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- Methodology to distinguish pulsed from continuous reconnection
- Determine the reconnection time for cusp magnetic field lines
- Determine the reconnection location simultaneously

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Distinguishing between pulsed and continuous reconnection at the dayside magnetopause

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Abstract Magnetic reconnection has been established as the dominant mechanism by which magnetic fields in different regions change topology to create open magnetic field lines that allow energy and momentum to flow into the magnetosphere. One of the persistent problems of magnetic reconnection is the question of whether the process is continuous or intermittent and what input condition(s) might favor one type of reconnection over the other. Observations from imagers that record FUV emissions caused by precipitating cusp ions demonstrate the global nature of magnetic reconnection. Those images show continuous ionospheric emissions even during changing interplanetary magnetic field conditions. On the other hand, in situ observations from polar-orbiting satellites show distinctive cusp structures in flux distributions of precipitating ions, which are interpreted as the telltale signature of intermittent reconnection. This study uses a modification of the low-velocity cutoff method, which was previously successfully used to determine the location of the reconnection site, to calculate for the cusp ion distributions the “time since reconnection occurred.” The “time since reconnection” is used to determine the “reconnection time” for the cusp magnetic field lines where these distributions have been observed. The profile of the reconnection time, either continuous or stepped, is a direct measurement of the nature of magnetic reconnection at the reconnection site. This paper will discuss a continuous and pulsed reconnection event from the Polar spacecraft to illustrate the methodology.

1. Introduction

Magnetic reconnection is one of the fundamental processes in space science and has been studied extensively with in situ observations of accelerated ion beams at the dayside magnetopause [e.g., Gosling *et al.*, 1990; Phan *et al.*, 2000; Trenchi *et al.*, 2008; Fear *et al.*, 2010, 2012; Fuselier *et al.*, 2011, 2012; Griffiths *et al.*, 2011; Trattner *et al.*, 2012a], precipitating ions in the cusp region of the magnetosphere where all the dayside magnetic field lines converge within a relatively confined space [Cowley *et al.*, 1991; Lockwood and Smith, 1992; Onsager *et al.*, 1993; Lockwood *et al.*, 1998; Fuselier *et al.*, 2000a; Escoubet *et al.*, 2008, 2013; Trattner *et al.*, 2007, 2012b], and ionospheric imagers and radar observations [Lockwood, 1995; Milan *et al.*, 2000; McWilliams *et al.*, 2001; Fuselier *et al.*, 2002; Frey *et al.*, 2003].

Once a geomagnetic field line is opened and begins convecting with the solar wind, there is a continuous stream of magnetosheath ions that travels along this field line toward the magnetospheric cusp regions. Precipitating ions in the cusp exhibit a distinctive dispersion profile caused by the joint action of newly opened and convecting field lines together with the different flight times of the ions from the injection point at the magnetopause to the observing satellite. During southward interplanetary magnetic field (IMF) conditions and subsequent poleward convecting flux tubes, high-energy ions from the magnetosheath are encountered close to the open-closed field line boundary, while lower energy particles arrive at successively higher latitudes. This velocity filter effect for reconnection during southward IMF conditions was predicted by Rosenbauer *et al.* [1975] and first observed by Shelley *et al.* [1976].

For a steady rate of reconnection at the magnetopause, the energy profile of downward precipitating ions should exhibit a smooth and continuous latitudinal dispersion on these open cusp field lines [e.g., Onsager *et al.*, 1993; Lockwood, 1997]. The most prominent example for steady, continuous reconnection at the magnetopause is the multispacecraft observation of a reconnection event by the Cluster and IMAGE satellites in the northern magnetosphere. The Cluster satellites on an outward trajectory crossed the magnetopause and observed a reversal of the accelerated ion beams from the reconnection site in the boundary layers. The

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reversal indicated that the spacecraft was at or very close to the reconnection site. Simultaneously, the IMAGE satellite observed a continuous bright spot poleward of the auroral oval in the ionosphere caused by the precipitating magnetosheath ions [e.g., *Frey et al.*, 2003; *Phan et al.*, 2003]. Using a magnetic field model to trace the location of the Cluster satellites at the newly reconnected field line to the ionosphere, it was demonstrated that the location of the spot coincided with the predicted footpoint of the reconnected field line. This bright spot in the ionosphere was observed for hours, and the stability of the spot was interpreted as evidence for a continuous reconnection process.

However, cusp ion precipitation does not always exhibit a smooth profile with invariant latitude. It generally shows flux variations and sudden changes in the cusp ion dispersion signature. These complicated structures are known as “stepped” or “staircase” cusp ion signatures 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].

The stepped or staircase cusp ion signatures have been interpreted as signatures for the temporal nature of the reconnection process, and their existence was predicted by the pulsating cusp model [e.g., *Lockwood and Smith*, 1989, 1990, 1994; *Cowley et al.*, 1991; *Smith et al.*, 1992]. These steps occur during periods of little or no reconnection between pulses. Magnetic tension and shocked solar wind flow convect these pulses poleward, providing an ever-changing cusp profile for the observing satellite. The time between reconnection pulses has been observed to be short. Using 21 DMSP crossings, *Newell and Meng* [1995] showed that reconnection would rarely completely stop for more than 1 min. Later, *Lockwood et al.* [1998] demonstrated that the precipitating and mirroring ions are well modeled by a series of reconnection pulses lasting 0.5–2.5 min separated by 1–3 min of slow (or no) reconnection. *Smith and Lockwood* [1990] pointed out that the reconnection rate variations thought to be responsible for magnetopause flux transfer events (FTEs) should also cause the cusp to vary on time scales of about 2–20 min. This pulsating cusp model reduces to a steady state cusp with constant reconnection rate at one limit and a cusp observed as a series of discrete events (bursts) at the other limit.

Cusp steps have also been interpreted as spatial structures [e.g., *Lockwood and Smith*, 1992] caused by changing solar wind parameters or changes in the magnetosheath ion populations. There is also evidence that cusp steps can be produced in steady state by spatial variations within the cusps. These spatial variations are clearly identified using simultaneous observations of high- and low-orbiting cusp satellites [e.g., *Onsager et al.*, 1995; *Trattner et al.*, 2002, 2003].

In this study we use a modification of the low-velocity cutoff method [e.g., *Onsager et al.*, 1990; *Trattner et al.*, 2007] to determine Δt , the “time since reconnection” that has occurred for the cusp field line at the position of the satellite, which is subsequently used to calculate the actual reconnection time R_T (UT) for the field line. With the satellite progressing through the cusp to different magnetic field lines, these reconnection times are a direct measurement of the continuity or pulsation rate of the reconnection process at the dayside reconnection location. We use two cusp crossings by the Polar satellite to demonstrate this methodology for a continuous and for a pulsed reconnection event.

2. Instrumentation and Methodology

The two events analyzed in this study are selected from a northern hemisphere cusp survey containing about 1500 Polar cusp crossings. Ion distributions were obtained by the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) [*Shelley et al.*, 1995] on board the Polar spacecraft.

Polar/TIMAS proton measurements cover the energy range from 15 eV/e to 33 keV/e in 28 energy steps and provide 98% coverage of the unit sphere during a 6 s spin period. The Polar spacecraft was launched on 24 February 1996 into a nearly 90° inclination orbit with a perigee of about 2 R_E and an apogee of about 9 R_E . Polar crosses the cusp regions during two periods each year, with each period lasting several months. Cusp ion distributions are observed at altitudes between 3.5 and 9 R_E and up to 90° invariant latitude.

In addition to Polar ion data, solar wind context measurements observed by the Wind Magnetic Fields Investigation (MFI) [*Lepping et al.*, 1995] and the Wind Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995] are used. These data are provided by the International Solar Terrestrial Physics (ISTP) key parameter Web page. Solar wind observations are convected from the Wind spacecraft to the magnetopause using the observed solar wind velocity.

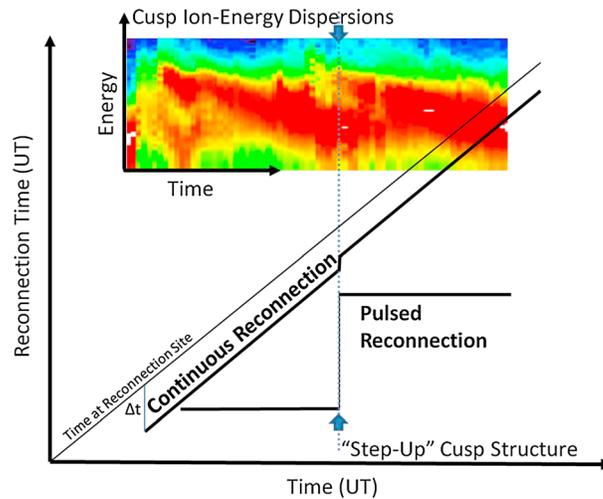


Figure 1. The reconnection time (RT) for cusp magnetic field lines versus unit time for continuous and pulsed reconnection. A high-altitude satellite such as Polar can be considered stationary in the cusp compared to the convection speed of the magnetic field lines by the solar wind. Sampling the reconnection time for these magnetic field lines as they convect over the satellite for a continuous reconnection event appears as a straight and positively sloped line segment(s) (thick black line), while a pulsed reconnection event would exhibit a stepped profile. The Δt is the delay time (time since reconnection) from when the magnetic field line was opened at the magnetopause to when the particle distribution reaches the satellite.

(earthward propagating) ions, and V_m is the cutoff velocity of the mirrored distribution [e.g., *Onsager et al.*, 1990; *Fuselier et al.*, 2000b]. X_m is determined by using the position of the Polar spacecraft in the cusp and tracing the geomagnetic field line at this position down to the ionosphere by using the Tsyganenko's (T96) model [*Tsyganenko*, 1995]. The location of the reconnection line at the magnetopause is determined by tracing the calculated distance to the reconnection site along the T96 model magnetic field lines back to the magnetopause. The method has been successfully used in several cusp studies and led to the development of the maximum magnetic shear model to predict the location of the reconnection line at the dayside magnetopause from solar wind parameters [e.g., *Fuselier et al.*, 2000b; *Trattner et al.*, 2007].

For the second step, we use the distance to the reconnection site X_r from equation (1) and the known cutoff speed of the precipitating ion distributions V_e to determine how long the present magnetic field line has been open, Δt , the time since reconnection occurred for the current plasma distribution on this field line.

$$\Delta t = X_r/V_e = 2X_m/(V_m - V_e) \quad (2)$$

The term time since reconnection was also used in modeling cusp dispersions and studies about flux transfer events (FTEs) [see, e.g., *Lockwood and Hapgood*, 1998]. However, with this method, we not only know the temporal evolution of cusp magnetic field lines but also the location and local conditions at the reconnection site.

To determine RT for the current cusp distribution, the time when the magnetic field line was opened and the magnetosheath distribution entered the now open field line, we subtract Δt from the current unit time UT of the cusp measurement. As we step in time through the observed distributions, the resulting profile for the reconnection time will reveal the continuous or pulsed nature of the reconnection process.

3. Observations

Figure 1 shows a schematic representation of the reconnection time RT (thick black lines) versus UT for continuous and pulsed reconnection as they would appear for a satellite crossing the cusp region. The thin

Measurements of TIMAS 3-D plasma distributions are used to first estimate the distance to the reconnection site and determine its location at the magnetopause. The procedure used for this distance estimate is generally known as the low-velocity cutoff method and is based on time-of-flight characteristics of precipitating ions in the cusp as first used by *Onsager et al.* [1990, 1991] in the Earth's plasma sheet boundary layer. Low-velocity cutoffs from precipitating and mirrored ion distributions in the cusp together with the known distance between the observing satellite and the ionosphere are used to estimate the distance from the observing satellite to the reconnection line X_r defined by

$$X_r/X_m = 2V_e/(V_m - V_e) \quad (1)$$

where X_m is the distance to the ionospheric mirror point, V_e is the cutoff velocity of the precipitating

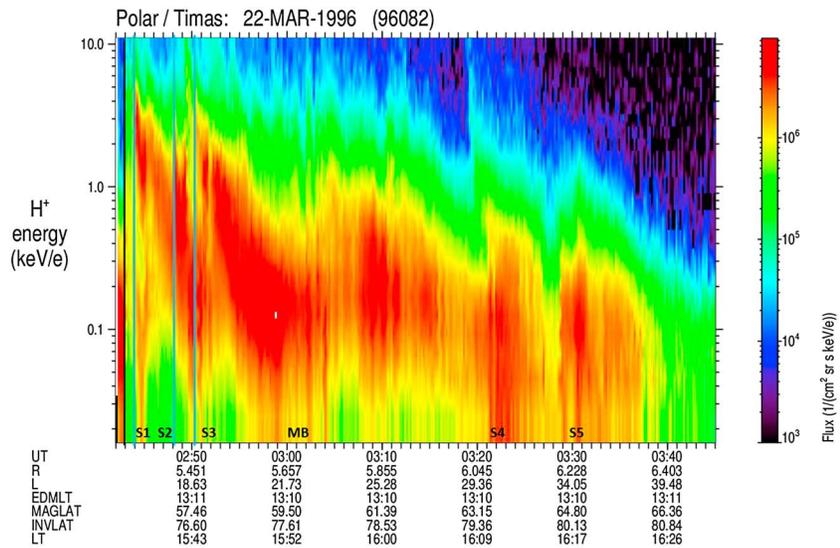


Figure 2. H^+ omnidirectional flux measurements ($1/(\text{cm}^2 \text{ s sr keV/e})$) observed by the TIMAS instrument on board the Polar satellite during a northern hemisphere cusp crossing on 22 March 1996. Polar was moving toward higher latitudes and encountered magnetosheath ions on open geomagnetic field lines at about 02:43 UT (black vertical line). The omnidirectional flux measurements reveal several cusp structures (S) and one large-scale motion of the boundary (MB). This study focuses on the first three step-up cusp structures (S1, S2, and S3) close to the open-closed field line boundary marked by blue vertical lines.

black line in Figure 1 represents $UT = RT$, the time at the magnetopause reconnection location. The inset shows color-coded flux measurements in an energy versus time representation for a typical high-altitude Polar cusp crossing with two distinctive cusp ion energy dispersions separated by a “step-up” cusp structure. The step-up cusp structure in the flux measurements is marked with a blue dotted line and characterized by a sudden increase in the energy of the precipitation ions in the cusp. Ions injected onto newly opened geomagnetic field lines at the reconnection site will travel the distance X_r in the time Δt to reach the observing cusp satellite.

If the reconnection process at the reconnection site is continuous in nature, then RT will appear as a continuous line, approximately parallel to the “present” throughout the cusp crossing. Different or changing Δt s between the present and RT can be attributed to (a) changes in the reconnection rate, (b) changes in the convection velocity of the cusp field lines, and/or (c) an increasing distance to the open-closed field line boundary (which increases Δt). For cusp crossings with step-up cusp structures as in the current example, RT will be a continuous line along the individual cusp structures with a brief step up at the encounter with the cusp step, indicating that either the reconnection process briefly ceased at the reconnection site or that the satellite entered into a spatial separated flux tube with its own RT emanating from a second reconnection line [Trattner et al., 2005].

If the reconnection process at the reconnection site was pulsed in nature, then RT will appear as a series of short, pulsed reconnection events with no reconnection activity at the reconnection site in between pulses [e.g., Smith et al., 1992; Lockwood and Smith, 1989, 1990, 1994]. For this condition, RT should exhibit a staircase profile with steps at the stepped ion energy dispersions. Within the individual cusp structures, RT would be constant, since all magnetic field lines for the cusp structure were opened in a short reconnection pulse.

The first event discussed in this study occurred on 22 March 1996. Figure 2 shows the H^+ omnidirectional flux measurements ($1/(\text{cm}^2 \text{ s sr keV/e})$) observed by the TIMAS instrument on board the Polar satellite during the 22 March 1996 cusp crossing. Polar was located in the postnoon sector around 13:00 magnetic local time (MLT) moving toward higher latitudes and encountered magnetosheath ions on open geomagnetic field lines at about 02:43 UT. Polar observed an overall ion energy dispersion typical for southward IMF conditions with the high-energy ions close to the open-closed field line boundary and lower-energy ions at subsequent

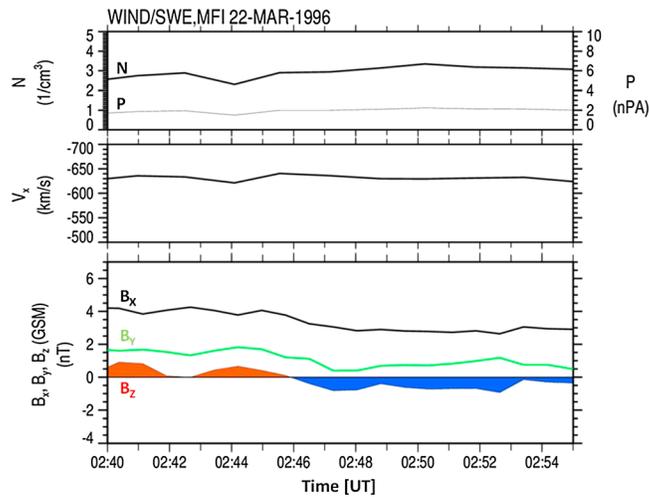


Figure 3. (top) Solar wind density, (middle) solar wind velocity, and (bottom) IMF conditions during the 22 March 1996 Polar/TIMAS cusp crossing. The event is characterized by a high solar wind speed of about 630 km/s and a dominant IMF BX component. The data are provided by the Wind SWE [Ogilvie et al., 1995] and MFI [Lepping et al., 1995] experiments and are convected to the magnetopause by about 9 min.

higher latitudes. The ion energy dispersion is interrupted by several cusp structures (S1 to S5) and a large-scale motion of the boundary (MB) [e.g., Trattner et al., 2003]. Polar remained in the cusp until about 03:55 UT.

At the open-closed field line boundary, the Polar satellite encounters three major step-up cusp structures in the ion energy dispersion (S1, S2, and S3, marked with blue vertical lines) followed by two more (S4 and S5) later during the cusp crossing. Such cusp structures, in agreement with the pulsating cusp model, are usually interpreted as the signature of temporal changes in magnetopause reconnection on open magnetic field lines. These observed changes in flux tubes are caused by changes in the reconnection rate at the

magnetopause and convect under the joint action of magnetic tension and momentum transfer from the shocked solar wind flow.

Such stepped cusp structures can also be caused by spatially separated flux tubes as a consequence of multiple reconnection lines [e.g., Newell and Meng, 1991; Onsager et al., 1995; Weiss et al., 1995; Wing et al., 2001; Trattner et al., 2002, 2005]. Distinguishing between temporal and spatial cusp structures can be achieved by determining their reconnection locations at the magnetopause with the above described low-velocity cutoff method. While temporal cusp structures map to the same location at the magnetopause [e.g., Trattner et al., 2008], spatial cusp structures map to separate locations/hemispheres [e.g., Trattner et al., 2005]. Both types of cusp structures manifest themselves as gaps (steps) in RT (see Figure 1) when the satellite crosses the boundary between neighboring flux tubes but do not provide insight into how continuous or pulsed the reconnection process was during the cusp structure.

At around 03:03 UT during the cusp crossing on 22 March 1996, TIMAS observed a gradual increase of the ion energy in the cusp before it reached another maximum at about 03:10 UT. Such gradual changes in the ion energy, in contrast to sudden step-up structures, are the result of reconfiguration of the convection path between the open-closed field line boundary and the satellite position. This feature has been discussed by Trattner et al. [2003] in a study with Cluster cusp crossings combined with the ionospheric convection pattern provided by Super Dual Auroral Radar Network radar observations. During the Cluster cusp crossing, the convection path between the open-closed field line boundary and the satellites was gradually shortened, bringing the Cluster satellites closer to the open-closed field line boundary and therefore onto field lines that have been reconnected more recently. For field lines that have been opened for shorter times, only ions with higher velocities can reach the observing satellites. Such a gradual increase of the precipitating ion energy was also present during the Polar cusp crossing on 22 March 1996 shown in Figure 2. However, for this study, only the first three major cusp steps are considered in the analysis of RT.

Another boundary motion is present in cusp structure S1 as a second maximum at about 02:45 UT. Cusp structure S2 also contains the signature of multiple reconnection lines at the magnetopause, with simultaneous (overlapping) ion energy dispersions at different energies for ions streaming parallel to the magnetic field. Both features have been discussed in detail in Trattner et al. [2012b].

Figure 3 shows the solar wind conditions from 02:40 UT to 02:55 UT observed during the three major cusp steps. The data from the Wind SWE [Ogilvie et al., 1995] and Wind MFI [Lepping et al., 1995] experiments have been convected by about 9 min to account for the travel time between the Wind satellite and the magnetopause.

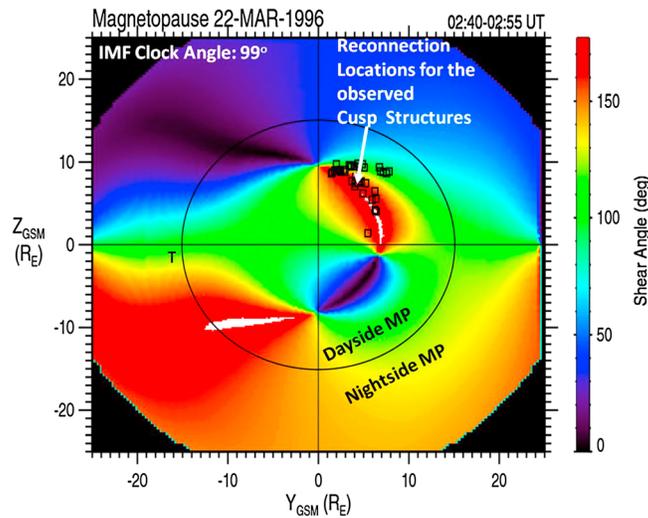


Figure 4. Magnetopause shear angle for the Polar cusp crossing on 22 March 1996 as seen from the Sun. The magnetopause shear angle was calculated using the magnetic field direction of the T96 model [Tsytanenko, 1995] combined with the fully draped IMF conditions at the magnetopause [Kobel and Flückiger, 1994] observed during the Polar cusp crossing. The white regions represent areas where the shear angle is within 3° of antiparallel. The black circle represents the magnetopause shape at the terminator plane (T). The black square symbols in the region where the magnetic fields are antiparallel show the location of the reconnection site determined by the low-velocity cutoff method [e.g., Onsager et al., 1990; Trattner et al., 2007].

The Wind satellite was located at about 54.6, 51.6, and 24.5 R_E for X, Y, and Z GSM, respectively. The average solar wind density, N , for this cusp event was about 3 cm^{-3} with a dynamic pressure, P , of about 2 nPa (Figure 3, top) and an average solar wind velocity, V , of about 630 km/s (Figure 3, middle). Figure 1 (bottom) shows the IMF components in GSM coordinates. The IMF is strongly dominated by the B_x component and shows a southward direction with a brief northward field at the beginning of the Polar cusp crossing until about 02:46 UT. The IMF is relatively stable throughout the event with 3.3, 1.1, and -0.2 nT for B_x (black line), B_y (green line), and B_z (colored area), respectively.

The low-velocity cutoffs of the mirrored and precipitating ion distributions are defined at the low-speed side of each beam where the flux is 1/e lower than the peak flux [see also Fuselier et al., 2000b; Trattner

et al., 2005]. The cutoff velocities determined from 3-D measurements by the TIMAS instrument are used in combination with equation (1) to calculate the distance to the reconnection site. Uncertainties in the distance calculation are defined as one half the difference between the peak velocity and the low-velocity cutoff with the associated error bars typically 1–2 R_E [see Trattner et al., 2007]. This distance is subsequently traced back to the magnetopause along T96 magnetic field lines. This methodology has been successfully used in several studies [e.g., Fuselier et al., 2000b; Trattner et al., 2007] and was essential in developing the maximum magnetic shear model to predict the dayside reconnection location as a function of the upstream solar wind and IMF conditions. The end points of the field line traces are marked with black square symbols in Figure 4, overlaid onto the magnetopause magnetic shear angle plot for the 22 March 1996 Polar cusp crossing, using the solar wind and IMF conditions from Figure 3. The dayside magnetopause magnetic shear angle was determined using the Kobel and Flückiger's [1994] analytical model as the external (magnetosheath) magnetic field and the T96 model at Sibeck et al.'s [1991] ellipsoidal magnetopause as the internal (magnetosphere) magnetic field. Differences in the magnetopause shapes between the two models are corrected by mapping the draped magnetosheath field conditions along the boundary normal onto Sibeck et al.'s [1991] magnetopause.

In Figure 4, the red areas show nearly antiparallel ($>150^\circ$ shear angle) magnetopause conditions, while the blue and black areas show locations where the merging fields become nearly parallel. The white areas in Figure 4 depict regions where the model magnetic fields are within 3° of antiparallel. The Polar cusp crossing occurred during an IMF clock angle of 99°, which resulted in antiparallel reconnection regions located in the southern dawn and northern dusk regions. The regions are asymmetric with respect to the hemisphere due to the dominant IMF B_x conditions. Note that dipole effects also cause asymmetries for the magnetic shear angles in the opposing hemispheres. These effects are automatically included in the T96 model for the magnetopause shear angle calculation but do not play a role during this spring equinox event. The black circle represents the location of the terminator plane (T) as it intersects the magnetopause, with the dayside magnetopause inside the circle and the nightside magnetopause outside the circle.

The field line trace points are located in the northern hemisphere along the dusk antiparallel reconnection region, extending from the northern cusp toward the equator. The grouping of the points in the antiparallel

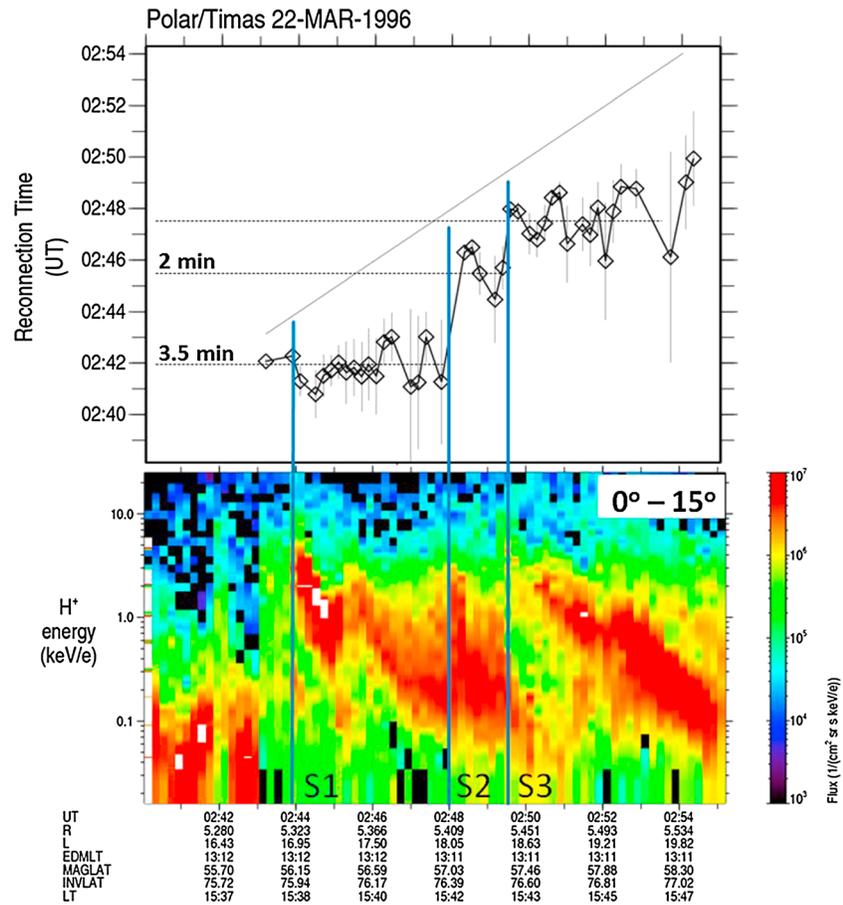


Figure 5. (top) The reconnection time for the cusp magnetic field lines during the encounter with these structures. The profile for the reconnection time shows for each cusp structure a specific time (pulse), 02:42 (S1), 02:45.30 (S2), and 02:47.30 UT (S3). The stepped appearance for the reconnection time indicates a pulsed reconnection event. (bottom) Flux measurements of precipitating ions in the pitch angle range from 0° to 15° observed by the TIMAS instrument on board the Polar satellite during a northern hemisphere cusp crossing on 22 March 1996. The blue lines mark the times when Polar encountered three step-up cusp structures (S1, S2, and S3).

reconnection region is consistent with B_x -dominant conditions in the maximum shear reconnection model [Trattner *et al.*, 2007; Fuselier *et al.*, 2011]. The location trace points also seem to bifurcate, with another location right next to the antiparallel shear angle region at the magnetopause. This bifurcation is the result of overlapping ion energy dispersions in cusp structure S2, indicating the existence of multiple reconnection lines discussed in Trattner *et al.* [2012b]. The common reconnection location of the trace points for all the cusp structures analyzed in this study indicates the existence of cusp structures with a temporal variability in the reconnection rate [e.g., Trattner *et al.*, 2008].

The information from the calculation of the distance to the reconnection site, X_r , is used to calculate Δt and RT as outlined in equation (2), which is displayed in Figure 5. Figure 5 (bottom) shows the flux measurements for precipitating ions in the pitch angle range from 0° to 15° during the 22 March 1996 Polar cusp crossing. The restriction in pitch angle was chosen to focus only on the incoming field-parallel magnetosheath distribution to identify cusp structures and eliminate gyroradius effects and to eliminate the ever present ion outflow distribution. In addition, only the first three cusp structures within the 02:40 to 02:55 UT time range are displayed. Previous studies using the low-velocity cutoff method in the cusp have shown that the precipitating, mirrored, and ion outflow distributions merge farther away from the open-closed field line boundary. This merging makes it more challenging to identify a clear separation of the peaks in order to determine the low-velocity cutoffs.

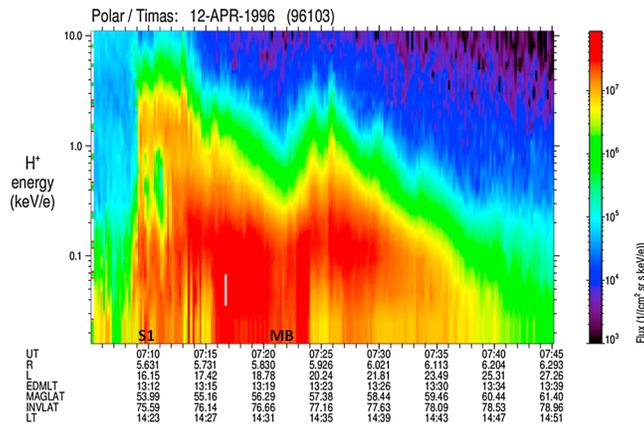


Figure 6. Plotted are H⁺ omnidirectional flux measurements (1/(cm² sr keV/e)) observed by the TIMAS instrument on board the Polar satellite during a northern hemisphere cusp crossing on 12 April 1996. Polar was moving toward higher latitudes and encountered magnetosheath ions on open geomagnetic field lines at about 07:09 UT. The omnidirectional flux measurements show the general ion energy dispersion for events with southward IMF conditions, dominated by one major cusp structure (S1) and a large-scale motion of the boundary (MB).

The locations of the three cusp steps used in this investigation are marked with vertical blue lines. Figure 5 (top) shows RT, the time when the field lines in the cusp encountered by the Polar satellite were reconnected at the magnetopause reconnection location. The first major cusp structure (S1) observed during the 22 March 1996 Polar cusp crossing was encountered by Polar at 02:44 UT. Figure 5 (top) reveals that the magnetic field lines were reconnected at the magnetopause 2 min earlier at 02:42 UT. RT further reveals that cusp structure S1 was caused by one brief reconnection pulse after which the reconnection process at the magnetopause

dramatically decreased or ceased altogether. Polar/TIMAS encountered all the field lines during the crossing of cusp structure S1 at about the same RT, even during the slight boundary motion that caused another maximum in the precipitating ion energy at 02:45:40 UT.

Cusp structure S2 was encountered by Polar/TIMAS at 02:48 UT. For this cusp structure, the average RT was at 02:45:30 UT, 3.5 min after the first reconnection pulse. Cusp structure S3 was encountered by Polar/TIMAS at 02:49:30 UT with an RT of 02:47:30 UT, 2 min after the last reconnection pulse. For all cusp crossings, RT is about constant during the crossings of the structures, indicating that this event is a pulsed reconnection event. The pulsation rate from 2 to 3.5 min is in agreement with the results reported by Lockwood and Wild

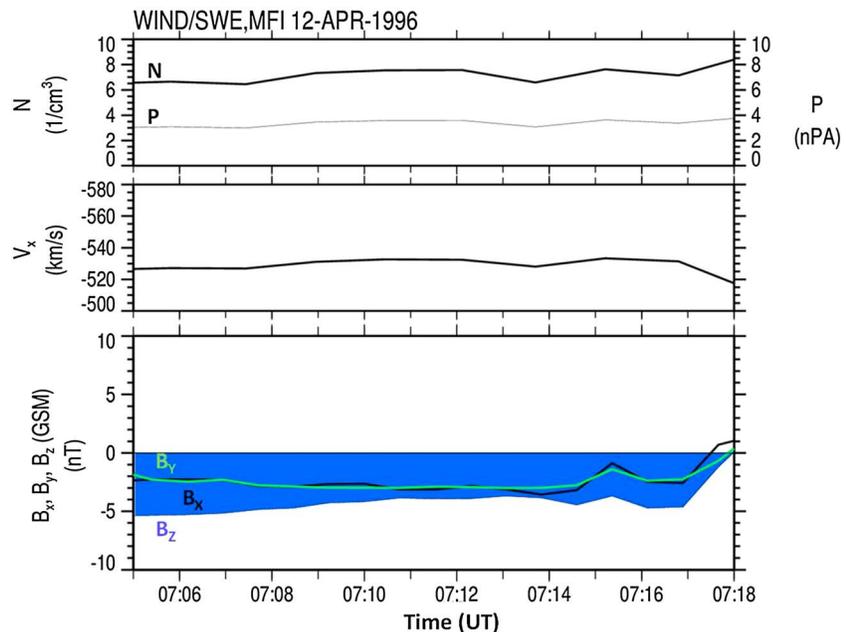


Figure 7. The solar wind and IMF conditions during the 12 April 1996 Polar/TIMAS cusp crossing. The layout is the same as Figure 3. The Wind observations are convected to the magnetopause by about 13 min.

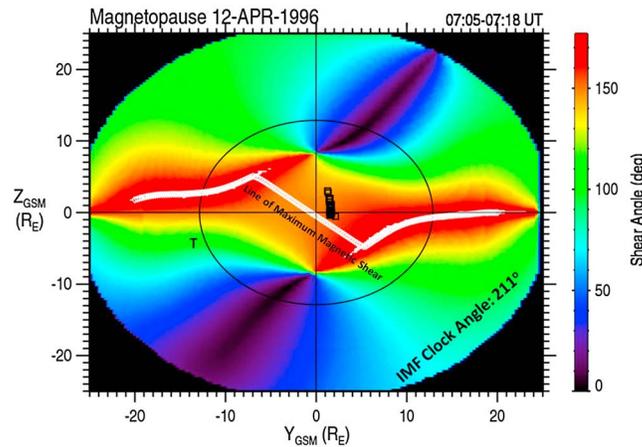


Figure 8. Magnetopause shear angle for the Polar cusp crossing on 12 April 1996 as seen from the Sun. The layout is the same as Figure 4. The white line crossing the dayside magnetopause is the line of maximum magnetic shear, the most likely location of the reconnection line [e.g., *Trattner et al., 2007*], and confirmed with the trace points from the distance calculation (black squares).

southward IMF conditions. However, this cusp crossing only exhibits one major ion energy dispersion (S1) and one large-scale motion of the boundary (MB).

Figure 7 has the same format as Figure 3 and shows the solar wind and IMF conditions observed by the Wind satellite located at 65., 39.5, and 6.3 R_E for X , Y , and Z GSM, respectively. The Wind data have been convected by about 13 min to account for the travel time to the magnetopause. Figure 7 shows the time interval from 07:05 UT to 07:18 UT, which covers the first major cusp step observed by Polar. The average solar wind density, N , for this cusp event was about 7 cm^{-3} with a dynamic pressure, P , of about 3.3 nPa (Figure 7, top) and an average solar wind velocity, V , of about 530 km/s (Figure 7, middle). Figure 7 (bottom) shows the IMF components in GSM coordinates. The IMF is dominated by a southward field and is stable throughout the period of interest with -2.5 , -2.5 , and -4.3 nT for B_x , B_y , and B_z , respectively.

Figure 8 has the same layout as Figure 4 and shows the magnetopause shear angle plot for the 12 April 1996 Polar cusp crossing. The IMF clock angle for this event was 211° . For these solar wind and IMF conditions, the maximum magnetic shear model predicts a tilted reconnection line across the dayside magnetopause (thick white line in Figure 8) that connects to and is continuous with the antiparallel reconnection regions in both hemispheres. The predicted location of the reconnection line was confirmed by applying the low-velocity cutoff method to the 3-D cusp distribution measurements from the TIMAS instrument. The calculated distances to the reconnection site were traced along T96 magnetic field lines to the magnetopause, which places the end points (marked with black square symbols) in the vicinity of the maximum shear line within the known error bars for the trace location. The region around the maximum shear line is known as the “saddle,” where the magnetic shear between the merging fields is only a few degrees less than at the ridge location at the maximum shear line. The effect of the gradient of the shear angle around the saddle region on the location of reconnection is discussed by *Petrinec et al. [2014]*.

Figure 9 has the same layout as Figure 5. The location of the dominant cusp structure during this event is marked with a vertical blue line. Figure 9 (top) shows RT, the time when the field lines in the cusp encountered by the Polar satellite were reconnected at the reconnection location. The cusp structure (S1) observed during the 12 April 1996 Polar cusp crossing was encountered by Polar at about 07:09 UT. Figure 9 (top) reveals that the magnetic field line was reconnected at the magnetopause 3 min earlier at 07:06 UT. Through that cusp crossing, RT is a continuous line, indicating that magnetic reconnection at the magnetopause was a continuous process. Over time, Δt slowly increased, which can be attributed to the Polar satellite moving poleward and away from the open-closed field line boundary, increasing the time the newly injected ions needed to reach the satellite.

[1993], who found that the time between successive flux transfer events (FTEs) varies from 1.5 to 18.5 min with an average of 8 min and a most common value of 3 min.

The second event discussed in this study took place on 12 April 1996. Figure 6 has the same format as Figure 2 and shows the H^+ omnidirectional flux measurements ($1/(\text{cm}^2 \text{ s sr keV/e})$) observed by the TIMAS instrument on board the Polar satellite. The satellite was located in the postnoon sector around 13:10 MLT moving toward higher latitudes. The TIMAS instrument observed magnetosheath ions on newly opened geomagnetic field lines from about 07:09 UT to 07:45 UT. As with the previous example, the overall ion energy dispersion is typical for

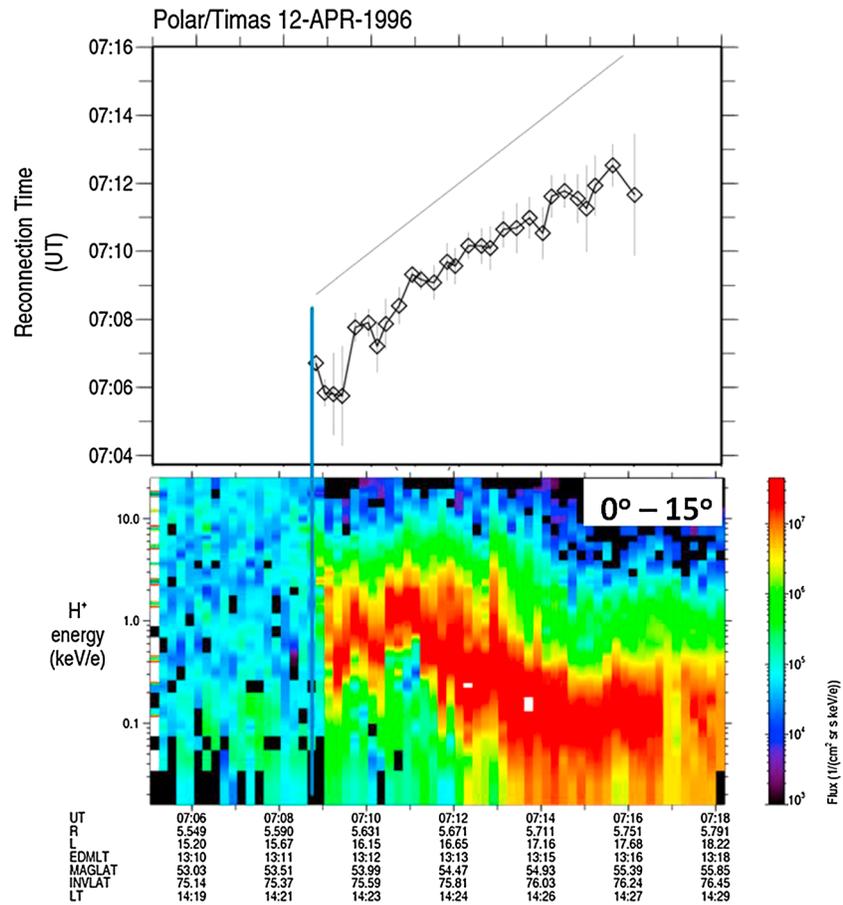


Figure 9. (top) The reconnection time for the cusp magnetic field lines, revealing that magnetic reconnection is a continuous and not a stepped profile, as expected for a continuous reconnection event at the magnetopause reconnection line. (bottom) The precipitating ions in the pitch angle range from 0° to 15° observed by the TIMAS instrument on board the Polar satellite during the northern hemisphere cusp crossing on 12 April 1996. The blue line marks the time when Polar encountered the cusp structures.

4. Summary and Conclusion

Studies of precipitating ions in the cusp regions have shown these ions to be a valuable source from which to gain insight and understanding of aspects of the magnetic reconnection process at the magnetopause [e.g., Lockwood and Smith, 1992; Onsager et al., 1993; Fuselier et al., 2000a; Escoubet et al., 2008, 2013; Trattner et al., 2007]. Plasma observations in the cusps in addition to in situ observations of field-aligned plasma flows in the boundary layers of the magnetopause [e.g., Gosling et al., 1990; Phan et al., 2000; Trenchi et al., 2008; Fear et al., 2012], consistent with the occurrence of magnetic reconnection, have demonstrated that the fundamental process of magnetic reconnection occurs somewhere at the magnetopause for any condition of the IMF [e.g., Sonnerup et al., 1981; Gosling et al., 1991; Kessel et al., 1996; Phan et al., 1996; Fuselier et al., 2000b] (yet may not be continuous in time).

The magnetospheric cusps bring together all the magnetic field lines that form the magnetopause in a relatively confined space. Wherever and in what manner magnetic reconnection happen along this boundary layer, it leaves a signature of the process in the distributions of precipitating magnetosheath ions observed in the cusp region. Understanding and defining these cusp signatures have allowed us to separate spatial from temporal reconnection signatures along the dayside reconnection line [e.g., Lockwood and Smith, 1990, 1992; Onsager et al., 1995; Trattner et al., 2002], confirm the existence of multiple reconnection lines [e.g., Omid and Sibeck, 2007; Trattner et al., 2012b], and determine the location of the magnetopause reconnection site, which subsequently led to the development of the maximum magnetic shear model [e.g., Trattner et al.,

2007; Fuselier et al., 2012; Petrinec et al., 2012]. In this study we expand on these earlier results and introduce a method to determine the continuous or pulsed nature of the reconnection process from single-satellite cusp observations.

A modification of the low-velocity cutoff method, used to estimate the distance to the reconnection site, allows for the calculation of the time when the current cusp magnetic field line observed by the satellite was opened at the magnetopause. In this study we use data from the high-altitude satellite Polar, which observes precipitating ions in the cusps for hours. The Polar orbital velocity is negligible compared to the connection speed of the solar wind which causes temporal variations of the reconnection process, manifested as cusp structures, to be convected over the satellite. The resulting time series of the reconnection time for magnetic field lines across the cusp reveals the nature of the reconnection process at the magnetopause, continuous or pulsed.

In this study, we analyzed two Polar/TIMAS cusp crossings on 22 March 1996 and 12 April 1996. Both crossings occurred in the northern hemisphere under southward IMF conditions. For the 22 March 1996 event, the reconnection location was in the antiparallel reconnection region at high latitudes and was dominated by a series of cusp step-up structures. The reconnection time also showed a stepped profile which coincided with the cusp step-up structures observed by the Polar satellite. However, within each cusp structure, the reconnection time for all the magnetic field lines encountered by the Polar satellite was about constant. This event was caused by short magnetopause reconnection pulses before reconnection ceased for about 3 min after which the next pulse was initiated at the reconnection site.

For the 12 April 1996 example, the reconnection location was in the equatorward region along the line of maximum magnetic shear. The event was dominated by a single-cusp dispersion. As in the previous example, that cusp dispersion could have been caused by one single-reconnection pulse for which the reconnection time would correspond to a single time. The reconnection time for the 12 April 1996 cusp crossing showed a continuous profile as the Polar satellite crossed the cusp, indicating that the reconnection process at the dayside-tilted reconnection line had a continuous nature.

By calculating the reconnection time, a methodology is provided in which the fundamental nature of the reconnection process, pulsed or continuous, is inferred and is associated with the reconnection location and the local conditions at the reconnection site (e.g., magnetic shear angle). The first event discussed in this study showed a reconnection location in the antiparallel merging region where the process of reconnection was fully pulsed with a periodicity of about 3 min. The second event discussed in this study showed a reconnection location across the dayside magnetopause (component reconnection line), along the line of maximum magnetic shear, where the reconnection process was continuous in nature throughout the Polar cusp crossing. It is too early to say if this result can be extended to all shear angles and reconnection locations. Future analyses of more complicated cusp structures and with a broader range of shear angles are required.

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