST. Depending on the convection speed of the reconnection pulses, the pulse frequency, and the spacecraft velocity in the cusp, we would expect to see many more pulses on Polar compared to FAST. However, if cusp structures are spatial, both spacecraft should encounter the same number of structures.

[13] Along with the advantages came several disadvantages of using spacecraft that widely separated in altitude:

1. While both satellites are crossing the cusp, stable solar wind conditions are required to avoid changes in cusp structures due to changes in the location of the X-line. The long cusp crossing time of Polar and the often large temporal separation of the spacecraft therefore require stable solar wind conditions of several hours. This requirement restricts the number of events.

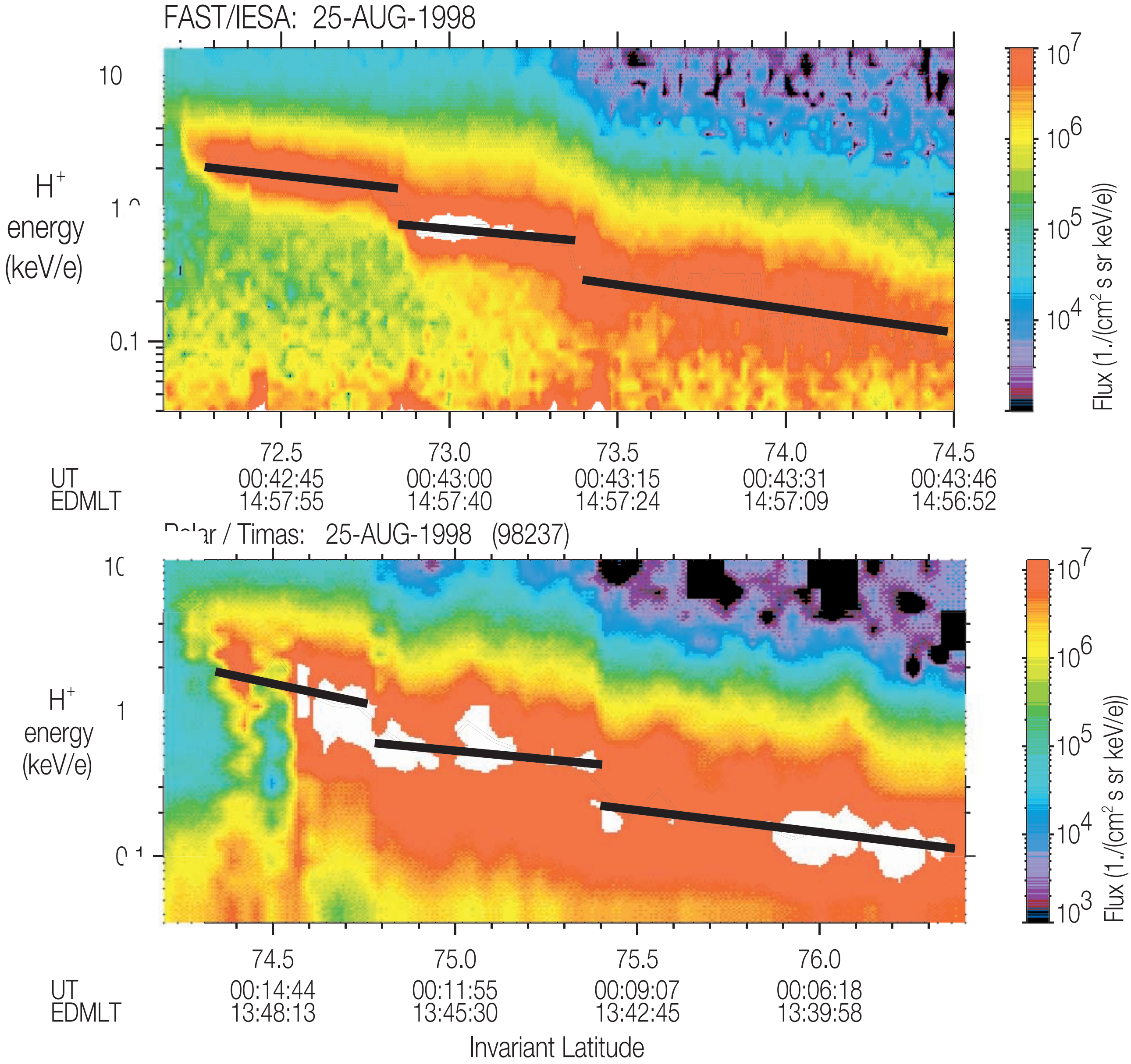

Figure 9. Comparison of FAST/IESA and Polar/TIMAS omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 25 August 1998. The observations are separated by ~1 hour in MLT and 30 min in time. While this event is very different from the 25 September 1998 event, there are remarkable similarities in this FAST/IESA and Polar/TIMAS observations.

2. Flux levels at Polar and FAST altitude will be different, which makes a direct comparison without extensive modeling difficult.

3. Observations at the slow moving Polar spacecraft could be affected by cusp motions. If the whole cusp moves due to variations in the solar wind dynamic pressure, Polar might cross a single structure several times while FAST would encounter it only once.

4. It could be difficult to resolve small steps in the cusp due to the different time resolutions at Polar and FAST in conjunction with different cusp crossing times of the spacecraft.

[14] This study will focus on H^+ measurements and investigate major jumps in the cusp ion energy dispersion. Because of the large altitude separation of the spacecraft, additional investigations of simultaneous variations in the ion flux levels at the two satellites are difficult. The development of an altitude dependency of the precipitating ion flux is not the subject of this paper.

[15] We have selected four Polar cusp crossings together with the closest FAST cusp crossings in the northern polar cusp. Any steps in the cusp ion dispersion signature observed by Polar are cross-checked with FAST observations for its position and appearance in the cusp. Cross checks of Polar/FAST ion dispersion signatures allow a distinction of temporal and spatial structures in the cusp: (1) As shown in Figure 1, temporal signatures do not line up and in addition should look different when observed at

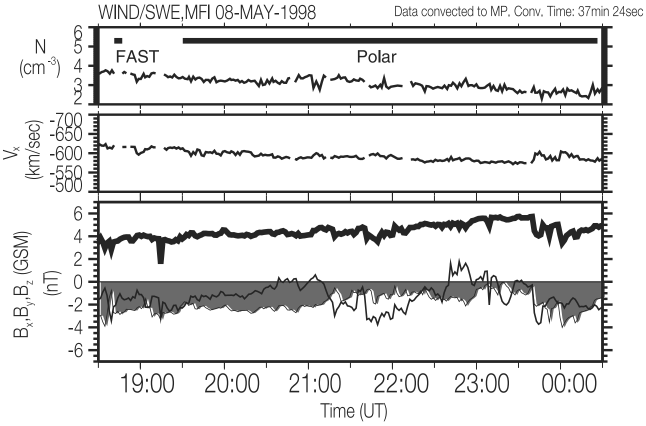

Figure 10. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 8 May 1998. The data have been propagated by ~38 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density N, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line), and B_z (shaded area). Solid bars indicate the times when Polar and FAST crossed the cusp to illustrate the temporal separation of the spacecraft.

Polar and FAST (Figure 4). (2) Features of true spatial signatures line up (Figure 2) and are independent of the altitude separation of the spacecraft, their velocities in the cusp, or the direction of the spacecraft motion in the cusp.

[16] It should be noted that a simple correlation of the position of steps in invariant latitude (ILAT) is misleading. *Trattner et al.* [1999] showed remarkable agreement of complicated cusp features observed by Polar and Interball. While these observations occurred at about the same MLT position, the cusp steps did not appear at the same ILAT because of the time-dependent shifting of the cusp location itself. Several processes like erosion of the magnetopause can influence the cusp location in time. Furthermore, erosion can occur even under steady IMF and solar wind plasma conditions. Other studies concluded that the cusp position is largely controlled by substorm processes internal to the magnetosphere rather than by direct merging and erosion processes with the interplanetary field [*Eather*, 1985]. In addition, the cusp is not located at constant ILAT for observations which are separated in MLT. These temporal and spatial effects on the cusp location in ILAT are further complicated by the altitude separation of the spacecraft in this study. Even if both satellites are at the same ILAT, the actual magnetic field line at the satellite positions might map to different positions on the ground, which will result in different cusp locations in ILAT. To avoid effects on the cusp location in ILAT we follow *Trattner et al.* [1999] and identify the boundary where we first encounter downward precipitating ions. Starting at this equatorward edge of the cusp, we treat the entire cusp as a "box" where we observe downward precipitating ions and steps in the cusp ion energy dispersion. While the location of the "box" in ILAT is not important, the position of the structures inside the "box" and their motion or change in space and time at Polar and FAST reveal their spatial or temporal nature.

3. Event 1: 25 September 1998

[17] Event 1 compares Polar and FAST cusp crossings with a temporal and spatial separation of ΔUT = 1 hour and ΔMLT = 0 hours, respectively. Figure 5 shows the magnetic foot points of Polar (thin line) and FAST (thick line) orbits in the northern polar regions for cusp passes on 25 September 1998. Also indicated are the average locations of the auroral oval and the terminator (dashed line). Both satellites crossed through the cusp at about the same MLT, near local noon (1230 MLT) but an hour apart in universal time. They also crossed the cusp in opposite directions. Polar was moving equatorward and encountered downward precipitating cusp ions from ~0510 to 0540 UT. FAST was moving poleward and crossed the cusp from 0428 to 0430 UT.

[18] Figure 6 shows solar wind observations by Wind/SWE and MFI for the Polar and FAST cusp crossings on 25 September 1998. The time of the solar wind observations has been adjusted by ~24 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density N, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line), and B_z (shaded area). Solid bars indicate the times when Polar and FAST crossed the cusp and illustrate the temporal separation of the spacecraft. For the entire interval the solar wind conditions were stable. The solar wind density was ~5 cm^{-3}, and a solar wind velocity was ~820 km s^{-1}, except for a brief rise in the solar wind density at ~0520 UT. The IMF observations indicate that B_z was strongly southward for the entire interval and the dominant component with about -13 nT. B_y was at ~-2 nT. This interval satisfies the requirements for stable solar wind conditions where we can also expect a stable location of the X-line. Thus we greatly reduce the possibility of cusp structures due to motion of the X-line.

[19] A comparison of omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for the Polar and FAST cusp passes on 25 September 1998, is shown in Figure 7. Plotted are H^+ flux measurements as observed by the IESA (Figure 7, top) and TIMAS (Figure 7, bottom) instruments on FAST and Polar, respectively. White regions in the color-coded plot indicate regions with flux levels above the maximum indicated flux level in the color bars. As mentioned above, a direct comparison of the flux measurements without carefully considering altitude effects on the plasma distribution is not valid, because of the large altitude separation of the spacecraft. We concentrate on major jumps in the ion energy dispersion. The FAST spacecraft, moving poleward, entered the cusp at ~0428 UT, crossed the downward precipitating ion region in 2 min and moved onto lobe field lines. The FAST cusp crossing is characterized by two major structures. The first structure consists of a sudden onset of precipitating ions with energies up to 10 keV at the open/closed field line boundary located at 62.2° ILAT followed by a sudden decrease in ion energy to ~1 keV at 63.3° ILAT. The second structure also consists of an increase in the energy of precipitating ions (at ~63.8° ILAT) followed by a sudden decrease (at 64.4° ILAT).

[20] The Polar spacecraft, moving equatorward, crossed the cusp in ~30 min and left the precipitating ion region at 0540 UT, ~1 hour later then FAST. The Polar cusp crossing is also characterized by two major structures. The first

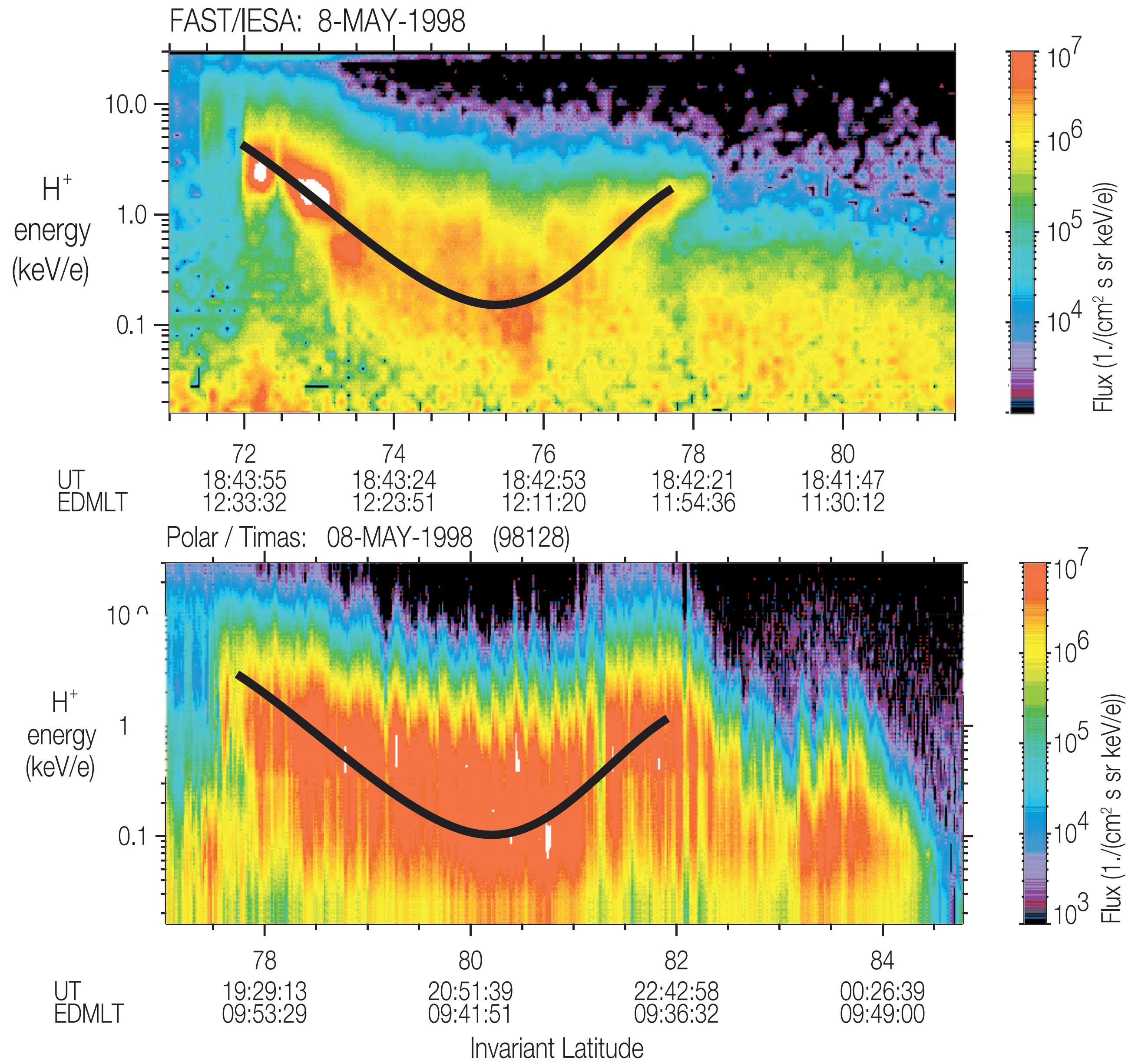

Figure 11. Comparison of FAST/IESA and Polar/TIMAS omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 8 May 1998. The observations are separated up to 3 hours in MLT and up to 5 hours in time. Even for this extreme spatial and temporal separations, there are remarkable similarities in these FAST/IESA and Polar/TIMAS observations.

structure consists of a sudden onset of precipitating ions with up to 10 keV at the open/closed field line boundary located at 66.8° ILAT followed by a sudden decrease in ion energy to ~1 keV at 69.3° ILAT. The second structure consists of an increase in the energy of precipitating ions at ~70.0° ILAT followed by a decrease at 70.9° ILAT.

[21] The difference in the cusp location as observed by Polar and FAST is ~5°. As pointed out by *Trattner et al.* [1999], individual structures can also appear shorter or wider and cover different latitudinal ranges. These differences can be attributed to (1) temporal effects, (2) spatial effects, and (3) problems in mapping of actual field lines to ILAT as mentioned above. These issues will be further discussed in the summary section. However, by ignoring the actual cusp position in ILAT and treating the cusp as a "box" where downward precipitating ions are observed, the observed structures at one satellite line up with structures observed by a second satellite.

[22] The Polar cusp crossing also shows additional steps and variations inside the individual structures, especially the first structure from 66.8° ILAT to 69.3° ILAT. Since Polar spends considerably more time in the cusp compared to FAST, this could be attributed to resolution differences. While FAST may be averaging over smaller structures, Polar is able to separate them. These small structures, however, could also be the signature of a temporal effect. While major steps in the cusp ion energy dispersion appear to be spatial, caused by spacecraft crossing spatially separated flux tubes,

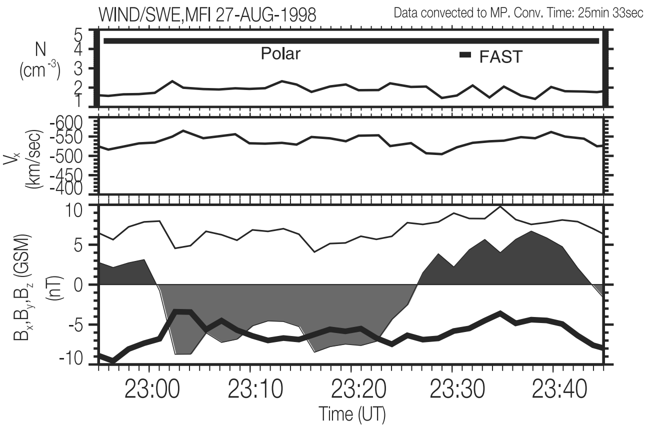

Figure 12. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 27 August 1998. The data have been propagated by ~25 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density *N*, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line), and B_z (shaded area). Solid bars indicate the times when Polar and FAST crossed the cusp to illustrate the temporal separation of the spacecraft.

features inside the flux tubes could be the result of variation of the reconnection rate and reconnection pulses.

4. Event 2: 25 August 1998

[23] Event 2 compares Polar and FAST cusp crossings with a temporal and spatial separation of ΔUT = 30 min and ΔMLT = 1 hour, respectively. Compared to the first event, the spacecraft cross the cusp deeper in the afternoon sector at 1345 MLT (Polar) and 1455 MLT (FAST). Figure 8 shows solar wind observations by Wind/SWE and MFI for the Polar and FAST cusp crossings on 25 August 1998. The data have been propagated by ~27 min to account for the travel time from the Wind spacecraft to the magnetopause. The format of Figure 8 is the same as in Figure 6. For the entire interval the solar wind conditions were stable. The solar wind density was ~6 cm^{-3}, and the solar wind velocity was ~430 km s^{-1}. The IMF observations indicate that B_z was southward for the entire interval with about −4 nT. B_y was at ~3 nT, while B_x was at ~4 nT. In contrast to event 1 with B_x as the weakest component, the IMF components for the 25 August 1998 event have about the same magnitude.

[24] A comparison of the Polar and FAST cusp passes on 25 August 1998 is shown in Figure 9. The format in Figure 9 is the same as that in Figure 7. Also indicated in the Polar and FAST flux panels is the energy where the maximum flux in the precipitating cusp ions occurred. To help to guide the eye, additional lines have been overlaid to emphasize the steps in the cusp ion energy dispersion. The FAST spacecraft, moving poleward, entered the cusp at ~0042 UT at 72.2° ILAT and crossed the downward precipitating ion region in ~2 min. The FAST cusp crossing is characterized by a classical downward step structure, featuring two steps at 72.9° and 73.4° ILAT.

[25] The Polar spacecraft, moving equatorward, crossed the cusp in ~20 min and left the precipitating ion region at ~0014 UT at 74.3° ILAT. The cusp ion energy distribution observed by Polar is much broader than the distribution observed by FAST, indicating again that direct comparison of flux levels is difficult due to the altitude difference. However, by marking the energy for the maximum flux in the cusp ion energy dispersion, two steps at 74.8° and 75.4° ILAT are identified. While the cusp structures in the 25 August 1998 event are very different from those of the 25 September 1998 event, the direct comparison of the FAST and Polar cusp crossings during stable solar wind conditions again revealed similar structures at both spacecraft, two classical steps in the cusp ion energy dispersion.

5. Event 3: 8 May 1998

[26] Event 3 compares Polar and FAST cusp crossings with a temporal and spatial separation of ΔUT up to 5 hours and ΔMLT up to 3 hours, respectively. The spacecraft crossed the cusp on field lines mapping to ~0940 MLT (Polar) and 1200 MLT (FAST). Figure 10 shows solar wind observations by Wind/SWE and MFI for the Polar and FAST cusp crossings on 8 May 1998. The data have been propagated by ~38 min to account for the travel time from the Wind spacecraft to the magnetopause. The format of Figure 10 is the same as that in Figure 6. For this 6-hour-long interval the solar wind conditions were stable with solar wind density slightly decreasing from 3.5 cm^{-3} to 2.5 cm^{-3} and a solar wind velocity of ~600 km s^{-1}. The IMF observations indicate that B_z was southward for the entire interval with an average of about −2 nT. B_y was the weakest component, with an average of about −1 nT, while B_x was the dominant component, with an average of ~4 nT.

[27] A comparison of the Polar and FAST cusp passes on 8 May 1998 is shown in Figure 11. The format in Figure 11 is the same as that in Figure 7. To help to guide the eye, additional lines have been overlaid, which represent an average location of the maximum flux in the cusp ion energy dispersion. The FAST spacecraft, moving equatorward in this event, left the cusp at ~1844 UT at 72.° ILAT and crossed the downward precipitating ion region in ~3 min. Seen from the equatorward edge of the cusp at 72.° ILAT, the FAST cusp crossing is characterized by a classical velocity dispersion with lower-energy particles arriving at higher latitudes. This velocity filter effect [e.g., *Rosenbauer et al.*, 1975; *Onsager et al.*, 1993] is smoothly reversed at higher latitudes, where the energy of precipitating ions starts to increase again and forms a new maximum. After this second maximum at ~78.° ILAT the cusp ion energy decreases again in agreement with the classical velocity dispersion.

[28] The Polar spacecraft, moving poleward, encountered downward precipitating ions at ~1915 UT at 77.5° ILAT. However, in contrast to the 3-min snapshot of the cusp by FAST, Polar observed precipitating cusp ions for 5 hours. Polar observed the same basic cusp structure as seen by FAST. Cusp ion energies first decreased with increasing ILAT and smoothly reversed at ~80.5° ILAT to form a new maximum at 82.° ILAT. After the second maximum the cusp ion energy continues to decrease again. The 8 May 1998 event is very different from the 15 August and 25 September 1998 events. However, even for these extreme separations in time and space, a direct comparison of the FAST and Polar

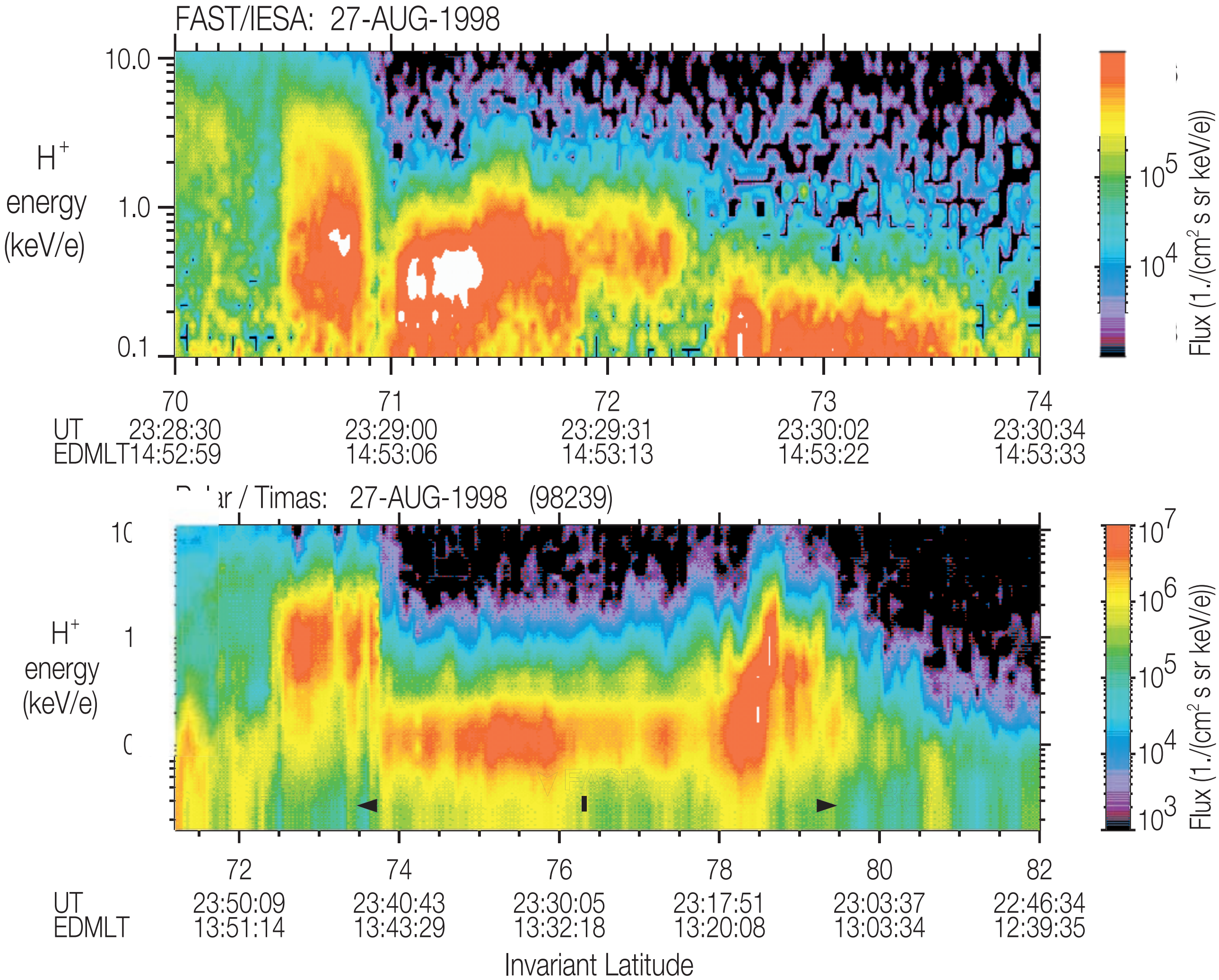

Figure 13. Comparison of FAST/IESA and Polar/TIMAS omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 27 August 1998. Both spacecraft were in the cusp at the same time. However, there was an IMF field rotation from southward to northward during the Polar cusp pass which changed the observed cusp structures.

cusp crossings showed similar basic cusp structures at both spacecraft for stable solar wind conditions.

[29] The Polar cusp pass also showed minor structures superimposed on the major cusp ion signature. There are variations in the cusp ion energy, regular increases with a period of ~10 min. This feature is often observed on Polar for cusp passes on field lines which map to the dawn or dusk magnetopause. These increases could be the signature of surface waves on the magnetopause. These waves push the X-line slightly in and out, thereby slightly changing the distance from the spacecraft to the X-line. This would allow ions with higher energies to reach the spacecraft at its current position. An alternative explanation was suggested by M. Lockwood (private communication, 2001). These small variations could be the signature of variations in the reconnection rate at the magnetopause. Lockwood pointed out that for this specific example the ratio of Polar to FAST cusp steps encountered by the spacecraft should be ~20, which is indeed the case. The form and number of the cusp steps are in agreement with predictions from the pulsed reconnection model [e.g., *Lockwood et al.*, 1998].

6. Event 4: 27 August 1998

[30] Event 4 on 27 August 1998 is somewhat different compared to the previous events. Both spacecraft are in the cusp at the same time. However, the slow motion of the Polar spacecraft results in a temporal separation from 0 to 40 min. Furthermore, the spacecraft are separated in MLT up to 2 hours. The spacecraft crossed the cusp on field lines mapping to the afternoon sector 1300 MLT (Polar) and 1453 MLT (FAST). Figure 12 shows solar wind observations by Wind/SWE and MFI for the Polar and FAST cusp crossings on 8 May 1998. The data have been propagated by ~25 min to account for the travel time from the Wind spacecraft to the magnetopause. The format of Figure 12 is the same as that in Figure 6. The solar wind conditions for this event are not stable. While solar wind density and solar wind velocity

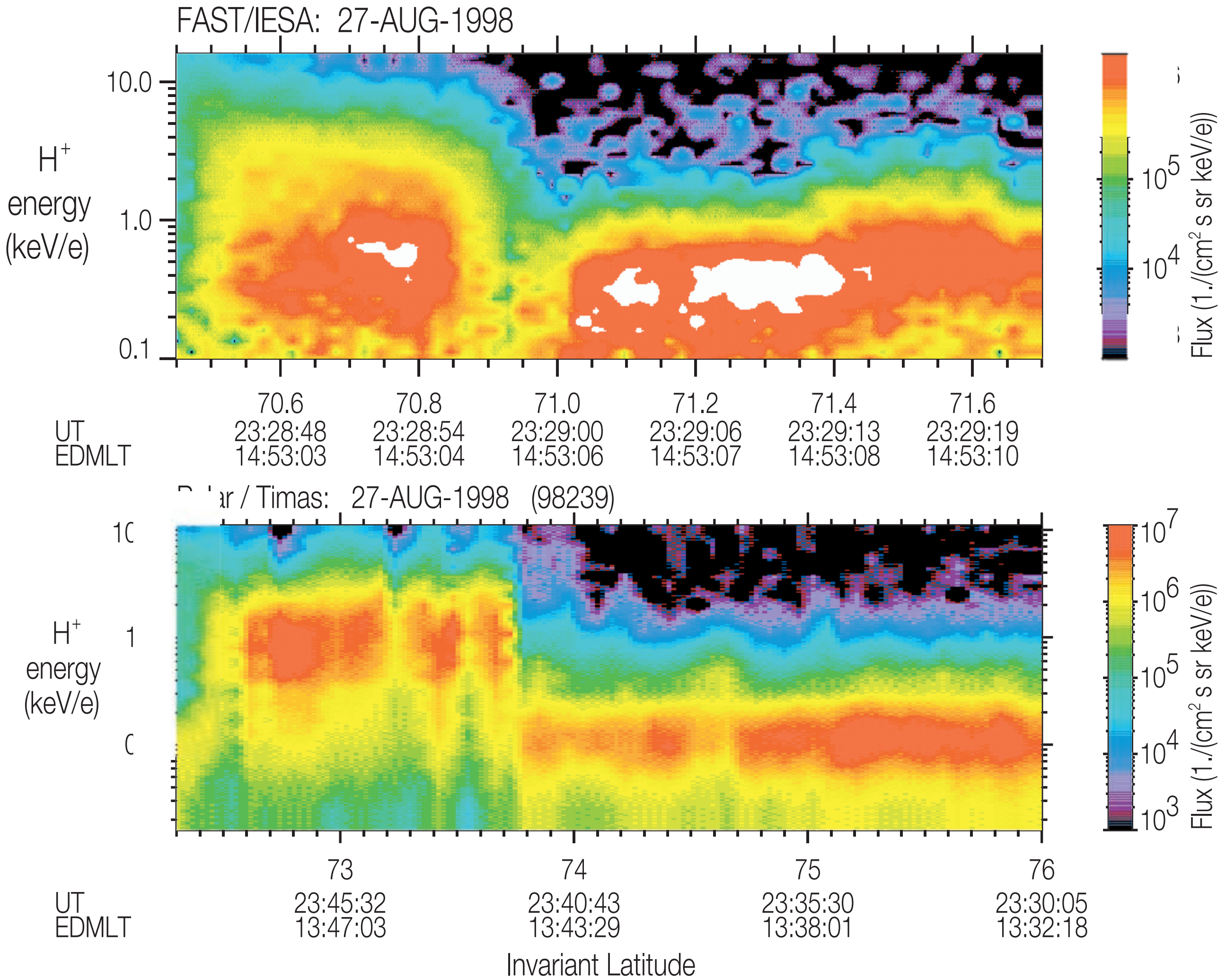

Figure 14. Comparison of FAST/IESA and Polar/TIMAS omnidirectional flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 27 August 1998. Only the cusp structures observed for the same IMF conditions are plotted in this figure.

are constant at ~2 cm^{-3} and 540 km s^{-1}, respectively, the IMF rotates from south to north at 2326 UT. This rotation will change the structures in the cusp while Polar is observing them. FAST crossed the cusp after the rotation when the field was northward. There are two more rotations in the IMF B_z component at the time when Polar entered and exited the cusp which had no observable influence on structures inside the cusp.

[31] A comparison of the Polar and FAST cusp passes on 27 August 1998 is shown in Figure 13. The format in Figure 13 is the same as that in Figure 7. Polar (Figure 13, bottom) moved equatorward and crossed into the cusp at ~2300 UT at ~80.° ILAT. For the first part of the Polar cusp crossing the IMF was southward, and Polar encountered cusp ions with steadily increasing energies. After forming a maximum at ~78.5° ILAT, the cusp ion energy decreased before staying constant for more than 20 min (>2.° ILAT). During this period as Polar reached 76.2° ILAT, the IMF changed from southward to northward. The cusp ion energy remained level until Polar reached 74.° ILAT, where a sudden increase was observed. Polar then left the cusp equatorward at ~72.5° ILAT at 2347 UT.

[32] After the field reversal the FAST spacecraft crossed the cusp in 2 min (as indicated in the bottom panel of Figure 13). A direct comparison of the Polar and FAST cusp passes shows that the maximum observed by Polar at 78.5° ILAT during southward IMF is not observed in the FAST cusp structures during northward IMF. FAST enters the cusp at 70.5° ILAT at ~23:29 UT and encounters a sharp drop in the cusp ion energy at ~71.° ILAT. The cusp ion energy then levels out till ~72.5° ILAT before decreasing further.

[33] Figure 14 shows a comparison of the 27 August 1998 cusp crossing by Polar and FAST for the segments observed during the northward IMF conditions. While there are again differences in the flux levels, changes in the cusp ion energies agree. Both cusp crossings, as seen from the equatorward edge, start with a sharp increase in cusp ion energy up to ~10 keV, followed by a segment with constant energy. After a sharp drop in ion energy the energy levels out and stays constant for the rest of this cusp segment. This event shows that changes in the IMF, which will move the reconnection site, do change the structures observed in the cusp. However, even after a IMF rotation from south to north, major cusp structures like sharp jumps in the cusp ion

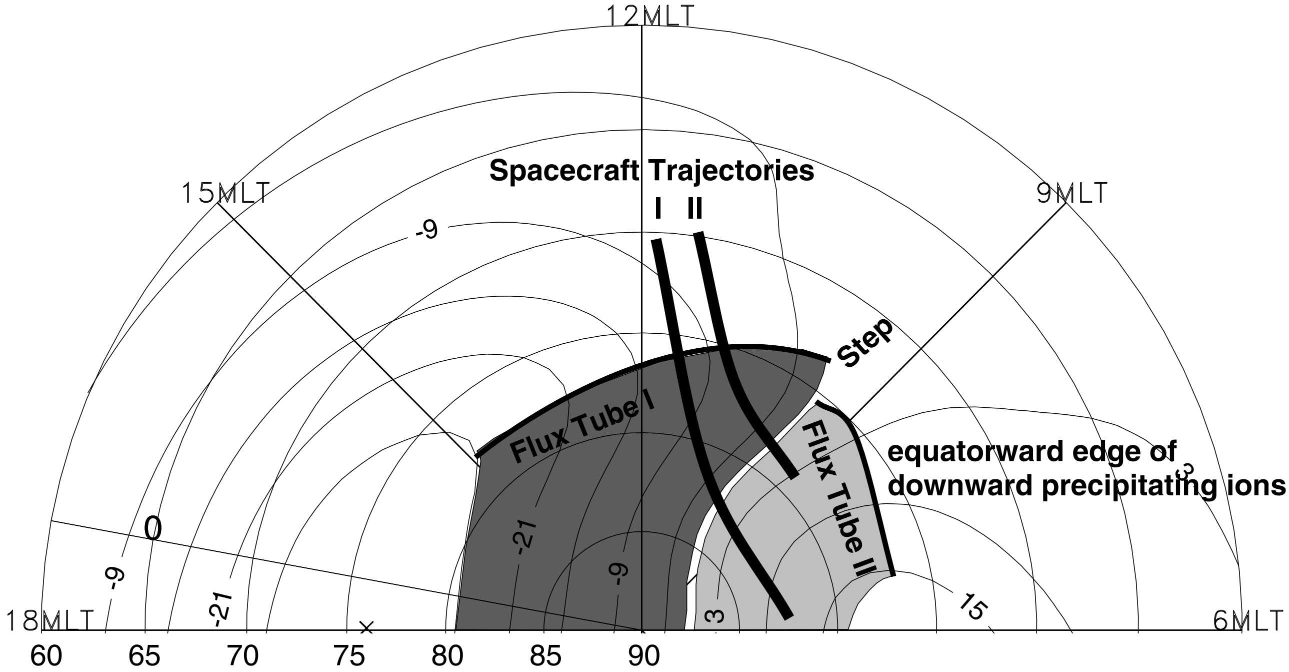

Figure 15. Ionospheric convection cells derived from the Applied Physics Laboratory (APL) statistical model for $-B_z$ and $-B_y$ input. To illustrate how major cusp structures could be spatial instead of temporal, two flux tubes and two satellite trajectories have been superimposed on the convection cells.

energy dispersion correlate for the segments observed during the same IMF conditions.

7. Conclusion and Summary

[34] Several recent papers [e.g., *Onsager et al.*, 1995; *Trattner et al.*, 1999] showed evidence that structures observed in the cusp ion energy dispersion signature could be a spatial feature. This interpretation is therefore in conflict with the widely used pulsating cusp model which explains structures in the cusp as the result of periods of little or no reconnection at the magnetopause [e.g., *Lockwood and Smith*, 1989, 1990, 1994; *Lockwood et al.*, 1998]. Such variations in the reconnection rate create a series of poleward convecting magnetic flux tubes (pulses) with different time histories since reconnection. Two spatially separated satellites in the cusp should therefore encounter a certain combination of steps with a time delay at different latitudes.

[35] In this paper we have presented cusp crossings observed by Polar/TIMAS and FAST/IESA separated in unit time and MLT of up to 5 hours and up to 3 hours, respectively. Because of the large altitude separation of Polar and FAST (up to 8 R_E), comparison of flux levels or variation in flux levels is difficult. This study concentrates on major steps in the cusp ion energy dispersion. While individual cusp crossings for different solar wind conditions are very dissimilar, cusp crossings by two satellites during stable solar wind conditions are remarkable similar. Based on these observations we conclude that major cusp structures during stable solar wind conditions are spatial in nature and do not convect poleward.

[36] A useful context in which to interpret the satellite conjunctions presented here is the convection of the cusp and polar cap magnetic flux tubes. Such large-scale convection patterns are routinely measured by the Super Dual Auroral Radar Network (SuperDARN) HF radar array [*Greenwald et al.*, 1995] and are commonly presented as equipotential maps [*Ruohoniemi and Baker*, 1998]. Unfortunately, for the conjunctions considered here, little useful scatter was recorded by SuperDARN in the local time sectors under consideration. Figure 15 presents the appropriate average pattern for the prevailing IMF conditions (IMF $-B_z$, $-B_y$, B_{total} = 4 − 6 nT) based on the statistical study of *Ruohoniemi and Greenwald* [1996]. Superimposed on it are two flux tubes and the magnetic ground tracks of two spacecraft. For IMF conditions with a significant B_y component there will be antiparallel merging regions in the Northern and Southern Hemispheres [e.g., *Crooker et al.*, 1985; *Luhmann et al.*, 1984]. These two X-lines will map into both cusps, forming two different flux tubes with their own history since reconnection. Magnetosheath ions will be able to enter the magnetosphere and propagate to the cusp regions. As depicted in Figure 15, the equatorward edge of these downward precipitating ions is defined where they are first observed by polar orbiting spacecraft. Moving poleward away from the equatorward edge, the spacecraft will observe the classical cusp ion energy dispersion with lower-energy ions arriving at higher latitudes. However, if they cross into flux tube II with its own history and dispersion signature since reconnection, they will experience a jump in their cusp ion energy dispersion. This step is a spatial structure defined as the boundary between flux tubes emanating from multiple X-lines and will not convect poleward. This scenario is in agreement with the Polar/FAST observations in this paper and earlier work [e.g., *Weiss et al.*, 1995; *Phillips et al.*, 1993; *Onsager et al.*, 1995; *Trattner et al.*, 1999].

[37] Figure 15 also illustrates why cusp structures observed by two spacecraft appear at different latitudes. Spacecraft I enters flux tube I at 77° while spacecraft II enters it at 75°. In addition to the earlier discussed difficulty with mapping actual field lines through satellites at the same latitude but separated in altitude, the differences in the cusp position are the simple consequence of the form of the equatorward edge of the cusp. Figure 15 also illustrates why individual structures observed by two satellites often have a different ILAT extent on one spacecraft compared to the other. While spacecraft I encounters flux tube II at 83°, spacecraft II encounters flux tube II at 77°, which results in an average width of the first structure of 6° and 2° for spacecraft I and II, respectively. To identify spatial structures, it is essential to line up cusp crossings beginning at the equatorward edge regardless of their actual position in latitude. Also, slight variations in the extent of structures are simply the consequence of the form of the flux tubes and how satellites cross them. These slight variations can, however, cause misleading results. Since temporal structures are expected to move with the convection flow, variation in the extent of structures could be interpreted as motion. This is especially difficult when spacecraft at about the same altitude and close together observe regular structures like the classical staircase. In this study the large altitude separation of the spacecraft counteracts misinterpretation since according to the pulsed reconnection model, temporal structures observed with satellite at different altitudes would not only move but look different (Figure 4).

[38] The interpretation of major cusp structures as spatial features caused by crossing over the boundaries of different flux tubes is, however, no proof that reconnection pulses do not exist. If there are reconnection pulses, there should be moving structures within the same flux tube. This would be in agreement with the observation of poleward moving transients in radar data [e.g., *Lockwood et al.*, 1995]. To observe poleward moving structures, two spacecraft would need to proceed along one flux tube and compare observed cusp structures. A moderate separation in altitude is desirable since the spacecraft would cross the cusp in different times and should encounter different numbers of steps for a periodic pulsating cusp. In all events in this study the slow moving Polar spacecraft observed a great number of smaller structures in between the major steps, which could be the signature of reconnection pulses at the X-line. If this is correct, then variations in the reconnection rate at the X-line are also small. Reconnection would not switch off completely but would be a continuous process. More research is needed to answer this question.

[39] The satellite data presented here reveal a highly structured cusp. Such structuring is not evident in the statistical convection map presented in Figure 15. For such small-scale spatial and temporal features to be accurately represented in such convection maps, extensive radar backscatter coverage is required as an input [*Ruohoniemi and Baker*, 1998]. Intervals with such data coverage have recently revealed far more spatial and temporal structuring of the cusp convection [e.g., *Neudegg et al.*, 2000; *McWilliams et al.*, 2001]. The combination of multisatellite data with such ionospheric convection maps will form a future study.

[40] **Acknowledgments.** W.K.P. thanks D. Baker and the staff at LASP for their hospitality. K.J.T. thanks A. Rodgers and M. Lockwood for helpful discussions. We acknowledge the use of ISTP KP database. Solar wind observations were provided by K. Ogilvie at NASA/GSFC (Wind/SWE); magnetic field observations were provided by R. Lepping at NASA/GSFC (Wind/MFI). The work at Lockheed was supported by NASA contracts NAS5-30302, NAG5-3596, and NAG5-9769.

[41] Janet G. Luhmann thanks Michael Lockwood and Terry G. Onsager for their assistance in evaluating this paper.

References

Carlson, C. W., J. P. McFadden, P. Turin, D. W. Curtis, and A. Magoncelli, The Electron and Ion Plasma Experiment for FAST, *Space Sci. Rev.*, *98*, 1–2, 2001.
Cowley, S. W. H., The cause of convection in the Earth's magnetosphere: A review of developments during IMS, *Rev. Geophys.*, *20*, 531, 1982.
Cowley, S. W. H., M. P. Freeman, M. Lockwood, and M. F. Smith, The ionospheric signatures of flux transfer events, in *CLUSTER: Dayside Polar Cusp*, edited by C. I. Barron, *Eur. Space Agency Spec. Publ., ESA SP-330*, *105*, 1991.
Crooker, N. U., J. G. Luhmann, J. R. Spreiter, and S. S. Stahara, Magnetopause merging site asymmetries, *J. Geophys. Res.*, *90*, 341, 1985.
Eather, R. H., Polar cusp dynamics, *J. Geophys. Res.*, *90*, 1569, 1985.
Escoubet, C. P., et al., Staircase ion signature in the polar cusp: A case study, *Geophys. Res. Lett.*, *19*, 1735, 1992.
Fuselier, S. A., D. M. Klumpar, and E. G. Shelley, Ion reflection and transmissions during reconnection at the Earth's subsolar magnetopause, *Geophys. Res. Lett.*, *18*, 139, 1991.
Gosling, J. T., M. F. Thomsen, S. J. Bame, R. C. Elphic, and C. T. Russell, Cold ion beams in low-latitude boundary layer during accelerated flow events, *Geophys. Res. Lett.*, *17*, 2245, 1990.
Greenwald, R. A., et al., DARN/SUPERDARN: A global view of the dynamics of high-latitude convection, *Space Sci. Rev.*, *71*, 761, 1995.
Lepping, R. P., et al., The Wind magnetic field instrument, in *The Global Geospace Mission*, edited by C. T. Russell, p. 207, Kluwer Acad., Norwell, Mass., 1995.
Lockwood, M., Ground-based and satellite observations of the cusp: Evidence for pulsed magnetopause reconnection, in *Physics of the Magnetopause, Geophys. Monogr. Ser.*, vol. 90, edited by P. Song, B. U. O. Sonnerup, and M. F. Thomsen, p. 417, AGU, Washington, D.C., 1995.
Lockwood, M., The case for transient magnetopause reconnection, *Eos Trans. AGU*, *77*, 246, 1996.
Lockwood, M., and C. J. Davis, On the longitudinal extent of magnetopause reconnection pulses, *Ann. Geophys.*, *14*, 865, 1996.
Lockwood, M., and M. F. Smith, Low-altitude signatures of the cusp and flux transfer events, *Geophys. Res. Lett.*, *16*, 879, 1989.
Lockwood, M., and M. F. Smith, Reply to comment by P.T. Newell on "Low-altitude signatures of the cusp and flux transfer events" by M. Lockwood and M.F. Smith, *Geophys. Res. Lett.*, *17*, 305, 1990.
Lockwood, M., and M. F. Smith, The variation of reconnection rate at the dayside magnetopause and cusp ion precipitation, *J. Geophys. Res.*, *97*, 14,841, 1992.
Lockwood, M., and M. F. Smith, Comment on "Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics" by P.T. Newell and C.-I. Meng, *Geophys. Res. Lett.*, *20*, 1739, 1993.
Lockwood, M., and M. F. Smith, Low- and mid-altitude cusp particle signatures for general magnetopause reconnection rate variations, 1, Theory, *J. Geophys. Res.*, *99*, 8531, 1994.
Lockwood, M., C. J. Davis, M. F. Smith, T. G. Onsager, and W. F. Denig, Location and characteristics of the reconnection X-line deduced from low-altitude satellite and ground-based observations, Defense Meteorological Satellite Program and European Incoherent Scatter data, *J. Geophys. Res.*, *100*, 21,803, 1995.
Lockwood, M., C. J. Davis, T. G. Onsager, and J. D. Scudder, Modelling signatures of pulsed magnetopause reconnection in cusp ion dispersion signatures seen at middle altitudes, *Geophys. Res. Lett.*, *25*, 591, 1998.
Luhmann, J. R., R. J. Walker, C. T. Russell, N. U. Crooker, J. R. Spreiter, and S. S. Stahara, Patterns of potential magnetic field merging sites on the dayside magnetopause, *J. Geophys. Res.*, *89*, 1739, 1984.
McWilliams, K. A., T. K. Yeoman, and S. W. H. Cowley, Two-dimensional electric field measurements in the ionospheric footprint of a flux transfer event, *Ann. Geophys.*, *18*, 1584, 2001.
Neudegg, D. A., et al., A survey of magnetopause FTEs and associated flow bursts in the polar ionosphere, *Ann. Geophys.*, *18*, 416, 2000.
Newell, P. T., and C.-I. Meng, Ion acceleration at the equatorward edge of the cusp: Low-altitude observations of patchy merging, *Geophys. Res. Lett.*, *18*, 1829, 1991.
Ogilvie, K. W., et al., SWE: A comprehensive plasma instrument for the

Wind spacecraft, in *The Global Geospace Mission*, edited by C. T. Russell, p. 55, Kluwer Acad., Norwell, Mass., 1995.
Ohtani, S., L. G. Blomberg, P. T. Newell, M. Yamauchi, T. A. Potemra, and L. J. Zanetti, Altitude comparison of dayside field-aligned current signatures by Viking and DMSP-F7: Intermediate-scale field-aligned current systems, *J. Geophys. Res.*, *101*, 15,297, 1996.
Onsager, T. G., C. A. Kletzing, J. B. Austin, and H. MacKiernan, Model of magnetosheath plasma in the magnetosphere: Cusp and mantle particles at low altitudes, *Geophys. Res. Lett.*, *20*, 479, 1993.
Onsager, T. G., S.-W. Chang, J. D. Perez, J. B. Austin, and L. X. Janoo, Low-altitude observations and modeling of quasi-steady magnetopause reconnection, *J. Geophys. Res.*, *100*, 11,831, 1995.
Phillips, J. L., S. J. Bame, R. C. Elphic, J. T. Gosling, M. F. Thomson, and T. G. Onsager, Well-resolved observations by ISEE 2 of ion dispersion in the magnetospheric cusp, *J. Geophys. Res.*, *98*, 13,429, 1993.
Reiff, P. H., T. W. Hill, and J. L. Burch, Solar wind plasma injections at the dayside magnetospheric cusp, *J. Geophys. Res.*, *82*, 479, 1977.
Rosenbauer, H., H. Grünwaldt, M. D. Montgomery, G. Paschmann, and N. Sckopke, Heos 2 plasma observations in the distant polar magnetosphere: The plasma mantle, *J. Geophys. Res.*, *80*, 2723, 1975.
Ruohoniemi, J. M., and K. B. Baker, Large-scale imaging of high latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, *103*, 20,797, 1998.
Ruohoniemi, J. M., and R. A. Greenwald, Statistical patterns of high latitude convection obtained from Goose Bay HF radar observations, *J. Geophys. Res.*, *101*, 21,743, 1996.
Shelley, E. G., R. D. Sharp, and R. G. Johnson, He^{++} and H^{+} flux measurements in the day side cusp: Estimates of convection electric field, *J. Geophys. Res.*, *81*, 2363, 1976.
Shelley, E. G., et al., The toroidal imaging mass-angle spectrograph (TIMAS) for the Polar mission, *Space Sci. Rev.*, *71*, 497, 1995.
Smith, M. F., and M. Lockwood, Earth's magnetospheric cusp, *Rev. Geophys.*, *34*, 233, 1996.
Smith, E. J., M. Lockwood, and S. W. H. Cowley, The statistical cusp: The flux transfer event model, *Planet. Space Sci.*, *40*, 1251, 1992.
Trattner, K. J., S. A. Fuselier, W. K. Peterson, J.-A. Sauvaud, H. Stenuit, and N. Dubouloz, On spatial and temporal structures in the cusp, *J. Geophys. Res.*, *104*, 28,411, 1999.
Weiss, L. A., P. H. Reiff, H. C. Carlson, E. J. Weber, and M. Lockwood, Flow-alignment jets in the magnetospheric cusp: Results from the Geospace Environment Modeling Pilot program, *J. Geophys. Res.*, *100*, 7649, 1995.

M. Boehm, S. A. Fuselier, W. K. Peterson, and K. J. Trattner, Lockheed-Martin Advanced Technology Center, 3251 Hanover St., B255, L9-42, Palo Alto, CA 94304, USA. (trattner@mail.spasci.com)

C. W. Carlson, Space Science Laboratory, University of California, Berkeley, CA 94720-7450, USA.

D. Klumpar, Physics Department, Montana State University, Space Science and Engineering Laboratory, P.O. Box 173840, Bozeman, MT 59717-3840, USA.

T. K. Yeoman, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK.