# Anomalous magnetosheath flows and distorted subsolar magnetopause for radial interplanetary magnetic fields

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[1]   On 12 August 2007 from 1436 to 1441 UT, when the five THEMIS probes (THA, THB, THC, THD, and THE) were located near the subsolar magnetopause, a sunward flow was observed in the magnetosheath. A fast anti-sunward flow ($-280$ km/s) was observed in the magnetosheath before the sunward flow. Although THA observed this fast anti-sunward flow, THC and THD, which were also in the magnetosheath, instead observed a slow flow, indicating that the fast flow was small in scale. With the observed flow vectors and the magnetopause normal directions estimated from tangential discontinuity analysis, we conclude that this fast flow creates an indentation on the magnetopause, 1 $R_E$ deep and 2 $R_E$ wide. The magnetopause subsequently rebounds, rotating the flow direction sunward along the surface of the magnetopause. The fast flow is likely related to the radial interplanetary magnetic field. **Citation:** Shue, J.-H., J.-K. Chao, P. Song, J. P. McFadden, A. Suvorova, V. Angelopoulos, K. H. Glassmeier, and F. Plaschke (2009), Anomalous magnetosheath flows and distorted subsolar magnetopause for radial interplanetary magnetic fields, *Geophys. Res. Lett.*, *36*, L18112, doi:10.1029/2009GL039842.

## 1.   Introduction

[2]   The bow shock and the magnetopause are formed when the supersonic solar wind interacts with the Earth's geomagnetic field. The magnetosheath is the region between the bow shock and the magnetopause [*Dessler*, 1964]. The large-scale properties of the magnetosheath have been studied with numerical gas dynamics models and in situ observations [e.g., *Spreiter et al.*, 1966; *Spreiter and Stahara*, 1980; *Song et al.*, 1999a, 1999b]. *Petrinec et al.* [1997] and *Shevyrev et al.* [2007] reported that the orientation of the interplanetary magnetic field (IMF) strongly affects the properties of the magnetosheath.

[3]   Magnetosheath flow near the subsolar point is usually slow (<200 km/s) and anti-sunward. Fast flow associated with magnetic reconnection occasionally occurs near the magnetopause, however [*Fuselier et al.*, 1991]. Sunward

flow can occur when the bow shock moves sunward because of a pressure imbalance [*Lin*, 1997]. Interaction between a solar wind disturbance and the bow shock can produce an additional discontinuity or shock that distorts the magnetopause [e.g., *Sibeck*, 1990; *Šafránková et al.*, 2007; *Přech et al.*, 2008; *Zhang et al.*, 2009].

[4]   Solar wind-like magnetosheath flows (or jets) near the flank or cusp have been reported by *Němeček et al.* [1998] and *Savin et al.* [2008]. Here we report a fast flow in the "subsolar" magnetosheath. With THEMIS's multiple observations [*Angelopoulos*, 2008; *Sibeck and Angelopoulos*, 2008], we can advance understanding of such fast flows and their interaction with the magnetopause.

## 2.   Data and Results

[5]   The five THEMIS probes were located near the subsolar magnetopause around 1433:10 UT on 12 August 2007, moving inbound in a string of pearls configuration, as shown in Figure 1a. The magnetopause, indicated by a thick line, was estimated using the magnetopause model of *Shue et al.* [1998]. The solar wind measurements (Figures 1b–1f) from Advanced Composition Explorer (ACE) [*Stone et al.*, 1998] were shifted by 49 min for the propagation time from ACE to THEMIS. The corresponding solar wind velocity ($\sim-460$ km/s) and density ($\sim3$ cm$^{-3}$) were relatively constant during the event. One unique feature of the IMF is its radial orientation during this event, i.e., the magnetic field was nearly aligned with the Sun-Earth line with a cone angle of 5–15 degrees.

[6]   Each of the five THEMIS probes carries an electrostatic analyzer [*McFadden et al.*, 2008] and a fluxgate magnetometer [*Auster et al.*, 2008]. During the 12 August 2007 event, the THEMIS probes observed several magnetopause crossings identified from discontinuities in the plasma and magnetic fields, as shown by the vertical dashed lines in Figure 2. All THEMIS probes except THE (due to missing data) observed "sunward" flow, which is seldom observed in the magnetosheath. The sunward flow was preceded by an anti-sunward flow. The anti-sunward flow observed by THA had a peak speed of $-280$ km/s at 1433:10 UT. The cone angle of the magnetic field in the fast flow (not shown) was small and similar to the small cone angle of the IMF.

[7]   During the event, THB was the innermost probe and THA was the outermost. Prior to the event (1430 UT), the magnetopause was located between THD and THA. Subsequently, the magnetopause crossed THD at 1431:20 UT. It then moved further in and crossed THC at 1431:35 UT. THB detected a magnetopause crossing at 1435:30 UT in association with the fast anti-sunward flow observed from

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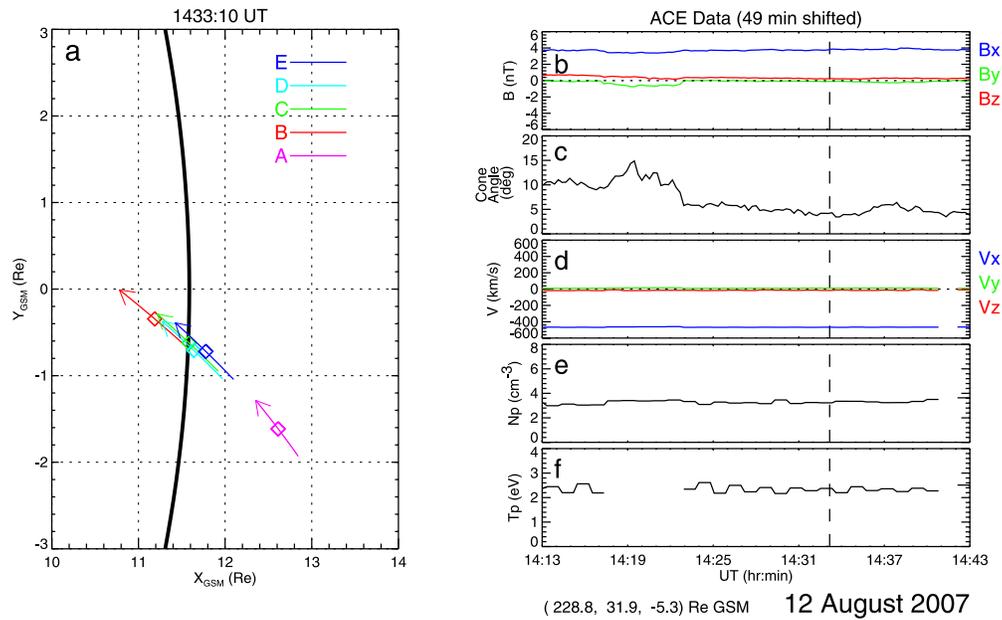
**Figure 1.** Locations of the five THEMIS probes and solar wind measurements from the ACE solar wind monitor around 1433:10 UT on 12 August 2007. (a) The colors of the diamonds represent different probes, as labeled in the legend. Colored arrows denote the moving directions of the probes. The thick solid line represents the magnetopause at 1433:10 UT. (b–f) From top to bottom, the parameters are magnetic field (B), cone angle, solar wind velocity (V), number density ($N_p$), and temperature ($T_p$). The vertical dashed line marks the time that THA first observed the fast anti-sunward flow at 1433:10 UT.

THA at 1433:10 UT. All these timings demonstrate the inward motion of the magnetopause. All four THEMIS probes were then located in the magnetosheath until 1438:10 UT. THA first detected the outbound magnetopause (1438:10 UT), followed by THD (1439:40 UT), THC (1439:45 UT), and THB (1440:30 UT). THA moved to the magnetosheath at 1440:30 UT and back to the magnetosphere at 1440:47 UT.

[8] In the absence of active magnetic reconnection, the magnetopause is commonly considered a tangential discontinuity. With tangential discontinuity analysis, we estimate its normal with the cross product of the magnetic fields on both sides of the magnetopause. We then depict the
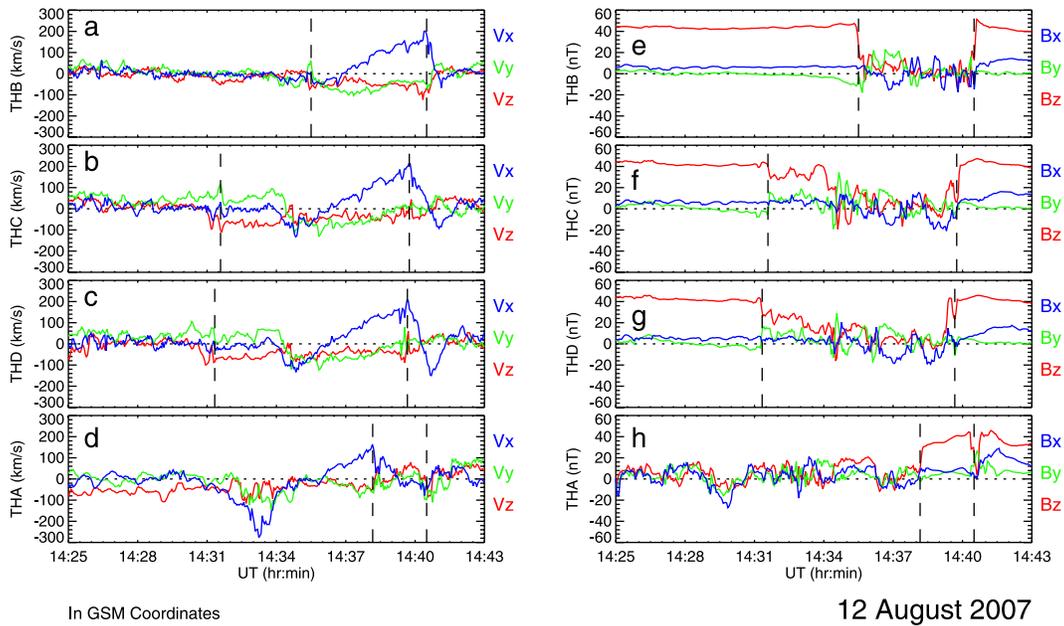


**Figure 2.** THEMIS (left) plasma velocity and (right) magnetic fields during the 12 August 2007 event. THB was the innermost probe and THA was the outermost. The vertical dashed lines mark the magnetopause crossings identified for this event.
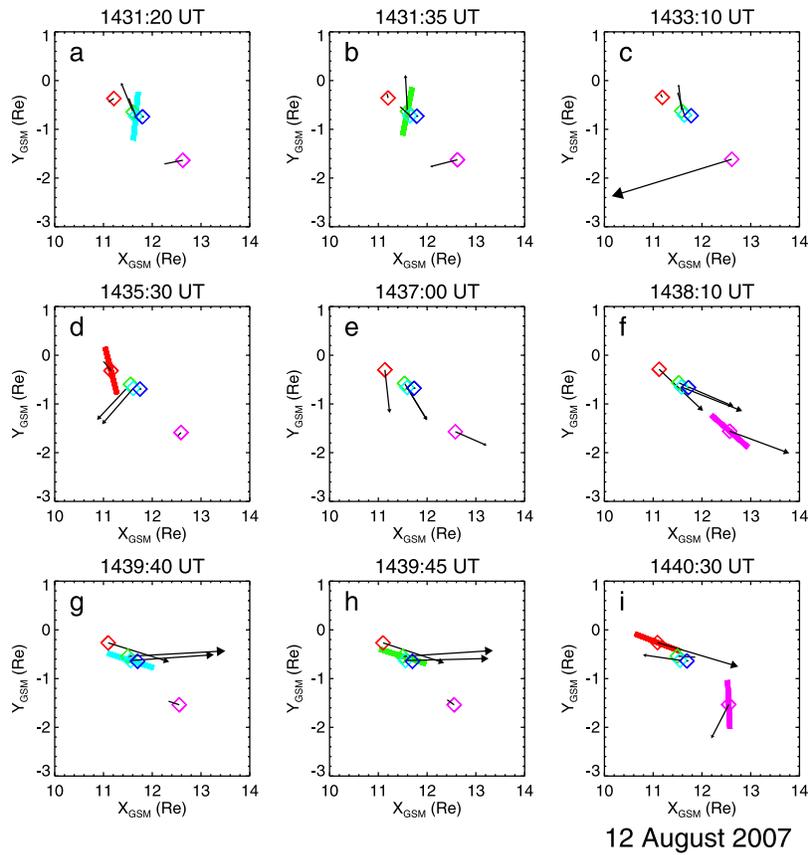
**Figure 3.** The flow vectors and the tangential planes of the magnetopause at various times. The colored diamonds indicate different THEMIS probes, as labeled in Figure 1a. The black arrows starting from the centers of the diamonds show the direction and magnitude of the plasma flows observed by the THEMIS probes. The thick colored lines represent the tangential planes of the magnetopause.

tangential plane of the magnetopause from the normal. Figure 3 shows the determined tangential planes (thick colored lines) and the observed flow vectors (black arrows) projected on to the X-Y plane. The normal directions pointed toward the Sun when the magnetopause moved inward and past THD, THC, and THB. The inward speed, ∼20 km/s, is estimated from the distance between THC and THD along the normal divided by the time difference of the crossings at THC and THD. The calculated normals changed to the +Y-directions after the fast anti-sunward flow impacted the magnetopause, indicating a significant distortion of the magnetopause's geometry.

[9] THA observed a fast anti-sunward flow when THD and THC observed a slow flow, implying that the fast flow in the Y-direction was small in scale. Because the duration of the fast flow was 1 min, we infer that its spatial scale was also small in the X-direction. Eventually the observed flow speed at THC and THD increased to one-third of the peak speed observed at THA. This is likely related to the wake created by the fast flow and the rarefaction effect on the surrounding plasma. All four probes were in the magnetosheath at 1437 UT. Their flow pattern shows a rotation of the anti-sunward flow to the sunward direction. The flow speed became even larger at 1438:10 UT, most likely due to an acceleration resulting from the magnetopause rebound. The rebounded magnetopause forced the flow to be nearly sunward, as shown in Figure 3h. THC and THD were in the

magnetosphere at 1440:30 UT. The speed of the rebounded magnetopause was ∼70 km/s.

[10] Figure 4 is a schematic diagram of the creation of the anomalous sunward flow and the degree of the distortion of the magnetopause suggested by the flow vectors and the tangential planes of the magnetopause shown in Figure 3. A small-scale, fast flow observed at the time created an initial indentation on the magnetopause (Figure 4a). The indentation broadened and reached a maximum size, 2 $R_E$ wide and 1 $R_E$ deep (Figure 4b). Rebound of the magnetopause changed the anti-sunward magnetosheath flow to the sunward direction. After the rebounded magnetopause passed THB, the indentation became smaller (Figure 4c). All the THEMIS probes were in the magnetosphere at 1440:47 UT (Figure 4d).

## 3. Discussion

[11] Subsolar magnetosheath flows are commonly slow and anti-sunward. The possibly anomalous sunward magnetosheath flow was apparently created by the impact of a small-scale, fast anti-sunward flow on the magnetopause and concave indentation and the rebound of the magnetopause. The origin of the small-scale, fast flow remains unknown. We speculate that the fast flow observed by THA is likely related to the radial IMF.
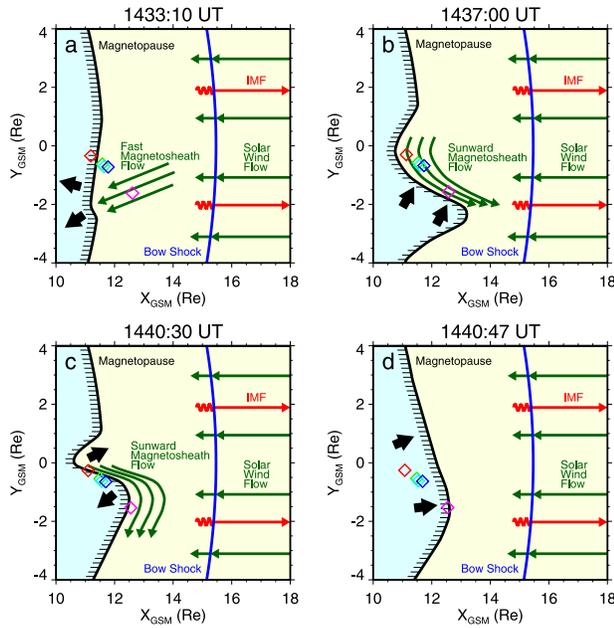
**Figure 4.** Schematic diagrams for the anomalous magnetosheath flows and distorted magnetopause. The colored diamonds represent different THEMIS probes. The large arrows represent the directions in which the magnetopause is moving. (a) The small-scale, fast anti-sunward magnetosheath flow was observed by THA. (b–c) The magnetopause underwent a tremendous distortion. (d) The distortion became much smoother. Figures 4a, 4b, and 4c are based on Figures 3c, 3e, and 3i, respectively.

[12]   *Lin* [1997], *De Sterck et al.* [1998], and *Cable et al.* [2007] reported that a concave bow shock can occur during radial IMF. The high-speed solar wind flows even closer to the Earth in this concave region. When upstream and downstream conditions are no longer suitable for the formation of the concave bow shock, the bow shock will relax into a convex shape. With such a change in geometry, a high-speed solar wind flow will move into the normal region of magnetosheath flow. In this event, we do not have observations near the bow shock, and therefore, are unable to verify this speculation. However, the temperature and density in the peak of the fast anti-sunward magnetosheath flow were at a level intermediate between the solar wind's and the magnetosheath's, but closer to the magnetosheath's (not shown).

[13]   A second possibility for the origin of the fast flow in the magnetosheath is interaction between the bow shock and an interplanetary discontinuity [*Lin et al.*, 1996]. Figures 1b and 1c show a small IMF discontinuity detected at 1423 UT. Assuming a small calculation error for the propagation time from ACE, this discontinuity might be related to the fast flow. However, we believe that this small discontinuity is insufficient to create the fast flow. Moreover, we infer an indented magnetopause, which is different from the bumped magnetopause associated with an IMF tangential discontinuity [*Sibeck et al.*, 1999]. Thus, such a possibility is very slim for this event.

[14]   Following the anti-sunward flow, a sunward flow was detected by all four THEMIS probes. Explaining the larger extent of this rebounded flow in the *Y*-direction requires consideration of interaction of the initially localized anti-sunward flow with the magnetopause. A narrowly confined anti-sunward flow would be expected to pancake as it interacted with the magnetopause, producing an indentation in larger extent than the initial anti-sunward flow. The rebound should subsequently propagate away from the initialization point as a surface wave, covering even a broader lateral area.

[15]   Our event differs from the event proposed by *Sibeck* [1990] who considered a propagating indentation along the magnetopause to the flank from a wide front of pressure variations through the bow shock. The pressure enhancement by the fast anti-sunward flow observed by THEMIS appears to be more confined in both time and space, resulting in a localized interaction with the magnetopause. Since the probes are confined to a relatively small area of the magnetopause, we do not expect to observe a propagating indentation. Therefore, we do not have a clear picture as to how or whether the excess energy in the fast flow dissipates locally.

[16]   An enhancement in solar wind dynamic pressure can produce magnetic perturbations at low and mid-latitudes [*Russell et al.*, 1992]. We have found evidence of such perturbations. The $3-5$ nT perturbations of the north–south component were observed at some low and mid-latitude magnetometer stations near the prenoon sector (not shown), indicating that the geomagnetic activity associated with the enhancement was weak.

[17]   We point out that simple indentation and rebound are inconsistent with the data and require the more complex geometry depicted in Figure 4. For a simple magnetopause undulation, one would expect that THB would observe the outbound magnetopause first, followed by THC, THD, and THA. However, our data show first detection of the outbound magnetopause by the outermost probe THA. All these results indicate a significant distortion on the magnetopause, as illustrated in Figures 4b and 4c. Magnetopause movement should have a significant component in the direction perpendicular to the Sun-Earth direction. The normals of the magnetopause determined by tangential discontinuity analysis confirm this picture.

## 4.   Summary

[18]   We used THEMIS multipoint observations to investigate the interaction between the solar wind and the magnetosphere for the 12 August 2007 event. This event has four unique features: (1) radial IMF; (2) a small-scale, fast anti-sunward magnetosheath flow; (3) a large, sunward magnetosheath flow; and (4) a localized magnetopause indentation. The origin of the small-scale, fast anti-sunward magnetosheath flow remains unknown. However, we believe that it is likely related to the radial IMF. The small-scale, fast anti-sunward flow created a localized indentation on the magnetopause, 1 $R_E$ deep and 2 $R_E$ wide. The magnetopause subsequently rebounded, producing a rotation in the flow direction to sunward along the surface of the magnetopause. The present study provides insights into the dynamics of magnetopause motion under conditions of radial IMF.

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