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Asymmetric magnetosphere deformation driven by hot flow anomaly(ies)

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[1] We present a case study of a large deformation of the magnetopause on November 26, 2008. The investigation is based on observations of five THEMIS spacecraft located at the dawn flank in the magnetosphere and magnetosheath, on Cluster measurements at the dusk magnetosheath, and is supported by ACE solar wind monitoring. The main revelation of our study is that the interaction of the IMF discontinuity with the bow shock creates either one very elongated hot flow anomaly (HFA) or a pair of them that is (are) simultaneously observed at both flanks. Whereas the dusk HFA is weak and does not cause observable deformation of the magnetopause, the pressure variations connected with the dawn HFA lead to a magnetopause displacement by ≈5 R_E outward from its nominal position. This is followed by a rapid inward motion of the magnetopause ≈4 R_E inward with respect to the model location. The surface deformation is so large that the outermost THEMIS spacecraft was in the magnetosphere, whereas the spacecraft located 9 R_E inbound entered into the magnetosheath at the same time. The whole event lasted about 5 minutes.
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1. Introduction

[2] Hot Flow Anomalies (HFAs), diamagnetic cavities filled with hot, tenuous, and deflected plasma population, cause non-negligible perturbations of the Earth's magnetosphere. They result from the interaction of interplanetary current sheets with the Earth's bow shock and were discovered more than two decades ago. The main observational features of HFAs in the solar wind include (along with *Schwartz* [1995]): (1) central regions with hot plasma flowing significantly slower than that in the ambient solar wind in a direction highly deflected (up to 90°) from the Sun–Earth line. The flow velocities are often roughly tangential to the nominal bow shock [*Schwartz et al.*, 1988]. (2) HFAs are bounded by regions of enhanced magnetic field strength, density, and temperature, however, many published examples indicated that HFAs are often bounded by only one enhancement. (3) HFAs occur in conjunction with significant changes of the IMF direction.

[3] HFAs have been observed in the solar wind [e.g., *Thomsen et al.*, 1988] or in the magnetosheath [e.g., *Paschmann et al.*, 1988; *Šafránková et al.*, 2002] but usually in close proximity to the bow shock. Simulations of *Thomas et al.* [1991] have shown that their creation is connected with the reflection of particles from the bow shock and a consequent focusing of specularly reflected particles to the discontinuity plane by the motional electric field [e.g., *Burgess*, 1989; *Thomas et al.*, 1991; *Thomsen et al.*, 1993]. HFAs are created at the intersection of the discontinuity and the bow shock. The simulation shows that HFAs evolve upstream on a time scale of several tens of ion gyroperiods and that a similar feature can be observed downstream over a depth of several ion gyroradii. An important feature of the simulations is that HFAs are not limited to the original current sheet but that they grow. In the simulation, the IMF change was only ≈10 ion gyroradii thick but the resulting plasma and magnetic field structures had grown to about 25 gyroradii when the simulation was stopped.

[4] A survey of *Schwartz et al.* [2000] has shown that HFAs are preferentially created by discontinuities nearly aligned with the solar wind flow (with large angles between the normal to the discontinuity plane and the X_{GSE} axis) because then they can sweep along the bow shock surface rather slowly, leaving enough time for the HFA development. The study of *Šafránková et al.* [2000] has shown that HFAs are a frequent phenomenon in the whole magnetosheath and that they interact with the magnetopause causing its both inward and outward displacements. This displacement can be rapid and large. *Sibeck et al.* [1999] reported an unusual event when the magnetopause was swept in 7 minutes to the original bow shock location and back due to the interaction of the bow shock with an interplanetary current sheet resulting in an HFA.

[5] A similar displacement of the magnetopause was presented by *Jacobsen et al.* [2009]. During the event, five THEMIS spacecraft observed the cause and consequence of an extreme motion of the dawn flank magnetopause, displacing the magnetopause outward by at least ≈5 R_E in 59 s, with flow speeds in the direction normal to the model magnetopause reaching 800 km/s. While the THEMIS A, C, D, and E observations allowed the determination of the velocity, size, and shape of a large bulge moving tailward along the magnetopause at a speed of 355 km/s, THEMIS B observed the signatures of a HFA upstream of the bow shock at the same time, indicating that the pressure perturbation generated by the HFA may be the source of the fast compression and expansion of the magnetosphere. As the authors noted, no source of the magnetopause motion was registered by ACE in the solar wind.

[6] The reported event differs from those previously published. From the referenced and many other papers it follows

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Table 1. The Coordinates of All Spacecraft at 1515 UT

Spacecraft	X_{GSE}, R_E	Y_{GSE}, R_E	Z_{GSE}, R_E
THA	4.1	−10.5	−2.4
THB	2.1	−19.1	−1.6
THC	−0.1	−18.5	−2.5
THD	3.7	−10.7	−1.5
THE	2.9	−11.0	−2.0
C4	1.2	+15.6	−11.5
ACE	+224.4	−34.8	+4.1

that the interaction of the interplanetary current sheet with the bow shock can produce an HFA that results in a large local magnetopause deformation propagating with this intersection. The dimensions of the disturbed region in the direction of normal to the current sheet plane were found to be several R_E. However, the intersection of the current sheet and bow shock is a long line and the conditions, namely a portion of energetic particles in the upstream region, change along this line. *Koval et al.* [2005] suggested a large elongation of the disturbance but their suggestion was based on indirect indices.

[7] We present observations documenting that HFAs produced by the same current sheet can be registered simultaneously in the dusk and dawn magnetosheaths near the dawn–dusk terminator. However, the strength of the disturbance was significantly different at these two locations. While it caused a 9 R_E magnetopause displacement within one minute at dawn, no significant magnetopause distortion was recorded on the dusk side. The study is based on simultaneous THEMIS and Cluster measurements and on monitoring of the solar wind conditions by ACE.

2. THEMIS and Cluster Observations

[8] Let us start with the most striking observations. All THEMIS probes [*Angelopoulos*, 2008; *Auster et al.*, 2008; *McFadden et al.*, 2008] were located on the dawn magnetosphere (THA, THD, THE) and magnetosheath (THB ahead of THC) on the afternoon of November 26, 2008. The locations of the probes are listed in Table 1. Note that the X and Z coordinates of the probes are similar, whereas the separation of the innermost (THA) and outermost (THB) spacecraft is larger than 8 R_E along the Y_{GSE} axis. The observations of three of them (THA, THB, and THC) are shown in Figure 1; the ordering of the panels from the left to right corresponds to the spacecraft distance from the Earth. Each panel shows from the top: the components and magnitude of the magnetic field, ion density, ion temperature, components of the ion velocity and ion energy spectrum.

[9] A compression of the magnetosphere starts at ≈1514 UT as the increase of the magnetospheric magnetic field in THA data indicates (the same features are observed by the THD and THE spacecraft, thus we do not shown them). This compression causes the magnetopause crossings observed nearly simultaneously by all three spacecraft at ≈1516:30 UT. The spacecraft entered magnetosheath for more than 1.5 minute and returned back to the magnetosphere. The magnetosheath interval can be easily identified by the sharp density increase and is marked with a red thick bar in the density panel. The magnetic field strength in the magnetosphere returned to its pre-event value. Note that the orientation of the magnetospheric magnetic field (northward and slightly dawnward) is consistent with the THEMIS location at the dawn terminator.

[10] A direct evidence of rapid and large-amplitude magnetopause motion is seen in measurements of THB and THC probes that were located outbound in the magnetosheath and, as already noted, separated from THA by ≈8 R_E along the Y_{GSM} axis. At ≈1515 UT (first vertical dashed line), THC observed a weak increase and then a sharp decrease of the density accompanied with the change of the flow direction. Such events in the magnetosheath are often connected with magnetosheath HFAs. Identification of the event as an HFA is supported by the fast–speed (≈575 km/s) solar wind [*Šafránková et al.*, 2000; *Facsko et al.*, 2008] and by the temporary density increase at 1515:30 UT that is often observed within magnetosheath HFAs [*Šafránková et al.*,

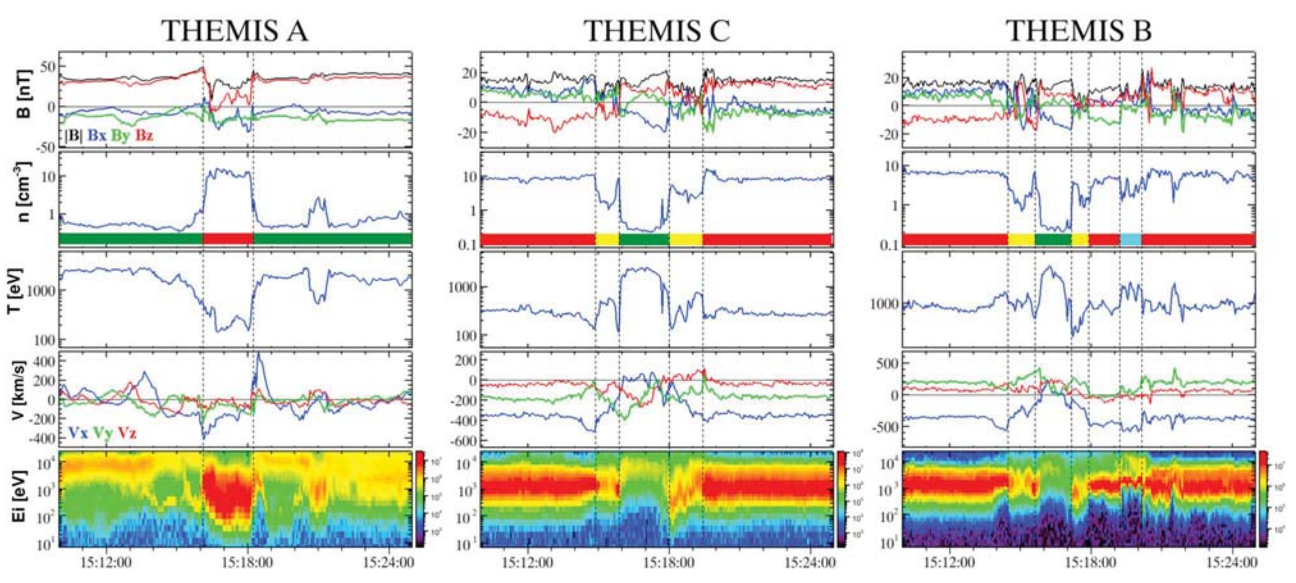

Figure 1. THEMIS A, C, and B measurements. (top to bottom in each panel) Three components and strength of the magnetic field; the ion density, temperature; three components of the ion velocity; and ion spectra. The heavy bars mark the different regions bounded by the dotted vertical lines: green - magnetosphere; red - magnetosheath; yellow - HFAs; and blue - solar wind.

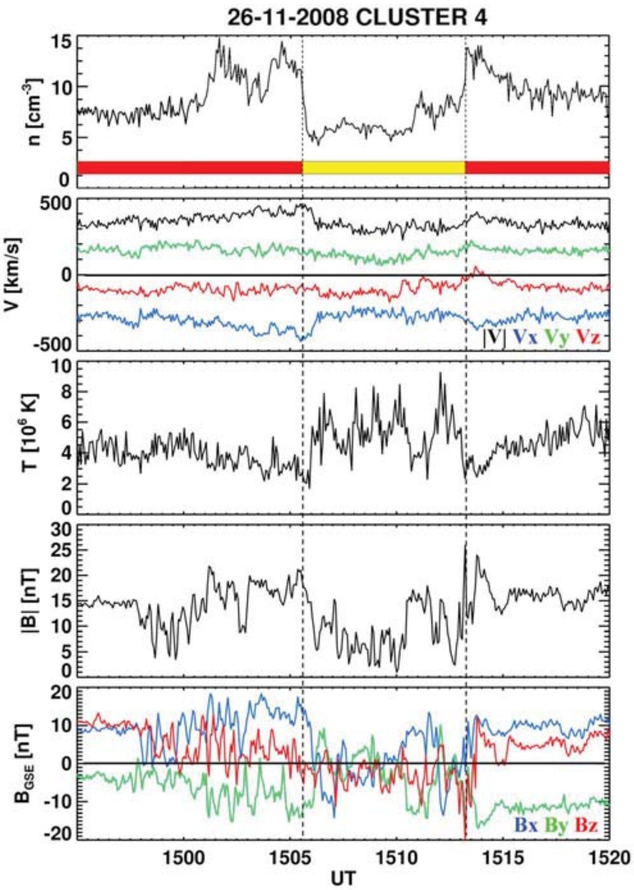

Figure 2. A detailed measurement of C4. (top to bottom) The ion density; three components and magnitude of the velocity; the ion temperature; the magnetic field strength; and three magnetic field components. The heavy bars identify: red - magnetosheath; and yellow - time of a HFA observation.

2002]. This enhancement is followed by a sharp magnetopause crossing to the magnetosphere. At 1518 UT, THC returned to a low density region bounded by the density spike between 1519:30 and 1520 UT. This region can be attributed to the second half of the HFA observed prior to the magnetospheric interval [*Šafránková et al.*, 2002]. THC entered the sheath proper at ≈1520 UT.

[11] Observations of THB resemble those of THC with a slightly different timing. A small difference is a pair of bow shock crossings observed at 1519:30 and 1520:30 UT. The solar wind interval is marked by the blue bar in Figure 1. It means that the whole region from the magnetosphere to the solar wind was swept within ≈2 minutes along THB. Moreover, THA was located in the magnetosheath, whereas THB entered simultaneously into the magnetosphere. It suggests either a very large magnetopause deformation or a detached blob of the magnetospheric plasma in the magnetosheath.

[12] However, we can check a possible distortion of the magnetosphere on the other flank because the Cluster spacecraft were located in the middle of the magnetosheath near the dusk terminator. Due to their short separations, all of them see generally the same features, thus we are showing Cluster 4 (C4) [*Reme et al.*, 2001; *Balogh et al.*, 2001] as an example in Figure 2. One can clearly identify the density and magnetic field depression bounded with their enhancements. The flow is deflected and the temperature increased within the core of the event. All these features characterize a HFA. Nevertheless, the event is not as strong as that observed by THEMIS; the density drops by a factor of two and the velocity decrease is small but the observed structure can be classified as a HFA.

3. Discussion

[13] Since the magnetosheath disturbances were identified as HFAs that would result from the interaction of the IMF discontinuity with the bow shock, we will search for such discontinuity in upstream observations. The location of ACE (+224.4; −34.8; +4.1 R_E in GSE) was favorable for such investigation because it was monitoring the solar wind just upstream of THB and THC if the Earth orbital motion is taken into account. The IMF and solar wind parameters from ACE, C4, and THC are shown in Figure 3.

[14] The low upstream density (≈2.5 cm^{-3}) and high velocity (≈575 km/s) resulted in typical driving parameters: the upstream dynamic pressure (p_{SW} ≈ 1 nPa) and Mach number (M_A ≈ 9). Their variations during the analyzed interval would lead to magnetopause displacements by ≈±0.1 R_E and thus they cannot be the source of the

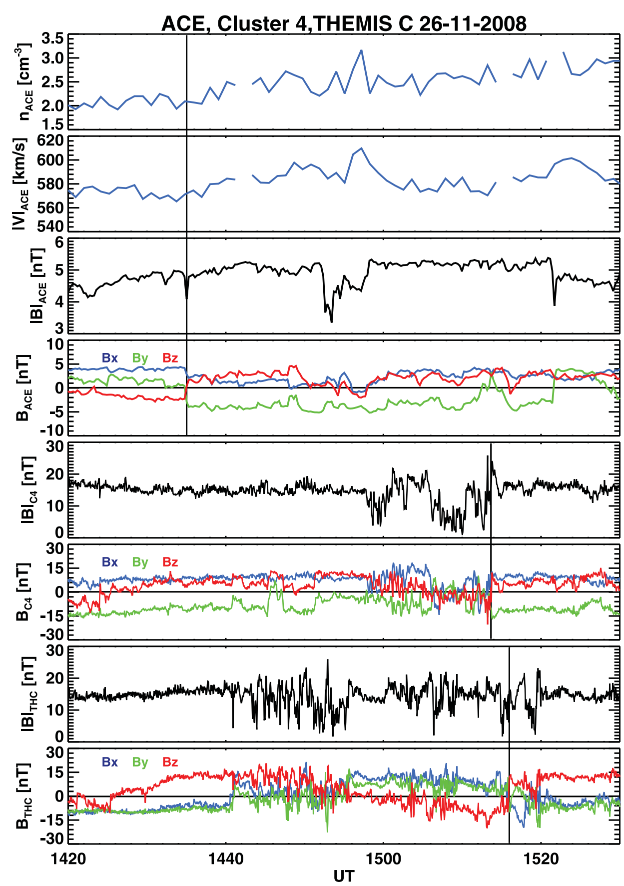

Figure 3. The ion density and solar wind speed observed by ACE and a comparison of the magnetic fields (the strength and three components) in the GSE coordinate system measured by ACE, C4, and THC.

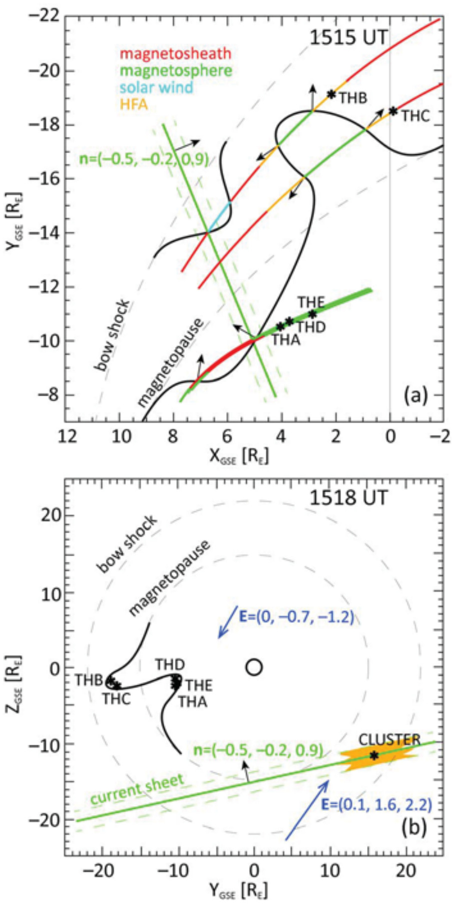

Figure 4. (a) A sketch of the event from THEMIS observations in the *XY* plane. The nominal magnetopause and bow shock locations were computed using the *Shue et al.* [1998] and *Jeřáb et al.* [2005] models, respectively (dashed lines). The regions visited by a particular spacecraft are distinguished by different colors (red - magnetosheath; green - magnetosphere; blue - solar wind; and yellow - time of HFA observations). The black arrows mark directions of the normals to the boundaries and black curves demonstrate schematically the estimated magnetopause and bow shock surfaces during the event. The light green line with the arrow shows the IMF discontinuity plane. (b) The magnetosphere cross–section at $X = -2\ R_E$ demonstrates the orientation of the IMF discontinuity leaving the Cluster location and approaching THEMIS. The thickness of the (dusk part) HFA is shown by the yellow area along the discontinuity plane that is marked by the light green line. Note that the value and direction of the motional electric field, E is shown by blue arrows.

observed crossings. On the other hand, the IMF direction changed several times at the ACE location. The ACE–THC separation and measured solar wind speed lead to time lag of ≈41 minutes and, indeed, at 1434 UT, one can identify the IMF rotation similar to that observed by THC and C4 within the HFA. These discontinuities are marked by vertical lines in Figure 3. All spacecraft measure the same profile of the B_Z component that is positive, nearly linearly decreases to negative values and jumps to positive values at the current sheet. The B_Z component is less sensitive to draping effect, especially at the THEMIS location. At the C4 location in the magnetosheath, positive IMF B_X adds a positive contribution to B_Z that is really observed.

[15] Consequently, the most probable cause of observed phenomena is the interaction of the IMF rotation seen by ACE at ≈1431 UT (Figure 3) with the bow shock. This discontinuity is characterized by a change of signs of the B_Y and B_Z components and can be identified in measurements of all spacecraft, in spite of modulation of THC and C4 data by the foreshock and HFA effects. Since there are only negligible changes of plasma parameters across the discontinuity, it can be classified as a tangential discontinuity and the normal can be determined by minimum variance technique. We have applied this technique to Wind and ACE data but the results were quite different, probably due to a small current sheet undulation. Since we are interested in global features, we have used four spacecraft (Wind, ACE, THB, C4) method and obtained a normal (−0.46; −0.19; 0.86). The discontinuity with such orientation will move very slowly (about 140 km/s) along the bow shock surface. The motional electric field ($E = v_{SW} \times B$) points towards the discontinuity on both sides ($E_{upstream}$ = (0; −0.7; −1.2) mV/m, ($E_{downstream}$ = (0.1; 1.6; 2.2) mV/m) and thus such discontinuity can create the HFA [][and references therein *Šafránková et al.*, 2000] that is observed by C4. The discontinuity is then swept along the bow shock surface and creates the HFA in the dawn magnetosheath registered by THEMIS probes. Such orientation is probably principal for a nearly simultaneous HFA observation in both dawn and dusk magnetosheaths.

[16] THEMIS probes in the dawn magnetosheath or magnetosphere observed a strange sequence of magnetopause crossings. In order to explain these crossings, we assume that they are caused by a tailward motion of a deformation along the magnetopause surface with a speed of 320 km/s measured in the magnetosheath by THC. Since the deformation creates a significant obstacle to the magnetosheath flow and no deflection or deceleration is observed, this assumption is well justified and leads to the sketch shown in Figure 4a. The locations of the spacecraft at 1515 UT are denoted by stars and the time sequences of the measurements were projected from these points along the mean magnetosheath streamlines taken from the *Spreiter et al.* [1966] gas dynamic model. The visited regions are distinguished with colors that correspond to those in Figures 1 and 2. The nominal magnetopause and bow shock locations were computed according to the *Shue et al.* [1998] and *Jeřáb et al.* [2005] models, respectively. The magnetopause first moves out by ≈5 R_E due to the density depletion inside the HFA and then it apparently moves ≈9 R_E inward being observed about 4 R_E inward from its nominal location.

[17] The analysis of the pressure balance shows that the total pressure within the HFA is depleted by a factor of 4–5 with respect to the magnetosheath value which roughly agrees with the observed outward magnetopause displacement. On the other hand, the pressure increase at the HFA trailing edge by a factor of 2 seems to be too small to explain the observed magnetopause compression. However, the changes are very fast in comparison with the time needed for the full scan of the velocity distribution and thus the maximum value of the plasma pressure can be underestimated. The pressure variations are weaker in the dusk magnetosheath, and thus no boundary motions are observed by C4.

The closest distance of the Cluster spacecraft to the model magnetopause [*Shue et al.*, 1998] is 1.6 R_E, which is an upper limit of a possible magnetopause expansion because none of Clusters observed the magnetopause crossing.

[18] Since the original IMF discontinuity proceeds along the bow shock from south to north, the cross–section of the magnetopause in the *X–Z* plane would be of interest but, unfortunately, all THEMIS spacecraft have approximately the same *Z* coordinate and there are no data that could support such drawing. Nevertheless, we are showing a sketch of the IMF discontinuity interaction with the bow shock in Figure 4b. This sketch is based on the calculated discontinuity normal and timing of observations at both flanks and shows the projection to the plane $X = 2\ R_E$ that is between C4 and THEMIS locations. It allows us to estimate the dimensions of the HFA core along the discontinuity normal given in the figure. The thickness of about 4 R_E (or ≈40 ion gyroradii) is significantly larger than that following from simulations of *Thomas et al.* [1991] but the errors of our estimations are rather large and the simulation conditions are simplified. The cross–section of the magnetopause deformation observed by THEMIS is shown approximately at 1518 UT when THA, THD, and THE were in the magnetosheath, whereas THB, and THC were located in the magnetosphere.

[19] The dawn–dusk asymmetry of the disturbance strength is probably connected with the time needed for its evolution. The current sheet first hits the southern part of the bow shock, arrives to C4 and proceeds to THEMIS where it was recorded several minutes later. *Schwartz et al.* [2000] suggest the ratio of the current sheet transit velocity along the bow shock and ion gyro-velocity is a criterion for HFA formation. This ratio would be smaller (<0.6) to leave enough time for HFA formation. Ratios appreciably smaller than unity require large current sheet normal cone angles in addition to a nearly perpendicular current sheet–bow shock intersection. We have calculated this ratio at C4 and THB locations and at the subsolar point. The values obtained range from 0.5 at C4 to 0.3 at THB and at the subsolar region. This indicates a probable HFA formation along the whole bow shock–current sheet intersection.

[20] Last but not least, we should point out that we have analyzed the observations of the GOES spacecraft as well as ground magnetograms. However, we did not find remarkable responses; the GOES magnetic field changes within 2% of nominal values only.

4. Conclusion

[21] We have analyzed simultaneous observations near the dawn magnetopause and bow shock by the five THEMIS spacecraft and Cluster measurements in the dusk magnetosheath. We can conclude that:

[22] 1. Although the precise IMF orientation just upstream from the Earth's bow shock may differ from that seen far upstream; the IMF discontinuity observed by ACE can be identified in both magnetosheath flanks.

[23] 2. The interaction of this discontinuity with the bow shock results in nearly simultaneous observations of HFAs in both the dawn and dusk magnetosheaths. Nevertheless, the analysis of the current sheet speed indicates that the observed features can belong to one large HFA that spans along the whole dayside magnetopause from the dawn to dusk.

[24] 3. Whereas the dusk HFA (or its dusk part) was weak and did not result in the observable motion of the bow shock and magnetopause, a significant deformation and displacement of both boundaries were observed on the dawn side.

[25] 4. The analyzed magnetopause displacement is generally similar to but larger than those reported by *Sibeck et al.* [1999] and by *Jacobsen et al.* [2009]. We are able to determine the size of the magnetopause deformation to be larger than 9 R_E along the Y_{GSE} axis. It is the largest magnetopause deformation ever recorded.

[26] These conclusions are based on a lucky configuration of the spacecraft and we think that the probability to find a similarly documented case is very low. However, a statistical processing of the data collected by THEMIS, Geotail, and Cluster at the dayside magnetopause would quantify the recurrence and thus the importance of such phenomena.

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