Spatial features observed in the cusp under steady solar wind conditions

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[1] Multispacecraft studies using Polar, Fast Auroral Snapshot (FAST), and Interball observations revealed that many cusp structures observed during stable solar wind conditions are spatial features. While individual cusp events appear to be very different from each other, multiple observations of the same cusp event during periods of stable solar wind conditions are remarkably similar. These spatial cusp structures have been interpreted as a result of the independent evolution of ion distributions from multiple reconnection sites (X-lines) in both hemispheres. The location of reconnection sites depends critically on the direction of the interplanetary magnetic field. Thus individual cusp events should have similar cusp structures if they occur in the same magnetic local time sector during comparable solar wind conditions, especially during similar interplanetary magnetic field orientations. Data presented in this paper show just such an effect. For three individual cusp events observed by Polar and FAST, similar stepped ion structures are seen by both satellites passing though these large-scale spatial structures. *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 structure, magnetic reconnection, reconnection rate, ion precipitation

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1. Introduction

[2] Based on the pulsating cusp model, structured cusp ion energy dispersions have been predicted by *Cowley et al.* [1991] and *Smith et al.* [1992]. Independent of this theoretical work, steps in the cusp ion energy dispersion have been observed by *Newell and Meng* [1991], *Escoubet et al.* [1992], and *Lockwood et al.* [1993]. In the pulsating cusp model, steps are the result of changes in the reconnection rate at the magnetopause which create neighboring flux tubes in the cusp with different time histories since reconnection [e.g., *Lockwood and Smith*, 1989, 1990, 1994]. Additional cusp observations in conjunction with ground-based observations by the European Incoherent Scatter (EISCAT) radar [see *Lockwood*, 1995; *Lockwood et al.*, 1995] revealed the temporal nature of cusp structures by showing flow across a step in the cusp ion energy dispersion. These observations are in agreement with the conclusion that the cusp is a series of poleward moving stepped events. The temporal interpretation of cusp structures was also discussed by *Boudouridis et al.* [2001]. A model based on the combination of the bursty single X-line reconnection model together with the multiple X-line reconnection model was used to explain overlapping cusp steps observed by two Defense Meteorological Satellite Program (DMSP) spacecraft. Temporal steps are convected with the open magnetic field lines under the joint action of magnetic tension and shocked solar wind flow, creating an ever-changing structural profile of precipitating cusp ions.

[3] *Trattner et al.* [1999, 2002] have noted that some stepped ion distributions are not consistent with the pulsed reconnection model. Steps in the cusp ion dispersion signature could be the result of neighboring flux tubes emanating from multiple X-lines. Spacecraft crossing the boundary between the flux tubes would encounter a step in the ion energy dispersion which will not convect with the solar wind flow. Instead, this boundary represents a spatial cusp structure. Evidence that cusp ion steps can be produced in steady state by spatial variations has also been discussed by *Newell and Meng* [1991], *Phillips et al.* [1993], *Lockwood and Smith* [1994], and *Weiss et al.* [1995]. The same conclusion was reached by *Onsager et al.* [1995], who used two cusp crossings of the high-altitude Dynamic Explorer 1 (DE 1) and low-altitude DE 2 spacecraft separated by 20 min. A similar step in the ion

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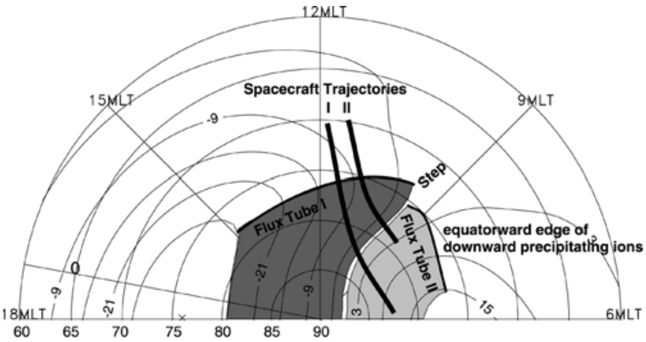

Figure 1. Ionospheric convection cells as routinely measured by the Super Dual Auroral Radar Network (SuperDARN) HF radar array. To illustrate how major cusp structures could be spatial instead of temporal, two flux tubes and two satellite trajectories have been superimposed on the convection cells.

dispersion signature at both spacecraft was interpreted as a spatial structure rather than a temporal variation. *Trattner et al.* [1999] compared two conjugated cusp crossings from Interball and Polar and found that complicated cusp structures appeared to be stable and unchanged for 1.5 hours. In a subsequent study, *Trattner et al.* [2002] compared four conjugated cusp crossings of Polar and Fast Auroral Snapshot (FAST) separated in universal time and magnetic local time (MLT) of up to 5 hours and up to 3 hours, respectively. While individual cusp crossings for different solar wind conditions are very different, cusp crossings by two satellites during stable solar wind conditions are remarkably similar. Based on these observations, *Trattner et al.* [2002] concluded that the major cusp structures they examined are not the signature of pulsed reconnection; rather, they are explained as spatial in nature and do not convect poleward.

[4] For interplanetary magnetic field (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 along the reconnected magnetic field lines and propagate to the cusp regions. Figure 1 shows a schematic representation of two flux tubes superimposed onto ionospheric convection patterns typical for southward IMF. Convection patterns are routinely measured by the Super Dual Auroral Radar Network (SuperDARN) HF radar array [e.g., *Greenwald et al.*, 1995] and commonly presented as equipotential maps [e.g., *Ruohoniemi and Baker*, 1998]. Also shown are the magnetic ground tracks of two spacecraft. The equatorward edge of the 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, the spacecraft will observe a discontinuous step in the 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 [*Trattner et al.*, 2002]. This interpretation is also in agreement with FAST observations by *Su et al.* [2001], who concluded that major ion structures observed in the cusp are the result of the spacecraft crossing flow streamlines. The classical pulsed reconnection scenario is not sufficient to explain these spatial structures.

[5] It has been pointed out by *Trattner et al.* [2002] that the interpretation of major cusp structures as spatial features does not eliminate pulsed reconnection as an important process at the magnetopause. Signatures of reconnection pulses, moving cusp structures, could be observed within one flux tube. This would, in principle, be in agreement with the observation of poleward moving transients in radar data [e.g., *Lockwood et al.*, 1995]. While major cusp structures observed by Polar and FAST were very similar, there was also 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 of the reconnection rate at the X-line are also small. Reconnection would not switch off completely but would be a continuous process.

[6] Since major cusp structures appear to be spatial features representing the boundary between different flux tubes which emanate from multiple X-lines, the shape and appearance of major cusp structures should depend mainly on the IMF conditions and the local time position of the observing satellites (see Figure 1). Therefore similar steady IMF conditions will result in a similar configuration of X-lines at the magnetopause, which in turn will result in similar spatial cusp structures. The purpose of this paper is the comparison of cusp events with similar steady IMF conditions to verify that cusp structures for different events under these conditions appear similar for all spacecraft flying through them, independent of altitude and time. We will use observations from two spacecraft, Polar and FAST, and investigate three dayside cusp passes in the noon and morning magnetic local time sectors with spacecraft separations in magnetic local time and time of ~1 hour. A comparison of cusp ion dispersion signatures observed during these intervals revealed that cusp structures observed at Polar and FAST are very similar for all events. This result reconfirms that major steps in the cusp ion energy dispersion are the result of spatial structures and not temporal variation in reconnection parameters.

2. Instrumentation and Data Selection

[7] 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].

[8] 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).

[9] 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

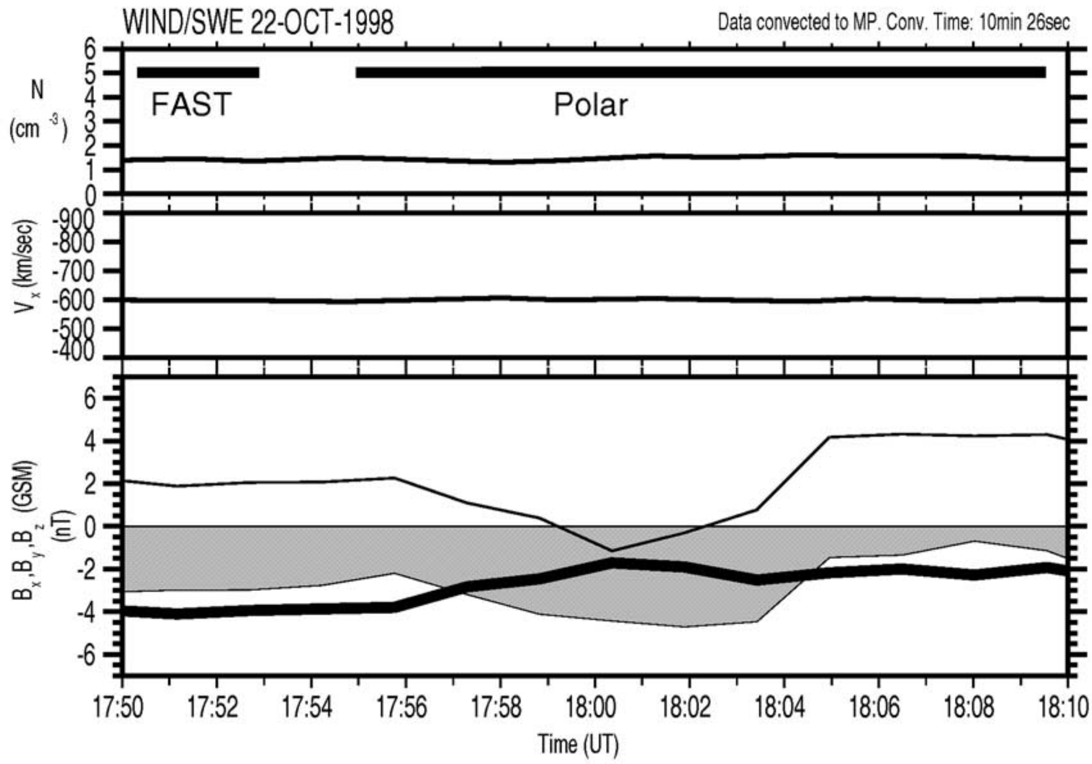

Figure 2. Solar wind parameter measurements by Wind/Solar Wind Experiment (SWE) and Magnetic Fields Investigation (MFI) upsteam of the Earth's bow shock on 22 October 1998. The data have been propagated by ~10 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are 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 Auroral Snapshot (FAST) crossed the cusp, illustrating the temporal separation of the spacecraft.

are observed at altitudes of ~3000 km in the cusp with an orbit inclination of 83°.

[10] In addition to the plasma observations in the cusp, Wind (Magnetic Fields Investigation (MFI) and Solar Wind Experiment (SWE)) data provided by the International Solar Terrestrial Physics (ISTP) key parameter Web page are used as solar wind context measurements [*Lepping et al.*, 1995; *Ogilvie et al.*, 1995]. As in the work of *Trattner et al.* [2002], we have selected cusp events with stable and similar solar wind conditions, especially stable and similar IMF conditions, to ensure similar locations of X-lines at the magnetopause and to avoid changes in cusp structures due to changes in the location of the X-line.

[11] We have selected three Polar cusp crossings together with the corresponding closest FAST cusp crossings in the northern polar cusp. The Polar and FAST cusp ion dispersion signatures are cross-checked to allow a distinction of temporal and spatial structures in the cusp (as described below). In addition, each event will be compared with the other events to determine if similar solar wind conditions cause similar cusp structures. This study will focus on H^+ measurements and investigate only major jumps in the cusp ion energy dispersion.

[12] Figure 1 shows that satellites at different local times will encounter the downward precipitating ion region at different ILAT. In addition, the spatial coverage of a cusp structure and the location of cusp steps will depend on the spatial location and shape of the flux tube. Therefore a comparison of cusp structures based simply on ILAT is not useful. To avoid effects on the cusp location in ILAT due to different local time position of the spacecraft, we follow *Trattner et al.* [1999, 2002] 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.

[13] It should be noted that due to the large altitude separation of Polar and FAST (up to 8 R_E), the spacecraft cross the cusp with vastly different velocities. This velocity difference has direct consequences of how temporal convecting cusp structure would appear at the observing spacecraft. 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. In the case of temporal structures, 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. FAST would

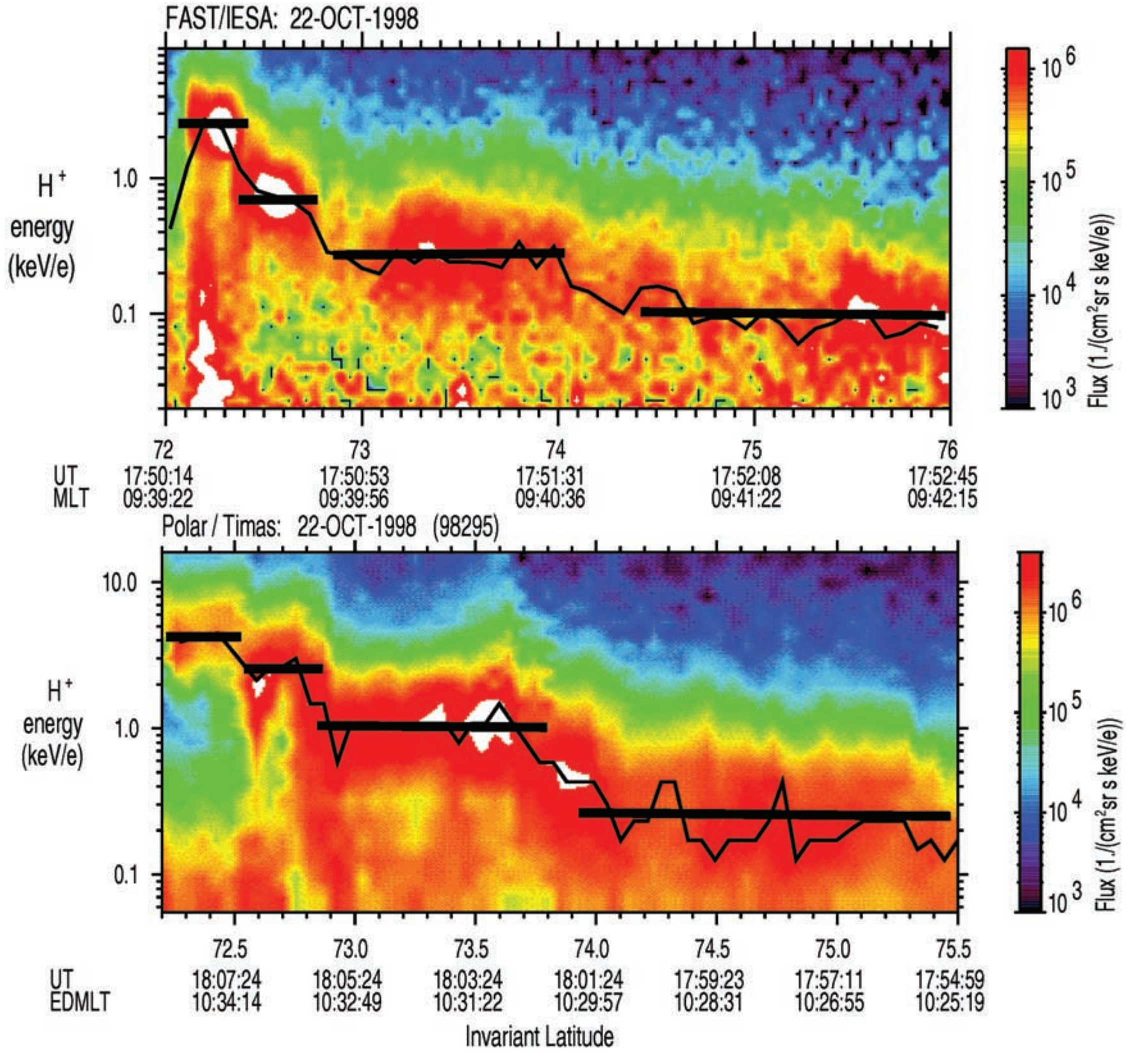

Figure 3. Comparison of FAST/IESA and Polar/Toroidal Imaging Mass-Angle Spectrograph (TIMAS) flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 22 October 1998. The observations are separated by ~1 hour in MLT and 20 min in UT. The cusp structures in the ion dispersion signatures are interpreted as spatial structures rather than temporal variability in the reconnection rate.

cross from a "new" flux tube into an "older" one, encountering a step-down in the cusp ion energy dispersion. In addition, Polar and FAST cross the cusp in 1–2 hours and 3 min, respectively. If temporal structures exist, caused by, for example, regular pulsations of the reconnection rate, Polar should encounter many more cusp steps than FAST while crossing the downward precipitating ion region. In summary, by comparing Polar and FAST cusp crossings, any temporal structures should not only be convected with the solar wind and encountered at different latitudes, the spacecraft should encounter different numbers of steps and the steps should appear different at the two spacecraft used in this study.

3. Event 1: 22 October 1998

[14] Event 1 compares Polar and FAST cusp crossings on 22 October 1998, separated by up to 20 min in UT and by ~1 hour in MLT. The spacecraft cross through the cusp in the morning sector at ~ 1030 MLT (Polar) and 0940 MLT (FAST) in opposite directions with Polar moving equatorward and FAST moving poleward. Figure 2 shows solar wind observations by Wind/SWE and Wind/MFI for the Polar and FAST cusp crossings on 22 October 1998. The data have been propagated by ~10 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. The solar wind density and velocity were ~1.5 cm^{-3} and 600 km s^{-1}, respectively. The IMF observations indicate that B_z was southward for the entire interval with an average value of about −3 nT, B_y was at ~3 nT with a brief negative period at 1801 UT, and B_x was also negative with an average value of about −3 nT.

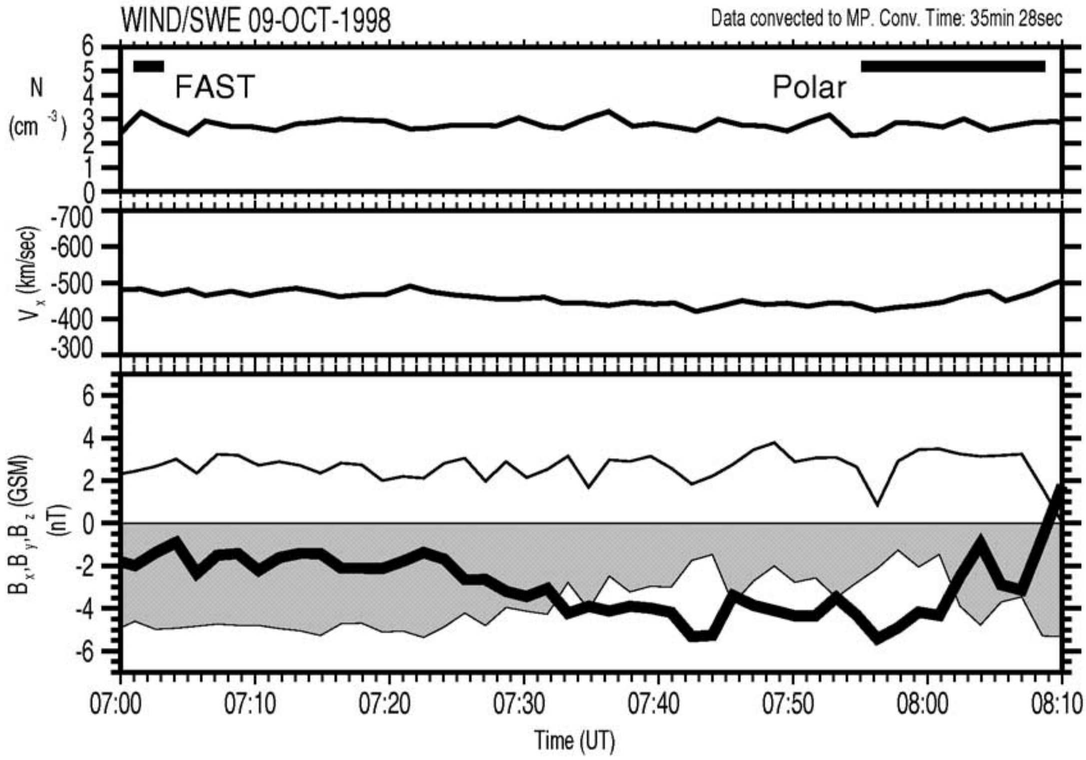

Figure 4. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 9 October 1998. The data have been propagated by ∼35 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density *N*, solar wind velocity V_x, and the 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, illustrating the temporal separation of the spacecraft.

[15] A comparison of Polar and FAST flux measurements (1./(cm^2 s sr keV/e) for the cusp crossings on 22 October 1998 is shown in Figure 3. Plotted are H^+ flux measurements as observed by the IESA (Figure 3, top) and TIMAS (Figure 3, bottom) instruments on FAST and Polar, respectively. White regions in the color-coded flux plot indicate regions with flux levels above the maximum indicated flux level in the color bars. Note that 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. Also indicated in the Polar and FAST flux panels is the energy where the maximum flux in the cusp ions occurred. To guide the eye, additional lines have been overlaid to emphasize structures in the ion energy distribution. Both spacecraft observe a distinctive energy-latitude dispersion typical for southward IMF [e.g., *Reiff et al.*, 1977] with the highest-energy ions arriving at the lowest ILAT and lower-energy particles arriving at successively higher latitudes [e.g., *Rosenbauer et al.*, 1975; *Shelley et al.*, 1976]. However, the continuously decreasing ion energy dispersions at both spacecraft are interrupted by three steps.

[16] The FAST spacecraft, moving poleward, entered the cusp at ∼1750 UT, crossed the downward precipitating ion region in 3 min, and moved onto lobe field lines. The FAST cusp crossing is characterized by three major steps in the ion energy dispersion, which are located at 72.3°, 73.°, and 74.2° ILAT. The cusp ion energy decreased sharply from ∼3 keV to 700 eV and subsequently to 300 eV for the first two steps. These two cusp steps are followed by a smoother decrease of the cusp ion energy to ∼100 eV.

[17] The Polar spacecraft, moving equatorward, crossed the cusp in ∼20 min and left the precipitating ion region at 1810 UT, 20 min later then FAST. In agreement with the cusp structures observed by FAST, the Polar cusp crossing is also characterized by three steps in the ion energy dispersion located at 72.6°, 72.9°, and 73.8° ILAT. As in the FAST cusp observations, the first two steps show sharp decreases of the cusp ion energy from 4 keV to ∼1.5 keV and subsequently to 1 keV, followed by a smoother decrease to ∼200 eV. Comparing the Polar observations with FAST observations, we find that while the spacecraft encounter cusp steps at slightly different latitudes, they have not moved within the cusp. This is in agreement with a spatial interpretation of cusp structures. The differences in the cusp ion energies can be attributed to the separation in local time of the two spacecraft and the subsequent different locations where the spacecraft enter neighboring flux tubes with their independent time history since reconnection. The cusp ion energy is also influenced by the location of the X-line and the degree of acceleration of the ions as they cross the dayside magnetopause [e.g., *Lockwood and Smith*, 1992].

[18] By comparing the Polar and FAST cusp crossings, there is no indication that Polar observed a different number

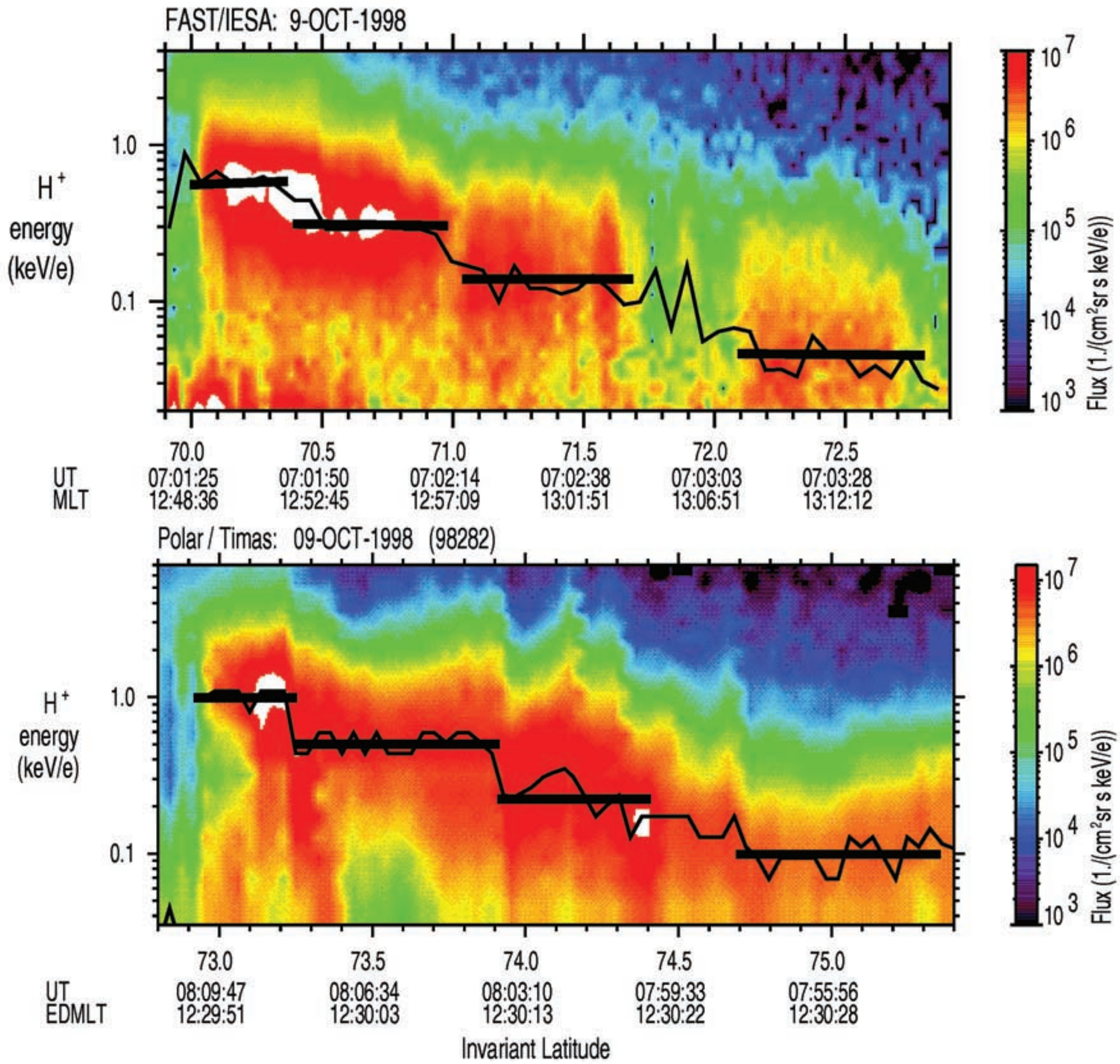

Figure 5. Comparison of FAST/IESA and Polar/TIMAS flux measurements (1./(cm^2 s sr keV/e)) for cusp crossings on 9 October 1998. The observations are separated by ~30 min in MLT and 1 hour in UT. As in the 22 October event, the cusp ion dispersion signature shows three steps.

of major cusp steps than FAST, as we would expect for temporal structures. There is also no indication that FAST encountered a "step-down" in the ion energy dispersion signature while Polar encountered a "step-up," which is also expected for the observations of temporal structures by spacecraft with large altitude separations. Both spacecraft observed the same number and orientation of cusp structures which also have not moved (convected) relative to each other, as expected for temporal cusp features. Thus, we conclude that Polar and FAST encountered spatial features inside the cusp.

4. Event 2: 9 October 1998

[19] Event 2 compares Polar and FAST cusp crossings on 9 October 1998 with a separation of 30 min in MLT and 1 hour in UT. The spacecraft crossed the cusp around local noon at 1230 MLT (Polar) and 1300 MLT (FAST) and moved again in opposite directions with Polar moving equatorward and FAST moving poleward. Figure 4 shows solar wind observations by Wind/SWE and Wind/MFI for the Polar and FAST cusp crossings on 9 October 1998. The data have been propagated by ~35 min to account for the travel time from the Wind spacecraft to the magnetopause. The format of Figure 4 is the same as that in Figure 2. For the entire interval the solar wind conditions were stable with similar IMF conditions in orientation and magnitude as observed for event 1. The solar wind density was ~3 cm^{-3}, and the solar wind velocity was ~460 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, and B_x was at about -3 nT.

[20] A comparison of the Polar and FAST cusp passes on 9 October 1998 is shown in Figure 5. The format in Figure 5 is the same as that in Figure 3. Also indicated in the Polar and FAST flux panels is the energy where the maximum

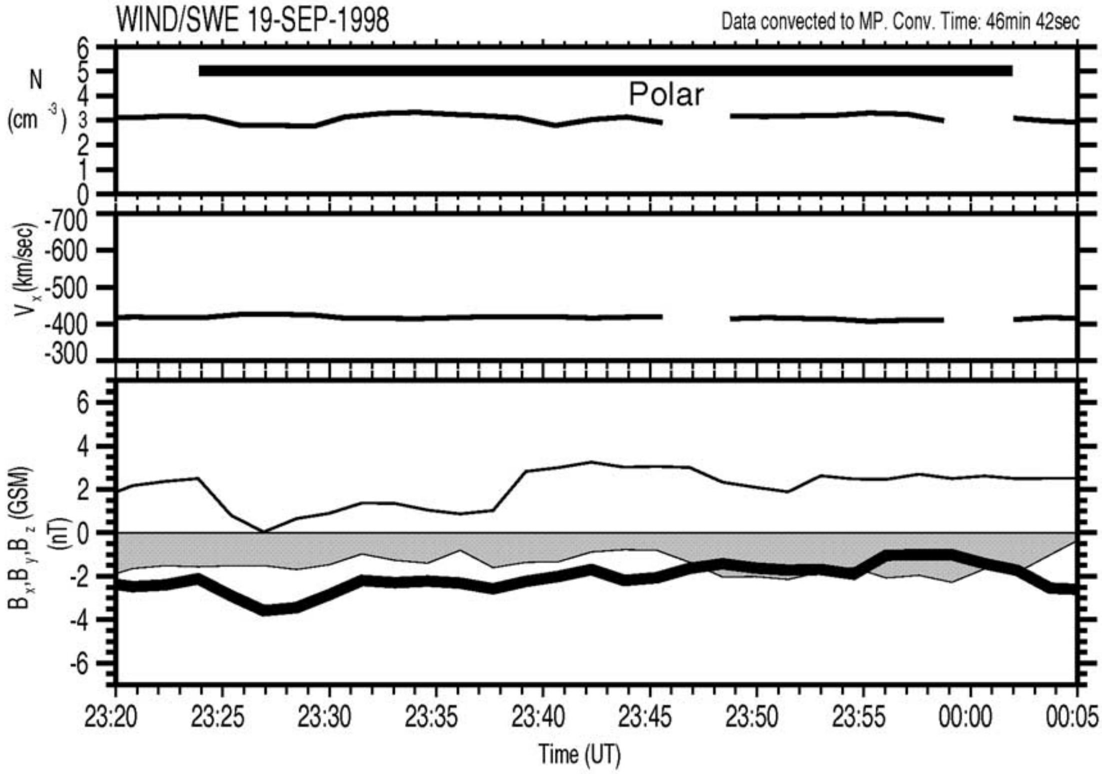

Figure 6. Solar wind parameter measurements by Wind/SWE and MFI upsteam of the Earth's bow shock on 19 September 1998. The data have been propagated by ~47 min to account for the travel time from the Wind spacecraft to the magnetopause. Plotted are solar wind density *N*, solar wind velocity V_x, and the magnetic field components B_x (thick line), B_y (thin line) and B_z (shaded area). The solar wind and IMF conditions are again similar compared to the previous examples.

flux in the cusp ions occurred together with additional lines to emphasize the steps in the cusp ion energy dispersion. The FAST spacecraft, moving poleward, entered the cusp at ~0701 UT at 70.° ILAT and crossed the downward precipitating ion region in ~3 min. The FAST cusp crossing is characterized by a classical downward step structure, featuring three steps at 70.4°, 71.°, and 71.9° ILAT. The first two steps are sharp decreases from 600 eV to 300 eV and to 150 eV followed by a smooth decrease to 50 eV on step 3.

[21] The Polar spacecraft, moving equatorward, crossed the cusp in ~20 min and left the precipitating ion region at ~0810 UT at 73.° ILAT. As observed in the FAST cusp pass, the Polar cusp pass shows three steps in the cusp ion energy dispersion at 73.25°, 73.9°, and 74.6° ILAT. The first two steps are sharp decreases in energy from ~1 keV to 500 eV and subsequently to 200 eV. The third step shows a smoother decrease to ~100 eV. As in event 1, Polar and FAST observe nearly the same major structures. These structures are also very similar to the ones in event 1, confirming that similar solar wind and IMF conditions are causing similar spatial cusp structures.

[22] The Polar cusp crossing also shows additional steps and variations inside the individual structures (e.g., the enhancement in energy at ~74.1° ILAT). It has been argued by *Trattner et al.* [2002] that these features could be the result of relatively small variations of the reconnection rate at the magnetopause. Several comparisons of Polar and FAST cusp crossings for different solar wind conditions revealed that Polar encounters more of these minor structures than FAST. This is consistent with the fact that Polar crosses the cusp slower than FAST and has more time to encounter convecting temporal features. If there are variations in the reconnection rate, then they are relatively small compared to the switch on and switch off of magnetic reconnection as suggested by *Lockwood and Smith* [1992].

5. Event 3: 19 September 1998

[23] No FAST data could be obtained for event 3 on 19 September 1998. However, the solar wind conditions and the Polar cusp crossing are similar to those in events 1 and 2, confirming that similar solar wind conditions are causing similar cusp structures. The Polar spacecraft crossed the cusp equatorward in ~40 min and was on field lines mapping to ~1115 MLT. Figure 6 shows solar wind observations by Wind/SWE and Wind/MFI for the Polar cusp crossings on 19 September 1998. The data have been propagated by ~47 min to account for the travel time from the Wind spacecraft to the magnetopause. The format of Figure 6 is the same as that in Figure 2. The solar wind density during the Polar cusp crossing was ~3 cm^{-3} with a solar wind velocity of ~420 km s^{-1}. The IMF observations indicate that B_z was again southward for the entire interval

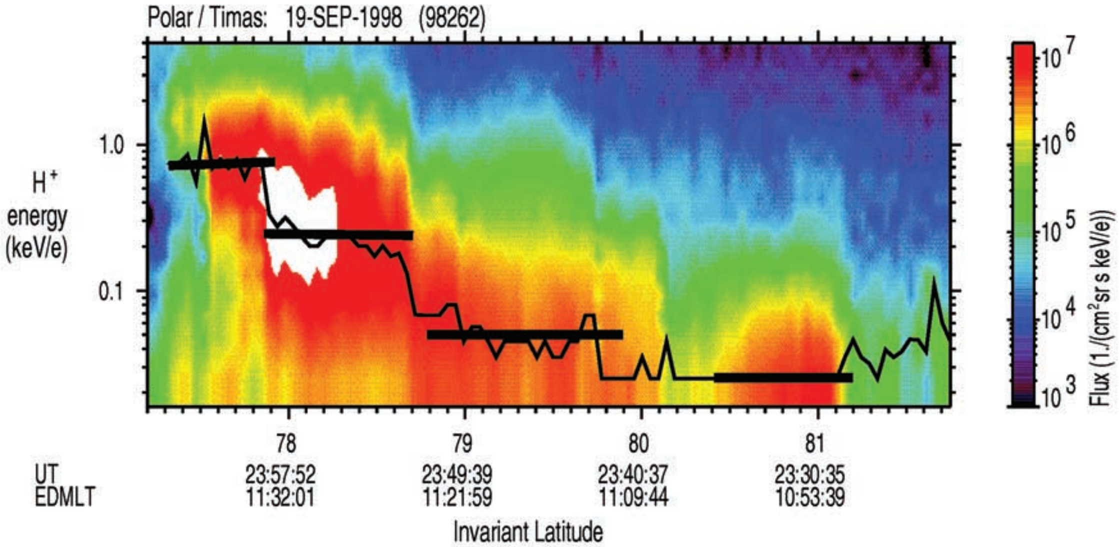

Figure 7. Flux measurements (1./(cm^2 s sr keV/e)) by Polar/TIMAS for cusp crossings on 19 September 1998. As in the previous examples, the cusp ion energy dispersion shows three major steps.

with an average value of about -1.6 nT; B_y was positive with an average value of ~2 nT, and B_x was negative with an average value of about -2 nT. Thus the solar wind conditions were stable with similar IMF conditions in orientation and slightly smaller magnitudes as observed for event 1 and 2.

[24] The Polar cusp pass on 19 September 1998 is shown in Figure 7. The format in Figure 7 is the same as that in Figure 3. The Polar spacecraft left the precipitating ion region at ~0003 UT (20 September) at 77.3° ILAT. The cusp crossing is characterized by the well-known velocity dispersion with the highest-energy ions at the lowest latitudes and ions with decreasing energies at higher latitudes. The Polar cusp crossing also shows three steps in the cusp ion energy dispersion at 77.9°, 78.7°, and 79.9° ILAT. The first two steps are sharp decreases in energy from ~800 eV to 250 eV and subsequently to 60 eV. The third step shows a smoother decrease to ~30 eV. The Polar cusp crossing in this event show the same major features as the other two events with similar IMF conditions.

6. Conclusion and Summary

[25] We have analyzed three cusp crossings by Polar and FAST to show that stable and similar solar wind conditions result in similar spatial cusp structures. Nearly magnetic conjugate observations by Polar and FAST have been used to ensure that structures encountered in the cusp are indeed spatial and not the result of temporal variations of the reconnection rate. The large altitude separation of Polar and FAST is ideal to distinguish between spatial and temporal structures and has several advantages over satellites crossing the cusp at about the same altitude.

1. The low orbiting FAST spacecraft spends an average 3 min in the cusp. In contrast, Polar cusp crossings can last several 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. For the events used in this study, Polar cusp crossings times were on the order of 30 min.

2. In the case of convecting structures [e.g., *Lockwood et al.*, 1995], the number of structures encountered by Polar and FAST should be vastly different. If cusp structures are caused by pulsed reconnection and we assume a constant pulsation rate of the order of several minutes, FAST with an average cusp crossing time of 3 min should encounter only about one structure during its cusp passage. In contrast, Polar observes the cusp more than 10 times longer than FAST and should encounter many more steps. The actual rate of steps observed by FAST and Polar will depend on the relative velocity of convecting cusp steps to the spacecraft velocities. However, if cusp structures are spatial, the relative velocities of the two spacecraft should have no influence on the number of structures encountered.

3. Polar and FAST cross the cusp with vastly different velocities. This velocity difference has direct consequences on how cusp structure appears to observing spacecraft. 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. 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. FAST would cross from a "new" flux tube into an "older" one, encountering a step-down in the cusp ion energy dispersion. The fact that Polar is moving equatorward during the events in this study only enhances that effect.

[26] By using Polar and FAST cusp crossings, temporal structures should not only be convected with the solar wind and appear in different numbers in the cusp, they should also appear different at the two spacecraft used in this study.

Spatial structures on the other hand should show none of these features.

[27] The comparison of Polar and FAST structures in this study showed that cusp structures were not moving with respect to each other. Both spacecraft encountered the same number of structures. The steps also appeared to be in the same direction in agreement with a spatial interpretation of cusp structures. This interpretation is also in agreement with several recent papers [e.g., *Onsager et al.*, 1995; *Trattner et al.*, 1999, 2002] which showed evidence that structures observed in the cusp ion energy dispersion signature could be a spatial feature. The spatial interpretation is 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].

[28] In addition, we have selected events with similar solar wind IMF conditions. The solar wind density was $\sim$3 cm^{-3} with solar wind velocities below 600 km s^{-1}. Especially important are the IMF components, since they will define the location of the reconnection line and subsequently the structures in the cusp. The magnitude for the IMF components during all events, B_x, B_y, and B_z, was $\sim$3 nT with negative B_x and B_z orientations and a positive B_y component. Our analysis showed that all events for these solar wind conditions had the same sequence of cusp steps, two sharp drops in the ion energy dispersion followed by a smoother transition to another energy level. In contrast, *Trattner et al.* [1999, 2002] discussed cusp structures for various solar wind and IMF conditions finding significantly different cusp structures. However, in the cases presented here, cusp structures observed during conjugate cusp crossings by two spacecraft and stable solar wind conditions are similar.

[29] These remarkably similar cusp structures are interpreted as spatial structures, a result of spacecraft crossing into neighboring flux tubes as depicted in Figure 1. For IMF conditions with a significant B_y component (like the conditions in this study), there will be antiparallel merging regions in the Northern and Southern Hemispheres. These regions of different flux tubes with different reconnection history map to different locations in the cusp. As spacecraft cross the boundary between the flux tubes, they observe a step in the cusp ion energy dispersion. Differences in the cusp position and the position of cusp steps at the two spacecraft are the simple consequence of the shape of the equatorward edge of the cusp and the shape of the flux tube, respectively.

[30] The example in Figure 1 illustrates only the existence of one spatial step in the ion energy dispersion, while the Polar and FAST observations show three steps. A comparison of the cusp crossings with available ionospheric convection pattern showed only a partial overlap of the Polar and FAST magnetic ground tracks and the convection cells. These partial overlaps are not enough to clearly indicate the existence of three steps as observed. An additional explanation could be the existence of multiple X-lines and therefore multiple flux tubes within the same convection cell.

[31] The observed cusp precipitating ion energy on Polar seams to be higher compared to the ion energy on FAST. The reason for the offset in energy between Polar and FAST could be their location relative to each other in the flux tube. A satellite in a position further downstream in the flux tube would see lower energies. Using the available partial convection cells, this scenario could not be confirmed without a doubt. Another possibility could be an altitude effect since the ions cross the acceleration region between the spacecraft.

[32] Future work will need to focus on the comparison of cusp structures with ground-based observations of radar or magnetometer arrays in order to find a match between cusp structures and convection boundaries. For spatial cusp structure the plasma flow must be parallel to the cusp step on both sides of the boundary. This requirement is in disagreement with an event study by *Lockwood et al.* [1995], who used data from the DSMP spacecraft together with EISCAT radar observations and showed a flow across the cusp structure. A link between spacecraft observations and ground-based data is essential to fully understand cusp structures and the role of reconnection at the magnetopause.

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