The location of reconnection at the magnetopause: Testing the maximum magnetic shear model with THEMIS observations

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Received 24 June 2011; revised 25 October 2011; accepted 26 October 2011; published 4 January 2012.

[1] Reconnection at the Earth's magnetopause is the 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 long-standing open questions about magnetic reconnection is the location of the reconnection line. There are two reconnection scenarios discussed in the literature: (1) antiparallel reconnection where shear angles between the magnetospheric field and the interplanetary magnetic field (IMF) are near 180° and (2) component reconnection where a tilted reconnection line which crosses the magnetopause in the subsolar region at shear angles not near 180°. Early satellite observations were limited to the detection of accelerated ion beams in the magnetopause boundary layer to determine the general direction of the reconnection line location with respect to the satellite. An improved view of the reconnection location at the magnetopause was determined from ionospheric emissions observed by polar-orbiting imagers which revealed that both scenarios occur. The time-of-flight effect of precipitating ions in the cusp in connection with the low-velocity cutoff method pinpointed reconnection locations and their dependency on IMF conditions. These results are summarized by the maximum magnetic shear model. This study uses confirmed magnetic reconnection locations from the THEMIS mission to test the predictions of this reconnection location model. The results reveal that the maximum magnetic shear model predicts the observed reconnection locations for dominant IMF B_Y conditions very well but needs further improvement and modifications for dominant southward IMF conditions.

Citation: Trattner, K. J., S. M. Petrinec, S. A. Fuselier, and T. D. Phan (2012), The location of reconnection at the magnetopause: Testing the maximum magnetic shear model with THEMIS observations, *J. Geophys. Res.*, *117*, A01201, doi:10.1029/2011JA016959.

1. Introduction

[2] Originally postulated by *Dungey* [1961] in order to explain the circulation of magnetic flux and plasma in the outer magnetosphere and high-latitude ionosphere, the interconnection of magnetic fields through magnetic reconnection at the magnetopause is thought to be the dominant process for mass, energy, and momentum transfer from the Earth's magnetosheath to the magnetosphere. After decades of research there is incontrovertible evidence that this process occurs when the Interplanetary Magnetic Field (IMF) is southward [e.g., *Paschmann et al.*, 1979; *Sonnerup et al.*, 1981; *Fuselier et al.*, 1991; *Phan et al.*, 1996, 2000] and when it is northward [e.g., *Gosling et al.*, 1991; *Kessel et al.*, 1996; *Fuselier et al.*, 2000; *Avanov et al.*, 2001; *Twitty et al.*, 2004]. There is also general agreement that reconnection is a fundamentally multiscale [e.g., *Burch et al.*, 1982; *Escoubet et al.*, 1992; *Onsager et al.*, 2001; *Trattner et al.*, 2004] and can be a continuous process [e.g., *Gosling et al.*, 1982; *Frey et al.*, 2003; *Phan et al.*, 2004], forming long reconnection lines along the magnetopause surface [e.g., *Fuselier et al.*, 2002; *Phan et al.*, 2006a] and in interplanetary space [e.g., *Phan et al.*, 2006b; *Gosling et al.*, 2007].

[3] Antiparallel reconnection occurs between magnetic field lines of (ideally) exactly opposite polarity. Newly reconnected field lines are sharply bent and act like slingshots, accelerating plasma transferred across the magnetopause while straightening out to reduce magnetic tension. During exactly southward IMF conditions, reconnection between the draped IMF and magnetospheric field lines should occur near the geomagnetic equator along the dayside magnetopause. In contrast, antiparallel reconnection during northward IMF conditions should occur at the high-latitude magnetosphere in the lobes, poleward of the cusps [see also *Dungey*, 1963].

[4] The IMF usually exhibits a significant west-east component ($B_Y \neq 0$). For such conditions, the *Crooker* [1979] and *Luhmann et al.* [1984] models predicted that the antiparallel reconnection region splits at local noon,

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0148-0227/12/2011JA016959

producing two separate reconnection regions in different hemispheres. This was observationally confirmed by *Trattner et al.* [2005] using a Cluster cusp crossing in the northern hemisphere in conjunction with observations from the Imager for Magnetopause-to-Aurora Global Exploration Far Ultraviolet (IMAGE/FUV) instrument, along with ground-based SuperDARN radar maps.

[5] An alternative to the antiparallel reconnection scenario is the component reconnection tilted X line model for southward IMF conditions [e.g., *Sonnerup*, 1974; *Gonzalez and Mozer*, 1974; *Cowley and Owen*, 1989; *Moore et al.*, 2002]. The component reconnection model predicts the location of the reconnection line at the subsolar point where the solar wind plasma first makes contact with the magnetopause. From there the reconnection line extends continuously along the dayside magnetopause while the ratio of the IMF B_Y component to the IMF south-north component (B_Z) determines the tilt of the X line relative to the equatorial plane. Newly reconnected field lines under these conditions are no longer as sharply bent as in the strictly antiparallel configuration, accelerating plasma less efficiently.

[6] The actual location of the reconnection line and which reconnection scenario dominates as a function of solar wind and IMF input conditions has long eluded researchers. The observation of high-speed plasma flows in the magnetopause and their interpretation in terms of the magnetic reconnection process [e.g., *Paschmann et al.*, 1979; *Sonnerup et al.*, 1981, 1995; *Scurry et al.*, 1994; *Gosling et al.*, 1990, 1991; *Fuselier et al.*, 2005; *Phan et al.*, 1996, 2000, 2004; *Trenchi et al.*, 2008] has been used in many previous studies to determine the general direction of the location of the reconnection line relative to the spacecraft but does not identify the location(s) of the reconnection site.

[7] Observations from the IMAGE satellite have demonstrated that both reconnection scenarios, antiparallel and component reconnection, occur at the magnetopause for southward IMF conditions [*Fuselier et al.*, 2002, 2003]. The FUV instrument on the IMAGE satellite is sensitive to Doppler-shifted Lyman α emissions around 121.8 nm caused by charge exchanging precipitating protons in the energy range from 2 to 8 keV [*Frey et al.*, 2002]. While component reconnection across the dayside magnetopause causes a continuous FUV emission profile along the dayside aurora oval, antiparallel reconnection exhibits an emission gap around local noon where the reconnection X line bifurcates. The gap is the result of precipitating ions being injected into the opposing hemisphere with respect to the IMAGE spacecraft location (e.g., injection at the magnetopause south of the equator, while the IMAGE spacecraft images the northern polar ionosphere from above). Plasma on such field lines must first make its way toward the equator against the magnetosheath bulk flow before being convected with the magnetosheath bulk flow over the northern polar region. This scenario results in small convection velocities such that ions injected onto these field lines will have a slower velocity compared to ions injected at the antiparallel reconnection line located in the same hemisphere as the IMAGE satellite.

[8] Recently there has been significant progress on the dayside location of the reconnection line by using a remote sensing method based on the low-velocity cutoffs of the precipitating and mirrored ion distributions [e.g., *Onsager et al.*, 1990, 1991; *Fuselier et al.*, 2000]. The cutoff velocities are used to calculate the distance to the reconnection line which is subsequently used to trace the distance along model magnetic field lines back to the magnetopause. These derived locations led to the development of the maximum magnetic shear model [e.g., *Trattner et al.*, 2007a, 2007b] which needs only the solar wind and IMF conditions to predict the reconnection location at the dayside magnetopause. The model predicts that during dominant IMF B_Y conditions, magnetic reconnection occurs along an extended line across the dayside magnetopause. In general the line does not go through the subsolar point (as in the original tilted X line model). Rather, the line follows the ridge of maximum magnetic shear across the dayside magnetopause. In contrast, for dominant IMF B_Z ($155° < \tan^{-1}(By/B_Z) < 205°$) or dominant B_X ($|B_X|/B > 0.7$) conditions, the reconnection location bifurcates and traces to high latitudes, in close agreement with the antiparallel reconnection scenario, and does not cross the dayside magnetopause as a single tilted reconnection line.

[9] This empirical model has not been tested with actual confirmed reconnection locations at the magnetopause. To determine the local conditions at the reconnection site a satellite would need to cross the reconnection line. However, these conditions are not easy to achieve since even small variations in the solar wind conditions cause significant changes in the location of the reconnection line. In addition, a spacecraft crosses the magnetopause only at a single location, which severely limits the chances of an encounter with the actual reconnection site.

[10] An example of a chance encounter is the multispacecraft observation of a reconnection event by the Cluster and IMAGE satellites in the northern magnetosphere. Cluster crossed the magnetopause and observed a reversal of the accelerated ion beams from the reconnection site while the IMAGE satellite simultaneously observed an ionospheric spot at the foot point of the Cluster magnetic field line caused by precipitating magnetosheath ions [e.g., *Frey et al.*, 2003; *Phan et al.*, 2003].

[11] A large database of dayside boundary layer crossings by the THEMIS satellites was searched for the signature of the reconnection location and seven of these events are discussed below. These boundary crossings are characterized by accelerated reconnection jets that reverse direction during the crossing [e.g., *Phan et al.*, 2003], indicating the presence of a reconnection X line at this single location along the reconnection line. In this study, these THEMIS chance encounters with a reconnection line are used to compare the location of the reconnection line with the predictions from the maximum magnetic shear model described above [*Trattner et al.*, 2007b]. The satellite positions, solar wind and IMF conditions for all events discussed in this paper are summarized in Table 1.

2. Instrumentation and Methodology

[12] This study uses proton observations from the dayside magnetopause observed by the THEMIS mission. The THEMIS satellites [*Angelopoulos*, 2008] were launched on 17 February 2007. Magnetic field data are provided by the fluxgate magnetometer (FGM) [*Auster et al.*, 2008] while ion plasma measurements are provided by the Electrostatic Analyzer (ESA) [*McFadden et al.*, 2008] over the energy range from $\sim$3 eV to 30 keV, covering the entire unit sphere

Table 1. Satellite Positions, Solar Wind, and IMF Conditions for the THEMIS Magnetopause Crossings in This Study

Date[a]	THEMIS	X, Y, Z (GSM) (R_E)	N (cm^3)	V (km/s)	B_X (nT)	B_Y (nT)	B_Z (nT)	Clock Angle	SW Sat.	Convection Time to MP
2008/7/27 20:15 UT	E	9.7, 4.6, −3.5	6.2	378	−4.2	5.1	−1.3	104°	ACE	1 h 3 min
2007/6/23 06:50 UT	C	10.3, 1.5, −2.8	3.7	552	2.1	−3.6	−0.9	255°	ACE	43 min
2007/6/23 07:40 UT	A	9.7, 0.8, −2.5	3.8	568	−2	−0.2	−3.2	183°	ACE	43 min
2007/7/22 02:20 UT	C	12, −2, −3.1	2.8	467	−0.3	−2.9	−0.2	226°	ACE	51 min
2007/8/28 08:20 UT	C	9.9, −1.8, −2	1.9	622	1.8	−2.2	−2.7	219°	ACE	40 min
2007/6/28 12:40 UT	E	10.9, 0.7, −3	6.5	366	0.6	−3	−0.9	253°	Wind	1 h 16 min
2008/8/31 15:05 UT	D	10.3, −2.6, −2	8.2	307	3.3	−2.2	−1	242°	Wind	1 h 10 min

[a]Date format is year/month/day.

during a 3 s spin. Only proton and magnetic field measurements from the THEMIS spacecraft will be used in this study.

[13] Solar wind context measurements are provided by the ACE Solar Wind Experiment (SWE) [*McComas et al.*, 1998] and the ACE Magnetic Field Instrument (MFI) [*Smith et al.*, 1998] and cross checked with data from the Wind Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995] and the Wind Magnetic Field Instrument (MFI) [*Lepping et al.*, 1995]. The Wind SWE and MFI instruments also serve as backups for time periods when ACE data are not available. All solar wind and IMF data are available at CDAWeb.

[14] All THEMIS magnetopause crossings used in this study feature a reversal of the accelerated ion flow while the spacecraft crossed the magnetopause, which is generally considered to be an indicator that a reconnection X line is close by [e.g., *Phan et al.*, 2003; *Frey et al.*, 2003]. In these cases the position of the satellite is recorded and transferred onto a magnetopause shear angle plot derived from the simultaneously observed solar wind and IMF conditions [e.g., *Trattner et al.*, 2007b]. This plot also contains the prediction of the reconnection line using the maximum magnetic shear model. This prediction is compared with the actual confirmed location of the reconnection line from the THEMIS observations.

3. Observations

[15] Figure 1 shows a chance encounter with the reconnection location by THEMIS E during the magnetopause crossing on 27 July 2008 at around 20:15 UT. The satellite was located at 9.7, 4.6 and −3.5 R_E in GSM coordinates. Shown from top to bottom are the magnetic field components B_X (blue), B_Y (green) and B_Z (red) (nT); H^+ omnidirectional energy flux measurements (eV/(cm^2 s^{-1} sr^{-1} eV^{-1})); the proton velocity moments V_X (blue), V_Y (green) and V_Z (red) (km/s); and the proton density N (cm^{-3}).

[16] THEMIS E briefly encountered the magnetopause with mixed magnetospheric and magnetosheath plasma at 20:10 UT before fully traversing the magnetopause between 20:12 and ∼20:20 UT. The satellite then crossed into the magnetosheath, but briefly encountered the magnetopause again at 20:22 UT. The magnetic field components switched from a dominant northward orientation in the magnetosphere

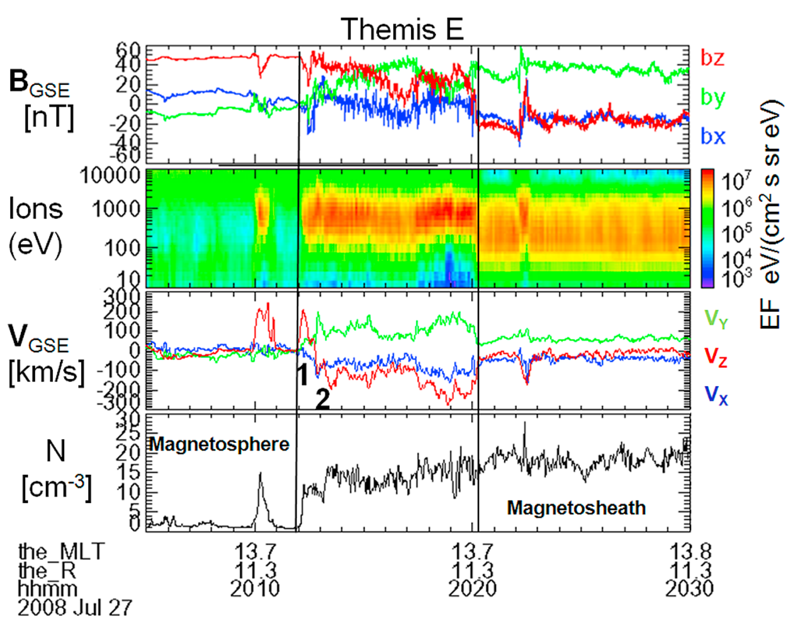

Figure 1. THEMIS E magnetic field and plasma observations during the magnetopause crossing on 27 July 2008 at about 20:15 UT. Shown are the magnetic field components (GSE), ion omnidirectional energy flux measurements (eV/(cm^2 s^{-1} sr^{-1} eV^{-1})), the plasma velocity components (GSE), and the plasma density.

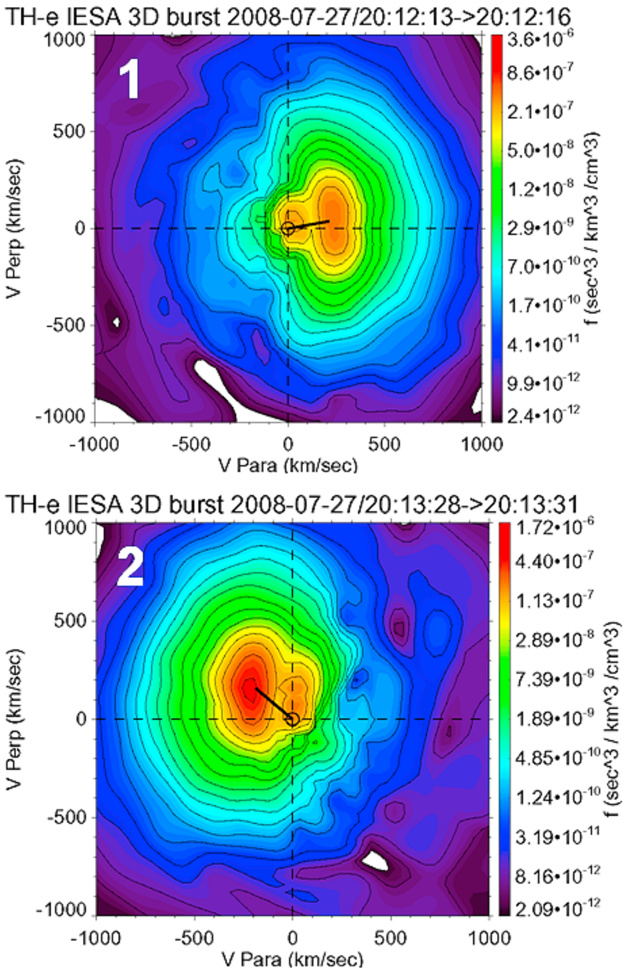

Figure 2. Two-dimensional cuts of the three-dimensional proton distributions in field-aligned coordinates observed by THEMIS E during the magnetopause crossing on 27 July 2008. Shown are classical D distributions exhibited by magnetosheath ions crossing the reconnection site as predicted by *Cowley* [1982]. Distributions 1 and 2 are from both sides of the reconnection location, moving in opposing directions away from the reconnection site.

to a southward field with a dominant positive B_Y component (green) in the magnetosheath. The B_X component (blue) is the weakest of the magnetic field components in the boundary layer at the near subsolar magnetopause location because it is approximately B_N. This component changes from positive to negative.

[17] In the magnetosphere, on the last closed field lines, the ion flux exhibits the typical bifurcated low- and high-energy populations (second panel in Figure 1). These populations are a common feature on these field lines and also well known in cusp studies at the open-closed field line boundary [e.g., *Trattner et al.*, 2010]. The high-energy population consists of ring current ions as described by *Cowley* [1982] and *Fuselier et al.* [1991], present on the last closed field lines, and are counterstreaming. The transition from these bifurcated populations toward the heated and shocked solar wind in the magnetosheath shown on the right side of the ion panel, is characterized by an accelerated magnetosheath-like distribution with magnetosheath-like densities on newly opened field lines, forming a boundary layer.

[18] This accelerated population in the magnetopause is known as a reconnection jet, indicating that the satellite is magnetically connected to the reconnection site [e.g., *Paschmann et al.*, 1979; *Sonnerup et al.*, 1981, 1995; *Scurry et al.*, 1994; *Gosling et al.*, 1990, 1991; *Fuselier et al.*, 2005; *Phan et al.*, 1996, 2000, 2004; *Trenchi et al.*, 2008]. The accelerated ion jet emanating from the reconnection site reaches about 250 km/s when THEMIS E first encounters the boundary layer at 20:10 UT and 20:12 UT (1) as seen in the velocity moments in Figure 1. At 20:13 UT (2) the accelerated ion jet switched direction and subsequently reached about −300 km/s, indicating that the reconnection line is close and THEMIS E has crossed into the reconnection exhaust on the other side of the X line. During the reversal of the reconnection jet, THEMIS E was still located on the magnetospheric side of the magnetopause as indicated by the positive B_Z component (top panel in Figure 1) and crossed into the magnetosheath at 20:20 UT where the B_Z component became negative.

[19] Figure 2 shows two-dimensional cuts of the three-dimensional proton distribution in phase space density f (s^3/km^3 cm^3) and field-aligned coordinates, observed by the ESA instrument on board the THEMIS E satellite during the magnetopause crossing on 27 July 2008. The small black line indicates the direction and bulk velocity of the distributions. Reconnection of Earth's magnetic field lines with the IMF 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 previously observed by many satellites [e.g., *Gosling et al.*, 1990; *Fuselier et al.*, 1991]. Figure 2 shows two such classical D-shaped distributions observed by THEMIS E at 20:12.13 UT (1) and 20:13.28 UT (2) on both sides of the reconnection line (see also marker in Figure 1), streaming in opposite directions. This scenario is interpreted as clear indication that THEMIS E crossed the reconnection line. The THEMIS E position will be subsequently used to test the prediction of the reconnection location from the maximum magnetic shear model.

[20] The average solar wind and IMF conditions during the 27 July 2008 THEMIS E magnetopause crossing are shown in Figure 3. The average solar wind density was about 6.2 cm^{-3} (Figure 3, top) and the average solar wind velocity was 378 km/s (Figure 3, middle). The IMF components were stable with only minor fluctuations in the IMF B_Z component (Figure 3, bottom). The average values were (−4.2, 5.1, −1.3) nT in GSM coordinates, which results in an IMF clock angle of 104° (dominant B_Y case). The thick black line in Figure 3 indicates the time window when THEMIS E was in the boundary layer during the 27 July 2008 magnetopause crossing. The solar wind and IMF input conditions are provided by the ACE spacecraft and convected to the magnetopause by 1 h 3 min. These data were used to predict the location of the reconnection line shown below.

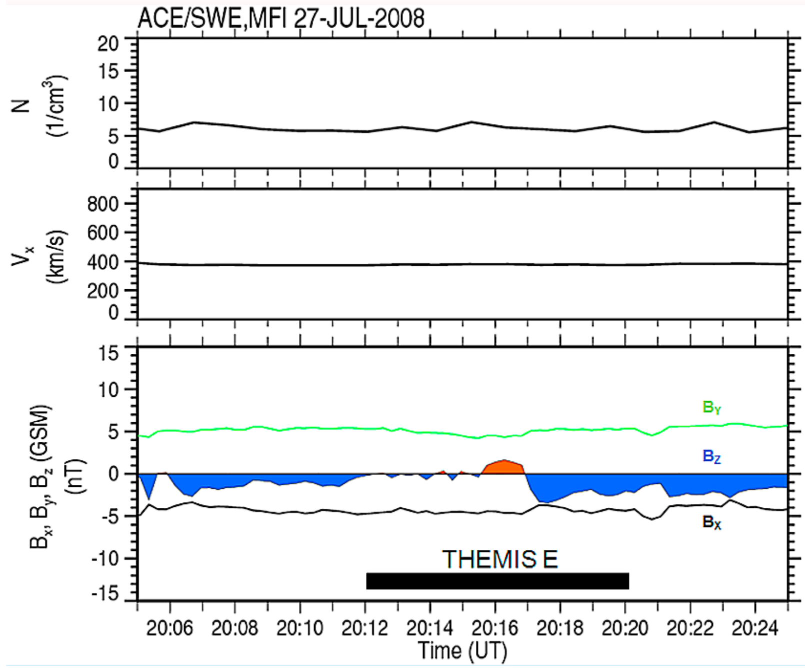

Figure 3. Solar wind and IMF conditions for the THEMIS E magnetopause crossings on 27 July 2008 observed by the SWE and MFI instruments on the ACE satellite. The data have been convected by about 63 min to account for the travel time from the satellite to the magnetopause.

[21] Figure 4 shows color coded the magnetopause shear angle as seen from the Sun for the THEMIS E magnetopause crossings on 27 July 2008. The magnetopause shear angle is calculated from the geomagnetic field direction and the fully draped IMF at the magnetopause for the time intervals and the solar wind conditions observed during the THEMIS E magnetopause crossing. For the analytic model of the external (magnetosheath) magnetic field, the *Cooling et al.* [2001] magnetopause is used as the outer boundary. The *Cooling et al.* [2001] magnetic field model is a restricted version of the more general *Kobel and Flückiger* [1994] model (which is an analytic representation of the magnetic field throughout the magnetosheath). For the internal (magnetosphere) magnetic field, the T96 model is employed. The T96 model uses an axially symmetric (about the solar wind direction) dayside magnetopause shape that is derived from the *Sibeck et al.* [1991, Table 2] magnetopause fit for intermediate solar wind pressures [see also *Trattner et al.*, 2007b].

[22] The black circle in Figure 4 represents the size of the magnetopause at the terminator (X_{GSM} = 0) plane. Red regions in Figure 4 represent the antiparallel magnetic field regions at the magnetopause (with shear angles from 150° to 180°) while black regions represent parallel magnetic field conditions. White areas within the red antiparallel regions represent areas where the geomagnetic fields and the fully draped IMF are within 3° of being exactly antiparallel.

[23] The antiparallel shear angle regions are located in the northern dusk and southern dawn sectors for this dominant IMF B_Y case. Due to the dipole tilt at that time, the cusps and the antiparallel shear angle regions are shifted toward the southern hemisphere. The white line crossing the dayside magnetopause and connecting the antiparallel shear regions is the line of maximum magnetic shear which was identified as the most likely location of the reconnection line in the maximum magnetic shear model [*Trattner et al.*, 2007b]. This line is in general agreement with the component reconnection tilted X line scenario [e.g., *Sonnerup*, 1970; *Gonzalez and Mozer*, 1974; *Cowley and Owen*, 1989; *Moore et al.*, 2002] for which reconnection occurs at the subsolar point where the solar wind plasma makes first contact with the magnetopause. However, the line of maximum magnetic shear exhibits a dependency on dipole tilt (seasonal effect) and is shifted considerably to the south for the THEMIS E magnetopause crossing. The THEMIS E location at the magnetopause is marked by a cross in Figure 4 and also south of the subsolar location and an almost perfect match with line of maximum magnetic shear. The THEMIS E position is located ~0.5 Re south of the predicted reconnection line and within the location uncertainties reported for maximum magnetic shear model. A detailed description about the ≈1 R_E uncertainties for the location predictions can be found in the work by *Trattner et al.* [2007b].

[24] The solar wind and IMF conditions for the next two events discussed in this study are shown in Figure 5 (same format as Figure 3). The data from the ACE SWE and MFI experiments, observed on 23 June 2007, have been convected by about 43 min to account for the travel time between the ACE satellite and the magnetopause. The average solar wind density, N, for this event was about 4 cm^{-3} (Figure 5, top) and the average solar wind velocity, V, was about 570 km/s (Figure 5, middle). The IMF components in GSM coordinates, B_X (black line), B_Y (green line), and B_Z (colored area) are shown in Figure 5 (bottom). The IMF components change considerably between the two time periods marked with thick black lines in Figure 5 (bottom). THEMIS C crossed the magnetopause at about

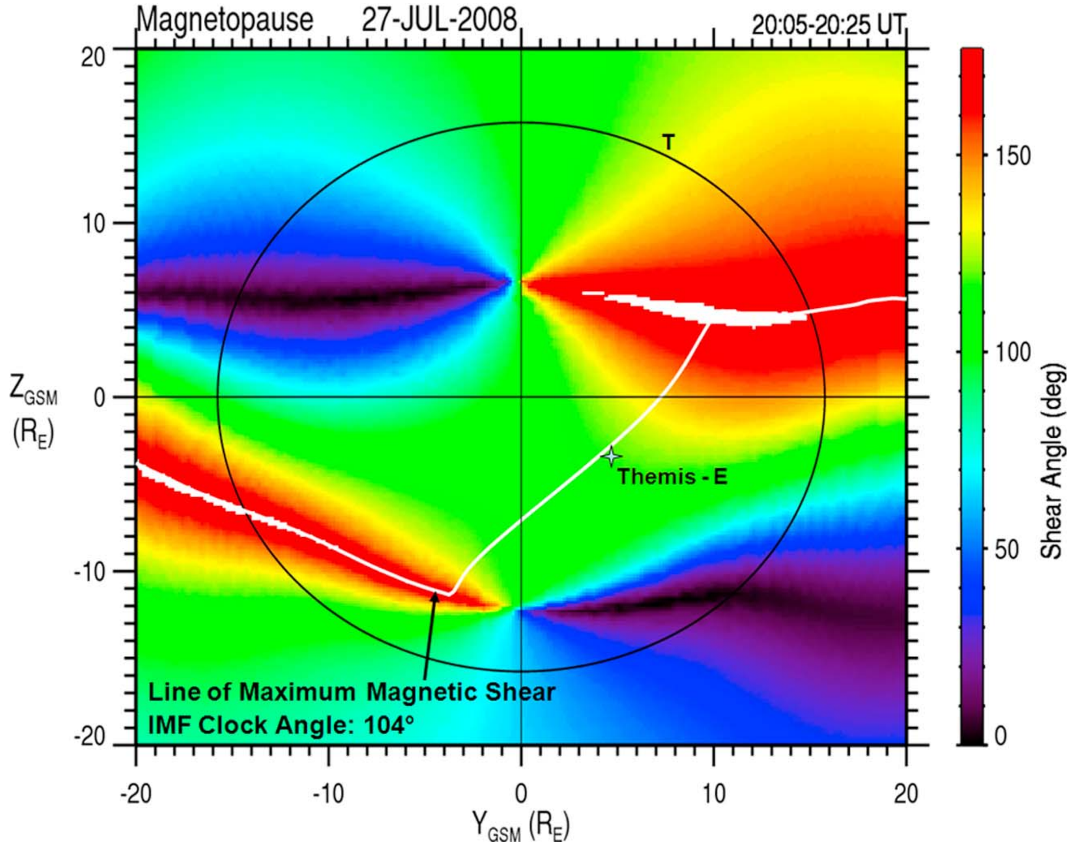

Figure 4. The magnetopause shear angle during the THEMIS E magnetopause crossing on 27 July 2008. The white line represents the line of maximum magnetic shear across the dayside magnetopause and is the most likely reconnection location for the solar wind and IMF conditions during this event [*Trattner et al.*, 2007b]. Red areas are regions with antiparallel field conditions while blue and black areas are regions where the merging fields are parallel. White regions embedded in the red areas are regions where the merging model magnetic fields are within ±3° of being antiparallel. The black circle represents the terminator plane (T) at $X_{GSM} = 0$, projected to the magnetopause.

06:50 UT while THEMIS A followed at about the same location around 07:40 UT. The IMF vector components change from dominant B_Y conditions with (2.1, −3.6, −0.9) nT during the THEMIS C crossing to dominant B_Z conditions with (−2, −0.2, −3.2) nT during the THEMIS A crossing.

[25] Figure 6 shows the magnetopause shear angle for the THEMIS C magnetopause crossing on 23 June 2007 at 06:50 UT. The layout is the same as in Figure 4. The shear angle plot shows the typical profile for dominant negative IMF B_Y cases with the antiparallel magnetic shear regions bifurcated at local noon and located in the northern dawn and southern dusk sectors. With a clock angle of about 255° the line of maximum magnetic shear S_{MAX} crosses the dayside magnetopause just southward of the subsolar location and connects the antiparallel magnetic shear angle regions. For this event the location of the line of maximum magnetic shear and THEMIS C are a perfect match.

[26] Figure 7 shows the magnetopause shear angle for the THEMIS A magnetopause crossing on 23 June 2007 at 07:40 UT. The layout is the same as for Figure 4. The THEMIS A satellite crossed the magnetopause at about the same location as THEMIS C 50 min earlier (see Table 1) and encountered also a reversal in the accelerated ion beam direction. That suggests that the reconnection site did not move over this time frame. However, at the time of the THEMIS A magnetopause crossing, the IMF changed from a dominant B_Y condition to a dominant B_Z condition with a clock angle of 183°.

[27] The maximum magnetic shear model for dominant B_Z conditions predicts that the reconnection site is located in the regions where the merging fields are exactly antiparallel (white areas in Figure 7). While this result was the statistically preferred location it was also a surprise since the entire dayside region for such IMF conditions is in an antiparallel stage (red areas in Figure 7) providing ideal conditions for magnetic reconnection to occur.

[28] For the THEMIS A magnetopause crossing the predicted location from the maximum magnetic shear model would bifurcate at local noon (see white areas in Figure 7a) and approach the high-latitude cusp regions. Since this is a northern summer event, everything is also shifted considerably to the south, which brings the reconnection region for the dawn sector close to the geomagnetic equator before extending to the high-latitude cusp region at local noon. The actual reconnection line for this event was however, close to the geomagnetic equator at local noon.

[29] Figure 7b shows the same plot as Figure 7a but replotted for relaxed conditions of the exactly antiparallel

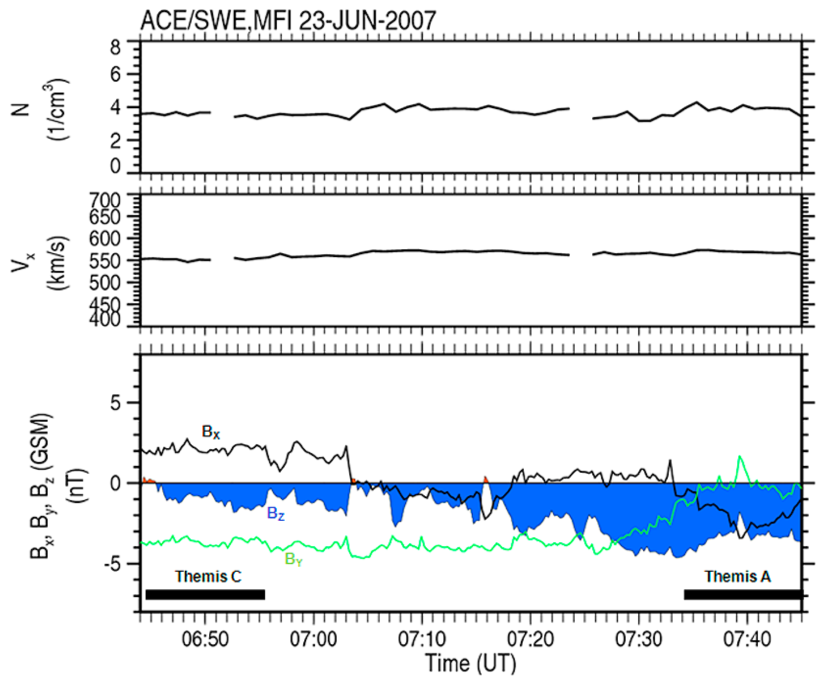

Figure 5. Solar wind and IMF conditions for the THEMIS C and A magnetopause crossings on 23 June 2007 observed by the SWE and MFI instruments on the ACE satellite. The data have been convected by about 43 min to account for the travel time from the satellite to the magnetopause.

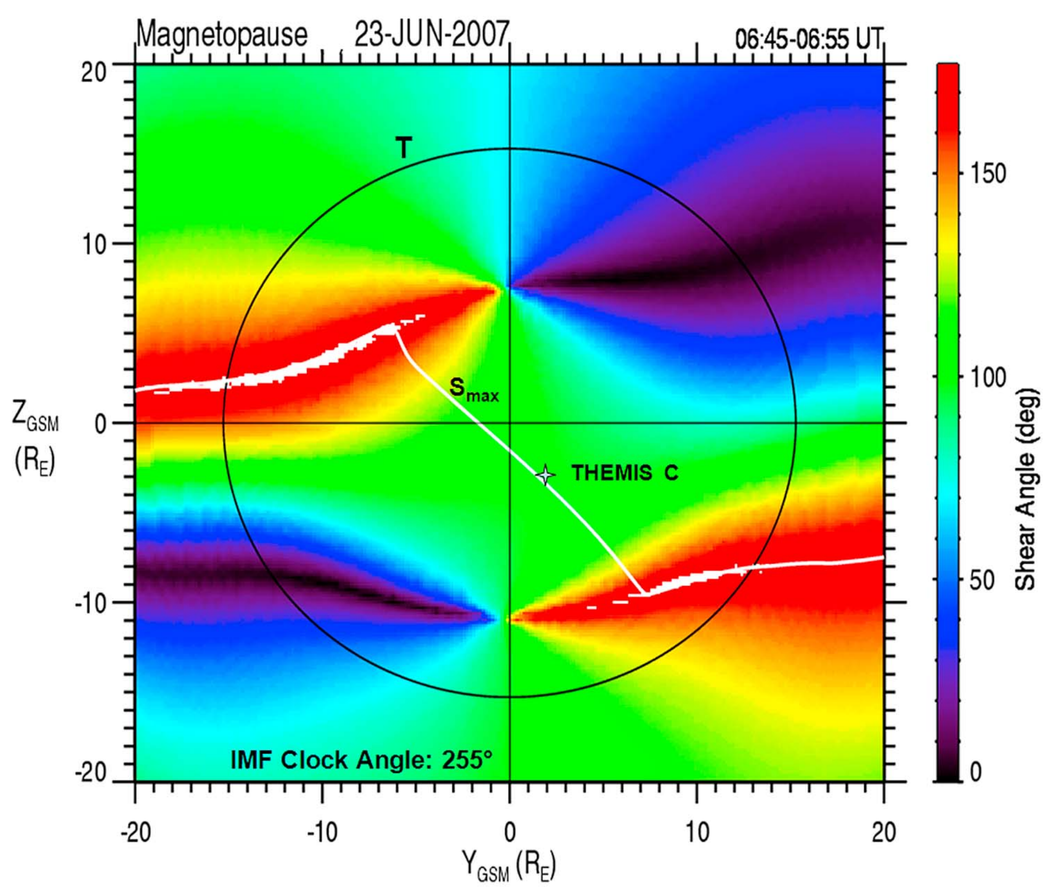

Figure 6. The magnetopause shear angle during the THEMIS C magnetopause crossing on 23 June 2007 at 06:50 UT. The layout is the same as Figure 4.

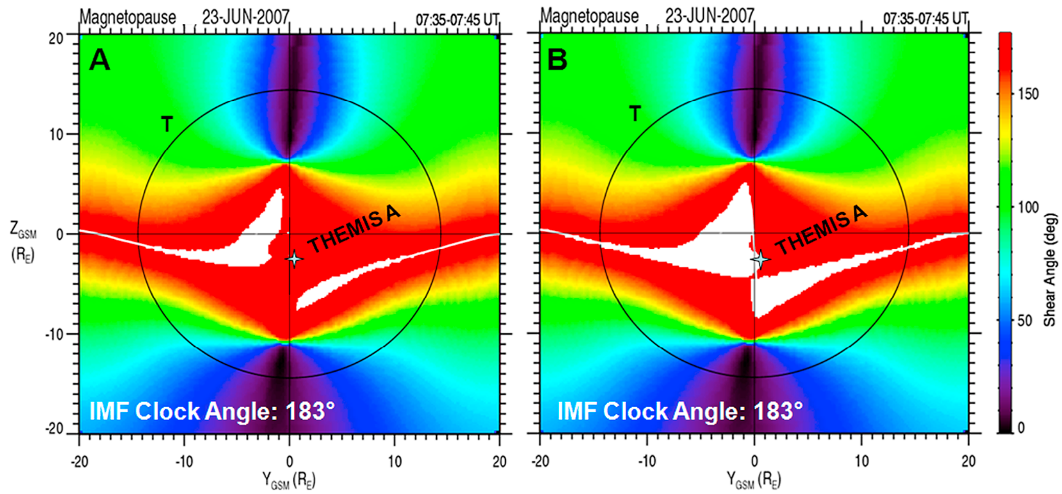

Figure 7. The magnetopause shear angle during the THEMIS A magnetopause crossing on 23 June 2007 at 07:40 UT. The layout is the same as in Figure 4. (a) The conditions for the maximum magnetic shear model [*Trattner et al.*, 2007b] with white areas representing regions where the model fields are within ±3° of being antiparallel. (b) The same event with modified conditions where the white areas represent regions within ±5° of being antiparallel.

criteria within the maximum magnetic shear model. Instead of requiring the merging field to be within ±3° of being exactly antiparallel (Figure 7a), Figure 7b shows the plot for a variance of ±5°. In this case the entire dayside including the position of the THEMIS A satellite is within the predicted reconnection location.

[30] Figure 8 shows four magnetospheric shear angle plots for four magnetopause crossings of the THEMIS satellites C, E and D. The layout of the plots is the same as in Figure 4. As in the event in Figure 4, all THEMIS magnetopause crossings in Figure 8 were close to the reconnection line because they exhibit the reversal of the accelerated ion in the magnetopause. The predicted locations for S_{MAX} in Figure 8a on 22 July 2007 at 02:20 UT and Figure 8b on 28 August 2007 at 08:20 UT are in excellent agreement with the THEMIS C satellite position.

[31] The prediction of the reconnection line for Figure 8c is lower than the actual position of the THEMIS E satellite. The line of maximum magnetic shear and the THEMIS E position are both clearly southward of the subsolar point, and therefore in agreement with the general trend of the reconnection location for summer events [*Trattner et al.*, 2007b]. However, the satellite is about 2 R_E away from the predicted location; larger than the uncertainties for the predicted reconnection locations. A possible reason for the difference between the actual and predicted reconnection location could be uncertainties in the solar wind and IMF input conditions convected to the magnetopause. The solar wind input conditions for this event were provided by the Wind satellite and could not be confirmed with ACE data due to a data gap. In addition, the actual location of the line of maximum magnetic shear across the dayside is drawn through a region of very shallow gradient in the shear angle, which results in negligible changes of the maximum shear condition if the line were to be shifted by a couple of Earth radii. A study on the effects of this "shallow gradient" on the certainty of locating the X line is in preparation.

[32] A similar result is derived for Figure 8d where the position of the THEMIS D satellite is lower than the line of maximum magnetic shear. This event is further complicated by a dominant IMF B_X component, which is known to be a weakness of the magnetic field draping models and subsequently with the actual shear angles at the magnetopause. For such events the maximum magnetic shear model statistically predicts the reconnection location to be bifurcated at local noon and located at high latitudes in regions where the merging fields are antiparallel. However, the THEMIS D location close to the magnetic equator suggests that this case also exhibits a component reconnection tilted X line across the dayside magnetopause.

[33] The multiple magnetopause crossings on 31 August 2008 are shown in Figure 9 (same format as Figure 1) which shows that THEMIS D encountered eight southward directed accelerated ion beams but only one northward directed beam. The large number of southward directed accelerated ion beams in the magnetopause is consistent with the general location of THEMIS D southward of the tilted line of maximum magnetic shear. If this reconnection location is correct, the maximum magnetic shear model predicting a bifurcated antiparallel reconnection location at high latitudes for dominant IMF B_X events needs to be modified. In particular, the solar wind conditions defining the transition between the high-latitude antiparallel reconnection location and the tilted line of maximum magnetic shear across the dayside magnetopause needs to be better defined.

[34] This event could also be interpreted as an antiparallel reconnection event in agreement with the maximum magnetic shear model due to problems in defining local noon in magnetic field models [e.g., *Trattner et al.*, 2005]. Due to the vicinity of THEMIS D to local noon it is possible that the satellite actually encountered accelerated ion beams from the high-latitude antiparallel reconnection site in the north and one time the accelerated ion beam from the southern antiparallel reconnection region and was mistakenly identified as a component reconnection tilted X line in the equator

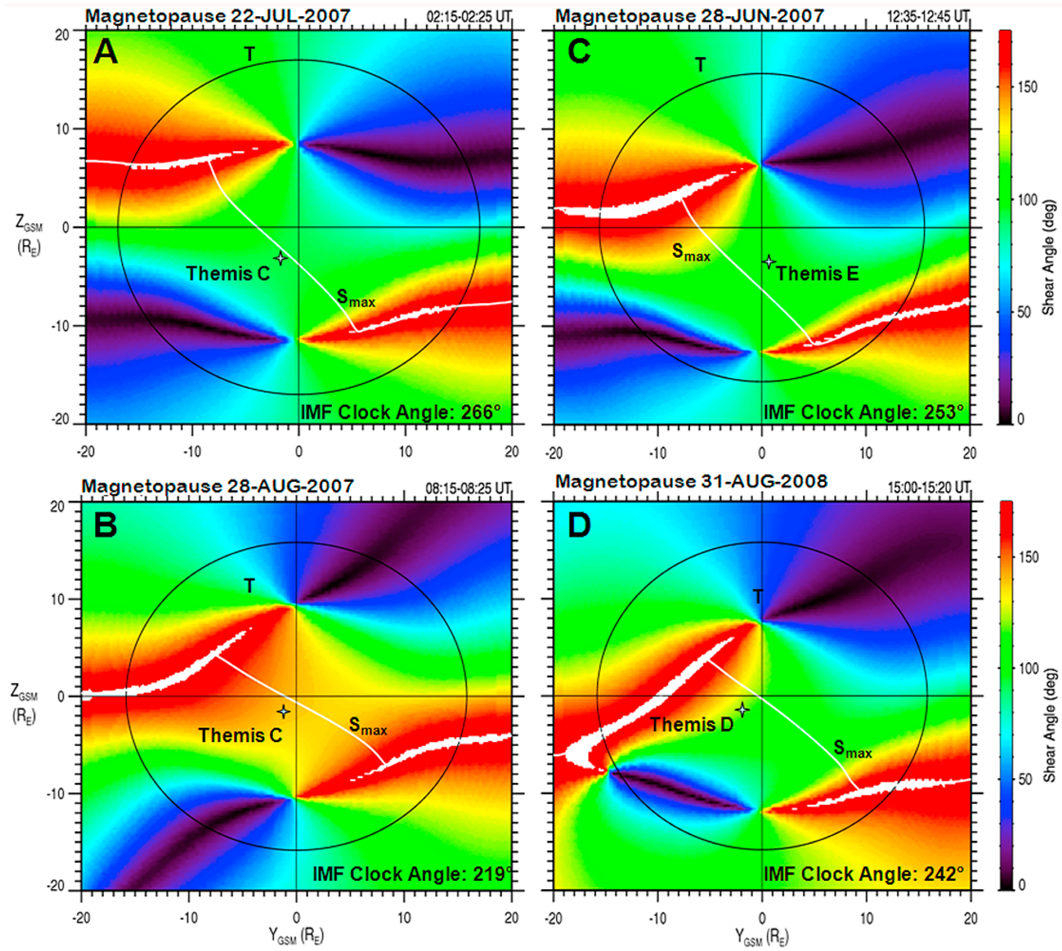

Figure 8. (a–d) The magnetopause shear angle with the most likely location of the reconnection line S_{max} derived from the maximum magnetic shear model [*Trattner et al.*, 2007b] for the solar wind and IMF conditions during four magnetopause crossings by the THEMIS satellites.

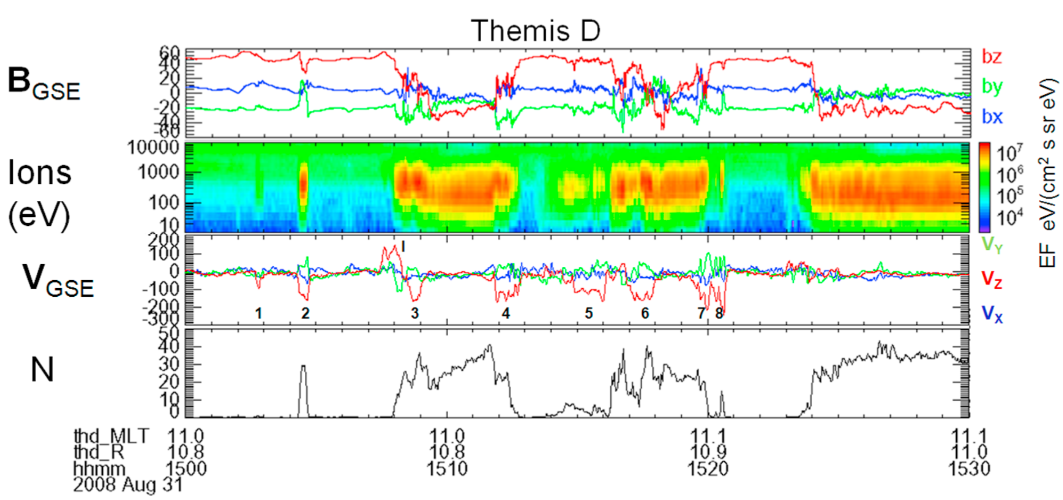

Figure 9. THEMIS D magnetic field and plasma observations during the magnetopause crossing on 31 August 2008 at about 15:00 UT. Shown are the magnetic field components (GSE), ion omnidirectional energy flux measurements (eV/(cm^2 s^{-1} sr^{-1} eV^{-1})), the plasma velocity components (GSE), and the plasma density.

region. The high-latitude antiparallel reconnection region would also be in agreement with the lower ion beam velocities reported for this event since it behaves similar to a northward IMF case.

4. Summary and Conclusion

[35] The maximum magnetic shear model is an empirical model to predict the location of the reconnection line at the magnetopause during southward IMF conditions [*Trattner et al.*, 2007b]. In this study we test prediction of the reconnection location with observations of actual confirmed reconnection locations from the THEMIS mission. The THEMIS satellites observe on a regular basis high-speed plasma flows in the boundary layers of the magnetopause which emanate from the reconnection site. Such accelerated ion flows indicate the direction to the reconnection site and have been investigated in many previous studies [e.g., *Paschmann et al.*, 1979; *Sonnerup et al.*, 1981, 1995; *Scurry et al.*, 1994; *Gosling et al.*, 1990, 1991; *Fuselier et al.*, 2005; *Phan et al.*, 1996, 2000, 2004; *Trenchi et al.*, 2008]. On rare occasions, a flow reversal of the accelerated ion beams in the magnetopause indicates that the observing satellite has been close to and crossed an active reconnection line.

[36] The observation of flow reversals in the boundary layer has also been interpreted as evidence for the existence of multiple reconnection lines at the magnetopause [e.g., *Hasegawa et al.*, 2010]. According to this scenario, already reconnected magnetic field lines at the magnetopause re-reconnect while the field line is convecting and form, as often depicted in 2D representations, magnetic loops or islands. In more realistic 3D representations those re-reconnected field lines will resemble the classical picture of the flux transfer event (FTE) [*Russell and Elphic*, 1979]. Evidence of re-reconnection has also been discussed in cusp observations [e.g., *Fuselier et al.*, 1997]. Every process occurring at the magnetopause will leave a signature in the precipitating ion distribution in the cusps. The signature for multiple reconnection lines in the cusp are overlapping precipitating ion beams at different energies which have been observed [e.g., *Trattner et al.*, 1998]. Years of cusp studies revealed only a handful of such events which suggests that multiple reconnection lines or re-reconnected flux tubes are rare. However, a detailed investigation into overlapping cusp structures and the special conditions required for their appearance is still needed.

[37] Seven THEMIS magnetopause crossings which exhibit a reversal in the high-speed plasma flow direction in the boundary layer have been identified for this study. The satellite positions, solar wind and IMF conditions for these events are summarized in Table 1. We found a remarkable to perfect agreement between the confirmed (provided by the satellite position) and the predicted (provided by the maximum magnetic shear model) location of the reconnection line for dominant IMF B_Y events. Such a reconnection line crosses the dayside magnetopause similar to the traditional component reconnection tilted X line scenario [e.g., *Sonnerup*, 1970; *Gonzalez and Mozer*, 1974; *Cowley and Owen*, 1989; *Moore et al.*, 2002]. However, in the component reconnection tilted X line scenario the reconnection line is centered at the subsolar point in contrast to the predictions of the maximum magnetic shear model where the reconnection line crosses the dayside magnetopause along the ridge maximizing magnetic shear. This has led to a distinctive dipole dependency (or seasonal dependency) of the reconnection line with a southward shift or northward shift during the northern hemisphere summer and winter seasons, respectively. This study confirmed the seasonal shifts of the reconnection line as predicted by the maximum magnetic shear model.

[38] Two of the observed events had dominant IMF B_X and B_Z conditions and showed different solutions. For these conditions the maximum magnetic shear model predicts a bifurcated reconnection location in the region where merging fields are antiparallel and does not cross the dayside magnetopause as a single component reconnection line.

[39] Dominant IMF B_X cases within the maximum magnetic shear model are complicated by the uncertainties in the IMF draping models. While statistically the majority of events that led to the development of the maximum magnetic shear model exhibit high-latitude antiparallel reconnection locations, some events in the survey showed a component reconnection location. The 31 August 2008 event discussed in Figure 8d could be one of these cases and require a modification of the maximum magnetic shear model. The reasons for these anomalies are currently unknown and require more study. Especially the transition between the maximum magnetic shear tilted X line and the antiparallel reconnection scenarios need to be better identified.

[40] The specific dominant IMF B_X event in this study (Figure 8d) was close to a line of maximum magnetic shear but also close to local noon. In an earlier reconnection location study close to local noon involving Cluster data, SuperDARN radar and IMAGE/FUV observations *Trattner et al.* [2005] found that the field line trace of the reconnection location was consistent with the antiparallel reconnection scenario but located in the component reconnection sector just past local noon. The location was confirmed by the ionospheric response of the precipitating ions observed by IMAGE/FUV. It was concluded that the event was an antiparallel reconnection event and the misplacement indicates a weakness in the models in defining local noon. A similar situation could be occurring for the dominant IMF B_X event in this study. The THEMIS D satellite observed eight southward directed accelerated ion beams emanating from a reconnection line in the north of the satellite (e.g., the antiparallel reconnection region at high northern latitudes) and only one northward directed ion beam located in between all those southward beams. This single northward beam could be emanating from the southern antiparallel reconnection region making this an antiparallel reconnection case in agreement with the maximum magnetic shear model. In addition to the above discussed draping problems with dominant IMF B_X events, this event could simply be misidentified as an event where THEMIS crossed the reconnection line.

[41] The dominant IMF B_Z event followed a dominant IMF B_Y event for which the agreement between the THEMIS C satellite position and the prediction from the maximum magnetic shear model was perfect. While the IMF slowly changed to a dominant IMF B_Z condition which would statistically cause a high-latitude antiparallel reconnection location, the reconnection location now identified by

THEMIS A seems to be unchanged. There are several possible explanations for the disagreement.

[42] 1. The reconnection location shows a certain resistance to change its location (see below).

[43] 2. The current criterion in the maximum magnetic shear model ($\pm 3°$ of being exactly antiparallel) is too stringent, as indicated in Figure 7b.

[44] 3. Similar to cases with dominant IMF B_Y, even the high-latitude antiparallel reconnection regions for dominant IMF B_Z are also connected by a steep tilted X line which so far has not been identified due to the limited number of events around local noon in the original study.

[45] With respect to option 1, the study that led to the development of the maximum magnetic shear model revealed a certain resistance of the reconnection location to migration to a new location when only moderate changes in the IMF and solar wind input conditions occur. This was the case during the last event in this study. A detailed study to quantify this effect and a description of what input condition changes are required to cause a change in the reconnection location is still needed. If this effect is responsible for the current disagreements, the modified model would include the time history of the input conditions to allow a more precise prediction for the reconnection location.

[46] In summary, while the agreement between the confirmed reconnection locations with the predictions from the maximum magnetic shear model is excellent for dominant IMF B_Y cases (component reconnection cases), input conditions that predict an antiparallel reconnection scenario need more studies.

[47] **Acknowledgments.** We acknowledge the use of ISTP KP database. Solar wind observations were provided by the ACE Solar Wind Experiment (ACE/SWE) [*McComas et al.*, 1998] and the Wind "Solar Wind Experiment" (Wind/SWE) [*Ogilvie et al.*, 1995]. The IMF measurements are provided by the ACE Magnetic Field Instrument (ACE/MFI) [*Smith et al.*, 1998] by the Wind "Magnetic Field Instrument" (Wind/MFI) [*Lepping et al.*, 1995]. The work at Lockheed Martin was supported by NASA contracts NNX08AF35G, NNX09AM72G, and NNG05GE15G.

[48] Masaki Fujimoto thanks the reviewers for their assistance in evaluating this paper.

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