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


Received 2 July 2009; revised 4 August 2009; accepted 11 August 2009; published 26 September 2009.

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.


1. Introduction

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. Detecting the large-scale properties of the magnetosheath have been studied with numerical gas dynamics models and in situ observations [Supr, 1990; Song et al., 1999a, 1999b]. Petrin et al. [1997] and Shevyr et al. [2007] reported that the orientation of the interplanetary magnetic field (IMF) strongly affects the properties of the magnetosheath.

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; Šafráneková et al., 2007; Přeč et al., 2008; Zhang et al., 2009].

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 “subsonar” 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

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 (~460 km/s) and density (~3 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.

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.

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...
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.

[s] 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 normal in Figure 1.

**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), and temperature (T). The vertical dashed line marks the time that THA first observed the fast anti-sunward flow at 1433:10 UT.

**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 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, $\sim 20$ 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.

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. 

All the THEMIS probes were in the magnetosphere at 1440:47 UT (Figure 4d).

3. Discussion

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.
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).

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.

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.

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.

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.

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

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) a 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.
[19] Acknowledgments. This work was supported in part by National Space Organization grant 97-NSPO(B)-SP-FA07-01 and in part by National Science Council grant NSC-98-2111-M-008-004 to National Central University and in part by Ministry of Education for the Aim for Top University program at NCU. The IGEP team was financially supported by the German Zentrum für Luft- und Raumfahrt under grant 50QP0402. The ACE solar wind data were provided by N. Ness and D. J. McComas through the CDAWeb web site. We acknowledge NASA contract NASS-02099. We downloaded the THEMIS data through the Taiwan AIDA web site.

References


V. Angelopoulos, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095, USA. (vassilis@igpp.ucla.edu)
J.-K. Chao, J.-H. Shue, and A. Suvorova, Institute of Space Science, National Central University, Taoyuan City, 32001, Taiwan. (jchaow@isu.edu.tw; alia@isu.edu.tw)
K.-H. Glassmeier and F. Plaschke, Institute of Geophysics and Extraterrestrial Physics, Technical University Braunschweig, D-38106 Braunschweig, Germany. (kh.glassmeier@tu-bs.de; f.plaschke@tu-bs.de)
J. P. McFadden, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA. (mcfadden@berkeley.edu)
P. Song, Center for Atmospheric Research, University of Massachusetts Lowell, Lowell, MA 01854, USA. (paul_song@uml.edu)