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Coordinated observation of the dayside magnetospheric entry and exit of the THEMIS satellites with ground-based auroral imaging in Antarctica

S. B. Mende,[1] H. U. Frey,[1] J. McFadden,[1] C. W. Carlson,[1] V. Angelopoulos,[2] K.-H. Glassmeier,[3] D. G. Sibeck,[4] and A. Weatherwax[5]

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[1] Data from the five-satellite Time History of Events and Macroscale Interactions during Substorms (THEMIS) constellation suitably located to study solar wind magnetospheric coupling during the austral winter of 2007 were compared to data from ground-based all-sky imagers (ASIs) at South Pole (74° magnetic latitude) and at AGO-1 (80° magnetic latitude). The THEMIS constellation entered and exited the magnetosphere near magnetic midday on 10 and 12 August 2007, respectively. On 12 August interplanetary magnetic field (IMF) ($B_z > 0$) the dayside aurora was located more poleward between AGO-1 and South Pole. The THEMIS satellites traversing the magnetopause saw it move in and out several times during the satellite crossings. The inward motion of the magnetopause was sometimes correlated with equatorward expansions of the aurora and sometimes with solar wind pressure pulses as seen by Geotail. The $B_z > 0$ auroral latitude was consistent with dayside cusp "spot" seen by the IMAGE spacecraft and had been associated with footprints of "steady state" lobe reconnection. The aurora consisted of a continuous stream of poleward moving auroral forms (PMAF) even during a period of slightly $B_z > 0$ and $B_y = 0$. On 10 August 2007 IMF $B_z < 0$ the dayside aurora was located more equatorward, over South Pole, and the THEMIS satellites crossed the bow shock from the magnetosheath into the solar wind. Negative B_z pulses observed at the satellite were correlated with large poleward expansions of the dayside aurora consistent with reconnection in the subsolar region accompanied by simultaneous plasma density increases at THEMIS B satellite consistent with outward radial motion of the bow shock.

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1. Introduction

[2] The dayside magnetosphere plays a crucial role in controlling the mass and energy inflow from the solar wind. The THEMIS satellite constellation [*Angelopoulos et al.*, 2008] was in a favorable position to study solar wind magnetospheric coupling during the northern summer (June, July and August) of 2007. The apogee of the orbits of the five THEMIS satellite orbits were aligned so that the major axes and apogees were approximately pointed toward the sun and the satellites repeatedly crossed dayside magnetospheric boundaries. During the northern summer (austral winter) period the high-latitude region in Antarctica near the South Pole is permanently dark allowing 24 h of optical auroral observations including the recording of magnetic midday (1530 UT at South Pole) auroras. To take advantage of this situation we deployed a network of observatories of U.S. Automatic Geophysical Observatories (AGOs) and operated all-sky imagers (ASI) at each station and also at South Pole. The THEMIS satellite configuration provided a unique opportunity to investigate the solar wind-magnetosphere-ionosphere interactions, its reflections in the aurora and in the plasma and field data measured simultaneously by the five THEMIS satellites. The ground-based optical observations provide a high-resolution two-dimensional dynamic view of the auroral context of the five single point satellite measurements. Conversely the satellites provide the plasma and field data required to interpret the conditions that cause the aurora and its dynamics.

[3] In the dayside magnetosphere the most important energy and mass entry process is magnetic reconnection. It

[1]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[2]Institute of Geophysics and Planetary Physics, Department of Earth and Space Sciences, University of California, Los Angeles, California, USA.
[3]Institute for Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, Braunschweig, Germany.
[4]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[5]Department of Physics, Siena College, Loudonville, New York, USA.

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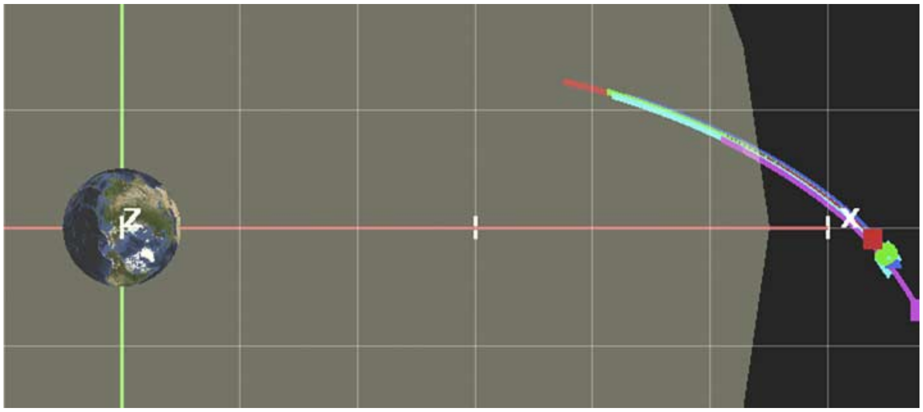

Figure 1. The THEMIS satellites were fairly close to the subsolar point as they were entering the magnetosphere on 12 August 2007. They are illustrated at their position at 1200 UT, but the orbit track is shown until 1800 UT. THEMIS B (red) leads with C, D, and E following in close formation with A (pink) trailing behind. The squares represent a 2 R_e grid.

is possible that a steady streams of solar wind particles enter the magnetosphere; however, there is much evidence from encounters with satellites that the dayside magnetosphere is highly dynamic and satellites often have multiple encounters with the highly variable magnetospheric boundaries. For example using data from the ISEE 1 and 2 satellites magnetic transient events were observed by *Russell and Elphic* [1978, 1979]. They interpreted it as pulsed reconnection or magnetic "flux transfer events" (FTEs). These events had specific magnetic signatures, a bipolar magnetic variation in the boundary normal component at the dayside magnetosphere. During these events previously closed geomagnetic field lines were connected to the interplanetary magnetic field (IMF) by the reconnection process. Ground-based signatures of FTEs were modeled by *McHenry and Clauer* [1987] but their detection proved to be difficult. *Mende et al.* [1990] showed that dayside magnetic impulsive events were often associated with transient equatorward motions of the equatorward boundary of the dayside aurora. Later on it was realized [*Sibeck et al.*, 1989] that the ground-based radar and magnetic signatures may well have been caused by pulsations of the solar wind dynamic pressure.

[4] Prior to the THEMIS mission we had relied usually on distant spacecraft (IMP 8, ACE or GEOTAIL) to measure the simultaneous IMF and solar wind parameters. With THEMIS we often have a satellite acting as solar wind monitor close by, measuring the relevant IMF and solar wind parameters with adequate temporal and spatial resolution. There is also the fundamental question associated with the spatial and temporal scales associated with pulsed reconnection. Both pulsed reconnection and solar wind pressure can cause dynamic changes in the magnetopause boundary position. The favorable location of the THEMIS satellites and the Antarctic observatories under the foot of the field lines from the satellites provide opportunities to relate the magnetopause boundary changes and the dynamics of the aurora.

[5] In this paper we will compare simultaneous observations of the magnetopause boundary by THEMIS and the dayside aurora during the midday period from 1200 to 1800 UT on 12 August and on 10 August 2007. Local magnetic noon at South Pole and at the AGO array is at about 1530 UT. In the first case the THEMIS satellite constellation entered the dayside magnetosphere while the IMF B_z was weakly positive and in the second case it exited during a period of B_z weakly negative.

2. THEMIS Spacecraft Entry Into the Magnetosphere on 12 August 2007

[6] The THEMIS satellite orbits between 1200 and 1800 UT are shown on Figure 1 using the NASA GSFC TIPSOD software. At the beginning of this period the satellites were just outside the magnetopause and they were in the process of entering the magnetosphere. On their elliptical orbit THEMIS B was leading the constellation and THEMIS A was the last. The others were clustered closely together.

[7] Geotail was slightly upstream but outside of the magnetosphere (x = 20,000 km, y = 160,000 km) on 12 August 2007. From Geotail measurements we know that B_z was fluctuating with mainly positive amplitudes up to about 2–3 nT until about 1500 UT. After that it was slightly negative but still fluctuating until 1650 UT. IMF B_y was almost zero with some positive fluctuations throughout this entire period. The solar wind plasma density was very low $\sim$1 cm^{-3} until 1500 UT after that there are stronger density pulses ($\sim$6 cm^{-3}) in the solar wind as measured by GEOTAIL.

[8] The position of the foot points of the satellites are illustrated in Figure 2 using the Tsyganenko 96 model and plotting the field line down to 100 km altitude while the satellites were inside the magnetosphere. The loci of the foot points is represented with colored solid lines where each color represents the appropriate satellite as called out by the legend in the top left corner. When the satellites were outside the magnetosphere the field line model did not provide a solution. In such cases the satellite positions were projected radially inward until a field line solution could be obtained and the calculated foot point of that field line was found and their track is indicated in Figure 2 as the thin line. In such cases the foot point represents only the region of the magnetopause located down stream of the satellite.

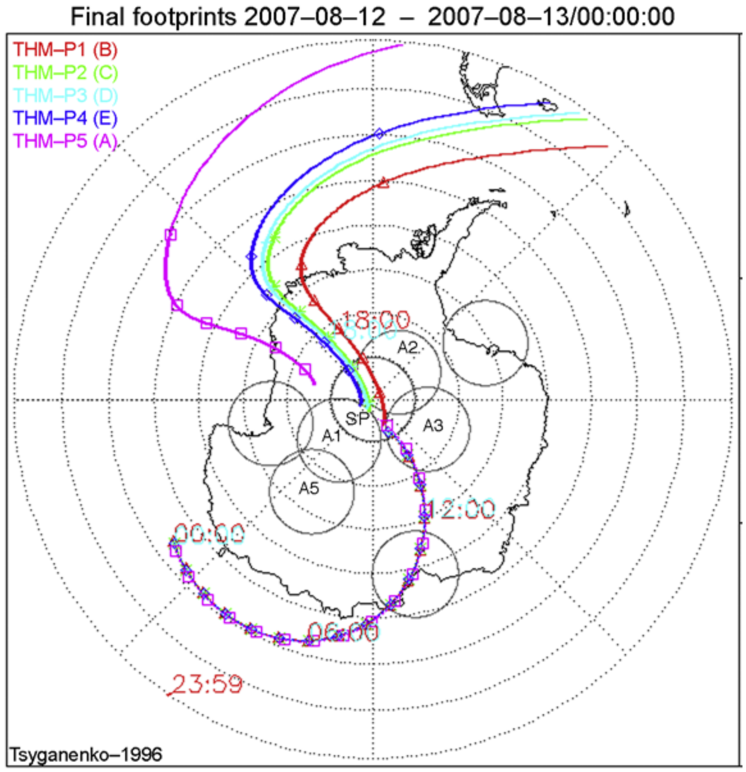

Figure 2. Foot point plots of the THEMIS satellites for 12 August 2007. The Antarctic stations and the field of view of their all-sky imagers are shown as circles. The U.S. Automatic Geophysical Observatories (AGOs) are labeled A1, A2, A3, and A5, and South Pole station is noted as SP. Magnetic midday occurs approximately at 1530 UT at South Pole.

[9] Figure 2 shows the foot points for the entire day of 12 August. At 0000 UT the satellites were outside of the magnetosphere and the foot point of their projection to the magnetopause had a relatively constant magnetic latitude, hence they show an approximately circular pattern around the earth magnetic pole located near AGO-5 (A5 on the map) FOV circle. 1200 UT is indicated in Figure 2 and THEMIS B enters the magnetopause at around 1500 UT, where the solid red line begins. This is well within the South Pole ASI field of view. The other satellites enter at different positions with THA being last and quite a distance north from South Pole (violet curve).

[10] The THEMIS overview plots were presented in Figure 3 for THEMIS B, which was the leading satellite. The keogram from AGO-1 and South Pole were shown above the THEMIS summary plots. The AGO and South Pole cameras have a field of view of 160° and cover a region which extends plus or minus 4.5° in latitude at an assumed auroral height of 110 km. The vertical axis of the keogram was given as a zenith angle from 0° (equatorward) to 160° (poleward) with the zenith being at 80°.

[11] Figure 3 shows the Geotail dynamic pressure (third panel) the THEMIS satellite fluxgate magnetometer [*Auster et al.*, 2008] (fourth panel), the plasma density (fifth panel), the plasma flow velocity (sixth panel), the plasma temperature (seventh panel), the ion spectrogram (eighth panel) and the electron spectrogram (ninth panel). The THEMIS overview plots clearly show the entry of the satellite into the magnetosphere. At first (1200 UT) the satellite is in the magnetosheath with the weak magnetic field (B_z) slightly positive and the plasma density (fifth panel) high. The chart shows that later, after 1530 UT the satellite was in the magnetosphere because the magnetic field was high, 30–40 nT and the plasma density was low. The change from inside to outside of the magnetosphere was quite abrupt and there is evidence that near the entry point the satellite made several entries and sometimes found itself sometimes inside and sometimes outside of the magnetopause boundary. We attribute the observed changes to rapid inward and outward motions of the boundary. The rest of the THEMIS panels of plasma temperatures and energy spectrograms are entirely consistent with this interpretation.

[12] Figure 4 is the same as Figure 3 except it is for THEMIS A, the trailing satellite. It is quite evident that THEMIS A sees the same kind of plasma signatures except that it is seen later.

3. Discussion of the 12 August 2007 Events

[13] In Figure 3 the first panel shows the keogram taken from AGO-1 ASI. The data shows the latitudinal variations associated with the poleward boundary of the aurora. The aurora was mostly near to the (magnetic) equatorward limit of the FOV of the AGO-1 ASI located at 80 degrees magnetic latitude. A similar ASI located at South Pole Station at 74 degrees magnetic latitude (see map on Figure 2) saw the same aurora near the poleward limit of its FOV. The same features of the aurora can be recognized in the two keograms.

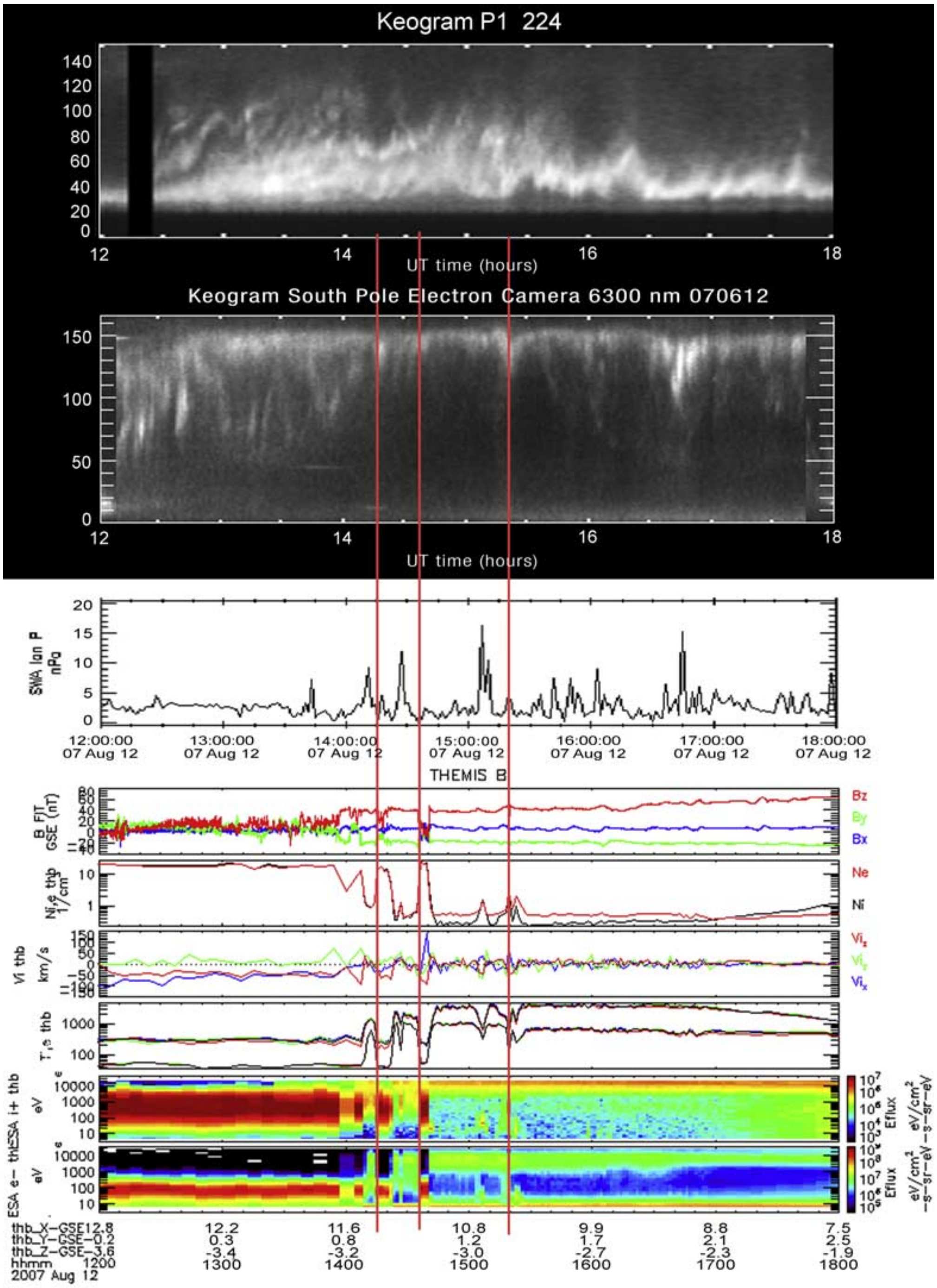

Figure 3. Keogram from AGO-1 (magnetic latitude (MLAT) = 80°) and South Pole (MLAT = 74°). Geotail dynamic pressure and THEMIS B (leading satellite) overview plots for 12 August 2007. The satellite foot point was in the South Pole camera field of view between 1500 and 1700 UT. The *y* axes on the keograms are zenith angle in degrees, where 80 is the local zenith.

[14] In Figures 3 and 4 the keogram from South Pole station (second panel) depicts the equatorward boundary of the aurora. We can distinguish several intensifications of the boundary and downward (magnetic equatorward) movement of the boundary or expansions of the aurora. An example is the intensification seen at 1415 UT indicated with the first red vertical line in Figure 3. This equatorward movement of the aurora is simultaneous with the large increase in plasma density at THEMIS B and signifies that the satellite appeared to return into the magnetosheath, because the data shows plasma properties characteristic of regions just outside the magnetopause. The simultaneous depression of the B_z component is consistent with this explanation. Thus the magnetosphere appeared to have contracted putting the satellite back out into the magnetosheath.

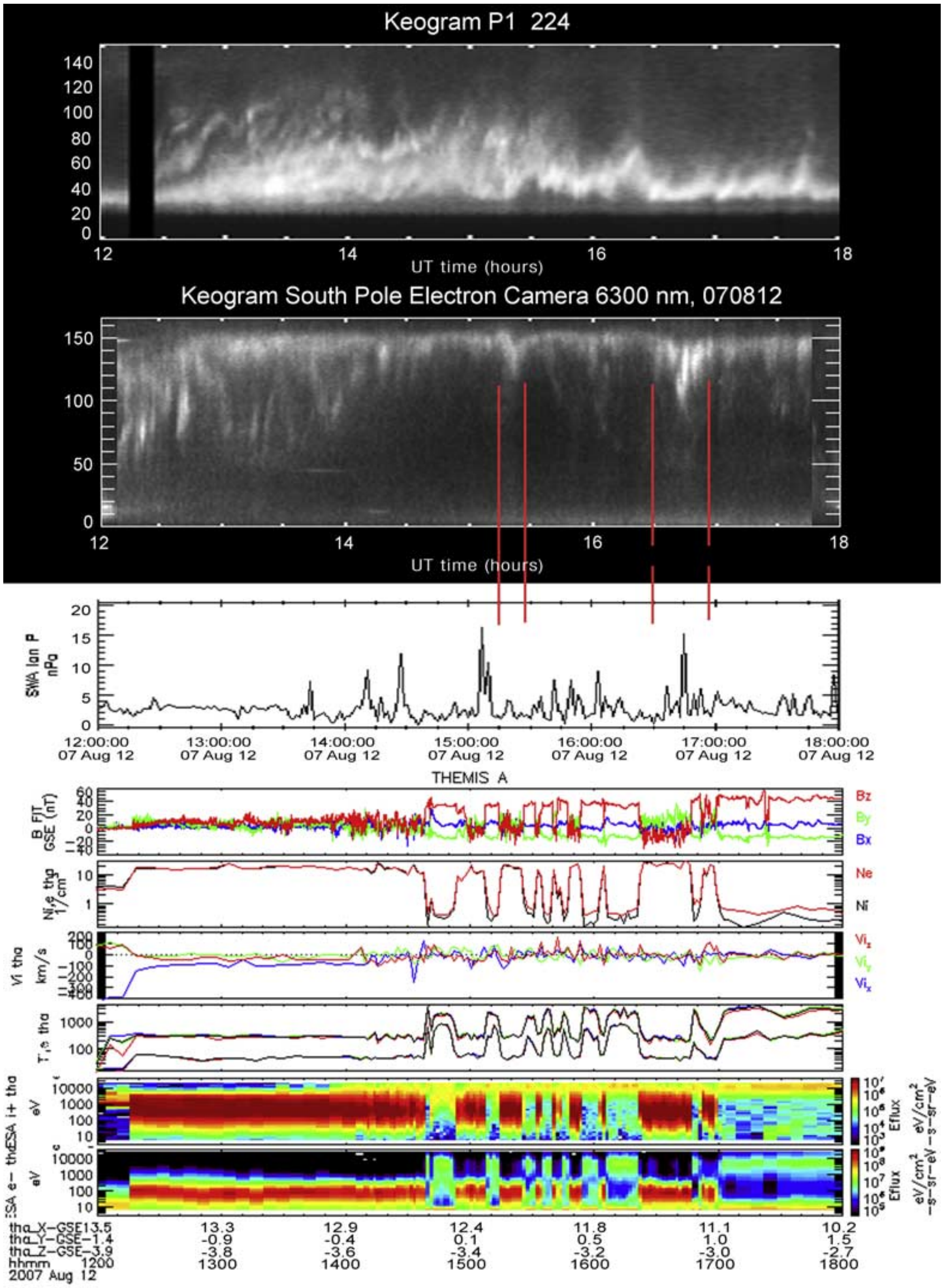

Figure 4. Same as Figure 3 but with THEMIS A (trailing satellite) overview plot.

[15] In general the radial motion of the magnetopause can be caused by two major mechanisms: (1) an increase or decrease of the solar wind dynamic pressure or (2) an erosion of the dayside closed field line region. In case 1 we would expect that the field line would bend to accommodate the change in pressure but its foot points would stay anchored in the very strong magnetic field near the earth surface. In case 2 we would expect to see the field line as a whole change from being an open to a closed field line or vice versa in which case we would expect an aurora associated with the boundary of open and closed field lines to move. We have presented the Geotail plasma pressure data in the third panel. We can see that there is also some simultaneous response in dynamic pressure at THEMIS B for three of the Geotail observed pressure pulses which occurred just left of the red lines.

[16] An equatorward auroral motion indicates that there was a contraction of the region of closed field lines involving the movement of the entire field line including its foot points. This behavior is consistent with an erosion of the closed field flux, i.e., showing that a flux region had become "open." This is contrasted with the effect of pressure pulses, which would push the closed field line region in the antisolar

direction at the satellite but leave the foot of the field line unchanged [e.g., *Mende et al.*, 1998].

[17] There was another marked decrease in the field and corresponding plasma density increase at 1437 UT indicated by the second red vertical line. We can recognize a corresponding intensity enhancement at the equatorward boundary although it is not as pronounced as the previous one. A third more distinct equatorward boundary intensification and equatorward movement took place at around 1520 UT (third red line). There was some appreciable response in plasma density at THEMIS B but only a minimal change in the B field. By this time the satellite was too far in the magnetosphere to be reenveloped by a moderate change in magnetopause boundary position. Similarly the pressure pulse at 1645 does not cause any change at the satellite.

[18] THEMIS A entered the magnetosphere at 1445 UT for the first time (see Figure 4). It is quite evident that THEMIS A sees the same kind of plasma signatures as THEMIS B saw except that it is seen later and there were more pulsations. The first crossing of the magnetopause is at 1440 UT. We marked two time intervals bounded with red vertical lines. The first one is from 1512 to about 1527 containing an equatorward excursion of the aurora. Similarly another one bounded by 1630 and 1656 encapsulates a second equatorward movement of the aurora. There are several pulsations of the magnetopause which appear as multiple entries and exits from the magnetosphere in between but they do not have obvious signatures in the equatorial boundary of the aurora.

[19] After 1445 UT when THEMIS A entered the magnetopause, we used GEOTAIL as our upstream monitor. The IMF field as measured by GEOTAIL was slightly positive until about 1500 and then it was negative until 1650. The event that took place at 1410 was during a prolonged period of B_z positive. The GEOTAIL plasma density observations show that after 1500 UT there were several pulsed increases (from about 3 nPa to about 15 nPa) in the solar wind dynamic pressure. There is excellent correlation between the Geotail dynamic pressure and THEMIS A ion density between from 1515 to 1815 UT. Since these are pressure pulse generated changes there is a lack of correlated auroral signatures.

[20] In summary we suggest that some inward motions of the magnetopause (without corresponding auroral equatorward extensions) were caused by the pressure pulses, while some (correlated to the auroral movements) were caused by the erosion of closed field flux and that the two mechanisms coexisted during the event interval.

[21] The coordinated observations between the THEMIS satellites and the ground-based optical data should have allowed us to associate the various auroral forms with dayside magnetospheric boundaries and thus test the magnetic field models. We expected the magnetospheric models to be fairly accurate because on the dayside the magnetic field should be compressed to produce a relatively "stiff magnetosphere." It is quite different on the nightside, where dynamic stretching of field lines can produce very large deviations from the average field configuration. However, it was clear from this work that the models, e.g., Tsyganenko 89C model as used in the SPDF GSFC Web site, were quite conservative and it put the magnetopause on lower latitude field lines than actually observed. According to the model predictions THEMIS B and THEMIS A should have arrived at 1533 and 1749 UT, respectively, according to the calculations on the SPDF Web site, which routinely uses Tsyganenko 89C with Kp = 3. The actual spacecraft measurements indicated that the satellite entry took place between 1410 and 1530 for THEMIS B and no later than 1700 for THEMIS A.

4. Discussion of PMAFs Seen on 12 August 2007

[22] During the midday hours (1200 to 1800 UT) AGO-1 observed a continuous stream of poleward moving auroral forms (PMAFs) (first panel of Figures 3 and 4). PMAFs have been the subject many studies in the literature [e.g., *Sandholt et al.*, 1986; *Rairden and Mende*, 1989; *Lockwood et al.*, 1989]. PMAFs and pulsed ionospheric flows (PIFs) seen by radar [*Provan et al.*, 2002] have been widely accepted as being the signatures of pulsed magnetopause reconnection or more specifically the ground-based manifestation of FTEs [*van Eyken et al.*, 1984; *Goertz et al.*, 1985; *Sandholt et al.*, 1986; *Lockwood et al.*, 1989; *Sandholt et al.*, 1990; *Sandholt and Farrugia*, 2007]. In spite of all the evidence shown in these papers there are still some disconcerting facts regarding the association of PMAFs with pulsed reconnection and FTEs. For example the frequency of occurrence of PMAFs seem to be surprisingly little dependent on the direction of the IMF [*Fasel*, 1995; *Drury et al.*, 2003]. In the early part of the observation period on 12 August the IMF B_z was mostly positive with near zero B_y. The presence of the PMAFs when B_z is positive questions the validity of their association with reconnection and subsequent flows [*Southwood*, 1987]. There are difficulties in reconciling the apparent discrepancy between the morphological description developed from ground-based observations dominated by PMAFs [e.g., *Sandholt and Farrugia*, 2007] and the high-altitude view of dayside region shown by the IMAGE satellite data, especially during periods of B_z positive [*Frey et al.*, 2002, 2003].

[23] Large number of poleward moving auroral forms (PMAFs) of various speeds and intensities were observed at AGO-1 during the period between 1200 to 1600 UT. PMAFs can be seen as tracks on a keogram in the direction upward (poleward) and toward right (later in time) [*Sandholt et al.*, 1985; *Rairden and Mende*, 1989]. We did not see any specific one to one correlation of these PMAFs with either plasma or magnetic field observations on the THEMIS satellites. There are many B field fluctuations seen by THEMIS B and A after entering the magnetopause but only one FTE event was identified occurring at 1729 UT.

[24] Before 1500 UT B_z was positive and reconnection should have taken place on lobe field lines. *Frey et al.* [2002] showed that during periods of positive B_z a high-latitude large-scale auroral patch is formed near noon, the location of which is consistent with field line mapped region to the dayside lobe reconnection. The auroras observed at AGO-1 during this period are consistent with the location of the *Frey et al.* [2002, 2003] observed reconnection spots and the P1 observations could be interpreted as "foot prints" of B_z positive reconnection. It has been argued that the stability of the reconnection "spot" seen by IMAGE implies steady state reconnection. It is therefore important for us to look at the dynamic properties of auroras in these "spots"

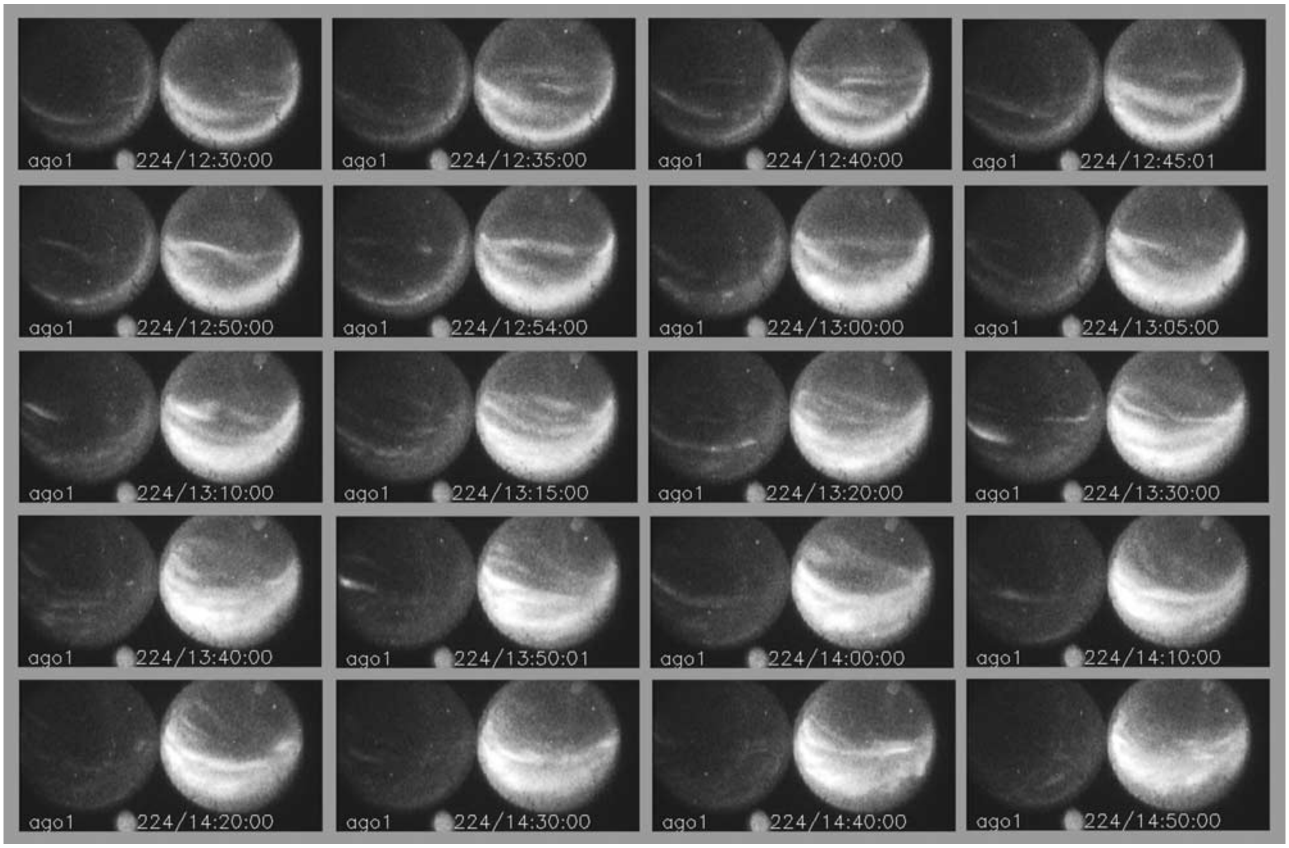

Figure 5. Noon time high-latitude auroras at AGO-1 while IMF B_z was positive. The two color channels are 427.8 nm (left, approximately proportional to deposited energy) and 630 nm (right, approximately proportional to electron flux). The location of these auroras is consistent with the high-latitude reconnection spot observed by *Frey et al.* [2002] with the IMAGE satellite. Only selected frames are shown.

with the spatial and temporal scales attainable with the AGO ASI instruments. We have therefore reproduced the AGO-1 images in the form of a collage between 1230 and 1450 UT (Figure 5). The time period was selected arbitrarily to demonstrate a time interval when highly visible PMAFs were taking place. These displays show a continuous stream of poleward moving arc structures pealing out from the equatorward lying more intense aurora.

[25] In Figure 6 we reproduced the full resolution sequence of images from AGO-1 from 1315 to 1330 to show the minute by minute development of the auroral dynamics. Figure 6 shows multiple arcs that move poleward and then fade out in the top third of the pictures. This is typical behavior for PMAFs. Perhaps the highly multiple nature of these PMAFs is unusual. If auroral structures like these were viewed by a high-altitude satellite such as IMAGE, they would appear as a continuous intensity auroral region whereas it is a highly dynamic display on the spatial scale of the ASIs.

5. THEMIS Spacecraft Exit From the Magnetosphere on 10 August 2007

[26] The NASA GSF TIPSOD software depiction of the THEMIS satellite orbits for this event between 1200 and 1800 UT are shown in Figure 7. In this case the satellites start within the magnetosphere and during the period under discussion they exit the magnetosphere. THEMIS B is first and THEMIS A is the last satellite following. The other satellites are closely clustered together.

[27] The position of the foot points of the satellites are illustrated in Figure 8. The foot points were derived by the method described previously. The loci of the foot points are represented with colored solid lines where each color represents a different satellite.

[28] At the beginning of the day 0000UT on 10 August the satellite foot points are at the bottom left of the map (Figure 6) in the 135° longitude sector. Note that on the southern hemisphere map longitudes increase counter clockwise with 90 being to our left and 270 to our right. The satellites fly rapidly through perigee at very low latitudes to reappear on the top right and then some of them enter the field of view of the South Pole ASI at around 1300 UT. THEMIS A only touches the FOV of South Pole at the lower magnetic latitude region.

[29] The THEMIS overview plots were presented in Figure 9 for THEMIS B, the lead satellite. The keogram from South Pole is shown above the THEMIS summary plots. AGO-1 was in the polar cap and the South Pole ASI data contained both poleward and equatorward boundaries of the aurora. The THEMIS summary plots are similar to Figure 3 except that we have included the ACE B_z magnetic field component measurements suitably delayed in the second panel. The ACE plot was delayed by a fixed

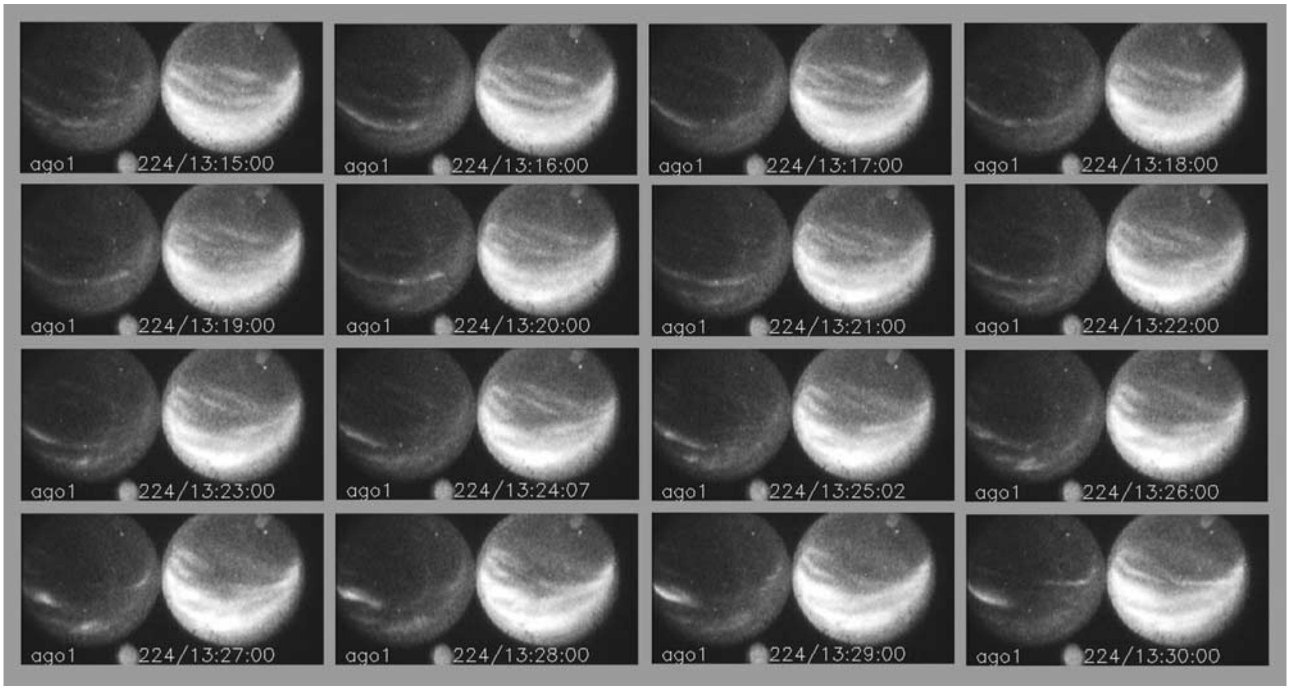

Figure 6. Same as Figure 5 except it is a full time resolution sequence (one image per minute) from 1315 to 1330 to illustrate the development of the poleward moving forms.

amount to match the obvious large feature seen at 1508 UT (third red line) with THEMIS and ACE thus no allowance was given for variations in the solar wind speed and some of the features may have a few minute time error one way or another. We show the satellite fluxgate magnetometer in the third panel, the plasma density in the fourth panel, the plasma flow velocity in the fifth panel, the plasma temperature in the sixth panel, the ion spectrogram in the seventh panel and the electron spectrogram in the eighth panel. The THEMIS overview plots clearly show the exit of the satellite from the magnetosphere. At first (1200 UT) the satellite is in the magnetosphere with the magnetic field (B_z) at about 50 nT and the plasma density (third panel) is less than 10 cm^{-3}. The plot shows that later, after 1330 UT the satellite was either in the magnetosheath (magnetic field was -30 to -40 nT and the plasma density was $\sim$100) or has gone through the bow shock and was in the solar wind where the field was much closer to zero and the plasma density <30. Every change, going from inside-out or outside-in, was quite abrupt. Again we attribute these observed rapid changes to rapid inward and outward motions of the bow shock. The other THEMIS panels of plasma temperatures and energy spectrograms are entirely consistent with this interpretation.

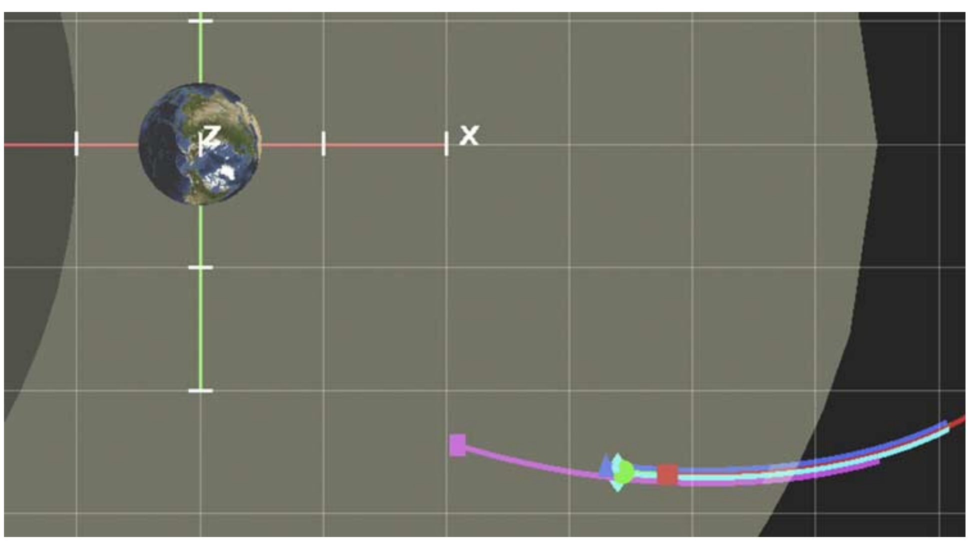

Figure 7. The THEMIS satellites are illustrated on 10 August 2007 at 1200 UT, but the orbit track is shown until 1800 UT. THEMIS B (red) leads with C, D, and E following in close formation with A (pink) trailing behind. The squares represent a 2 R_e grid.

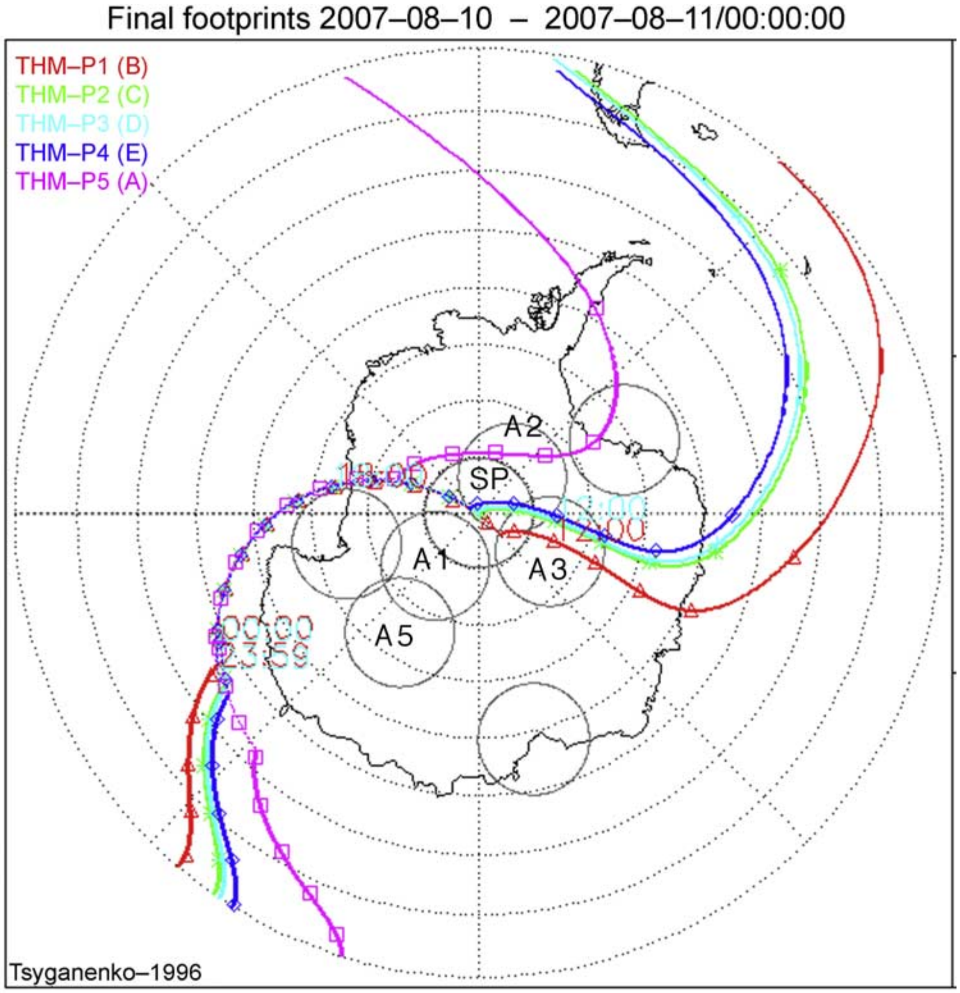

Figure 8. Foot point plots of the THEMIS satellites for 10 August 2007.

[30] In Figure 10 we show the same for THEMIS D rather than THEMIS A because D was in the field of view of the South Pole ASI during this period.

[31] In Figure 10 we present THEMIS D's crossing of the magnetopause and magnetosheath. It goes through the magnetopause at about 1240 UT. Although there are several magnetic field fluctuations, the plasma density is rather constant signifying that D unlike B does not leave the magnetosheath until about 1600 UT. We have marked 3 intervals of interest where the magnetic field measurements on D are quite clearly relatable to the ACE measurements.

6. Discussion of the 10 August 2007 Events

[32] THEMIS B was the first satellite to leave the magnetopause at 1246 UT with its first entry into the solar wind occurring at 1330 UT (1st red line). There is no geophysical significance to its entry other than it serves as a position marker for the bow shock. The magnetometer data in Figure 9 from Geotail (second panel) and THEMIS B magnetometer (third panel) show several southward turnings at 1350, 1417, 1505 and 1550. The same southward turning can be seen in Figure 10 in the THEMIS D data. All of these are well correlated with poleward expansion of the aurora at South Pole as shown in the keograms (first panel). In fact the keograms resemble substorm onsets. It is therefore tempting to say that the increase in negative B_z caused enhanced reconnection resulting in a poleward moving auroral form.

[33] There is, however, an inconsistency, namely, that in Figure 9 THEMIS B shows an increase in plasma density (fourth panel) associated with every one of these southward turnings and coincident auroral expansions. One would think that the stepwise increase of the plasma density at THEMIS B means that each time the satellite returns into the magnetosheath, i.e., there is an expansion of the bow shock. This is opposite to what would expect of subsolar reconnection in which we would expect the magnetosphere to shrink. Admittedly THEMIS B does not monitor the magnetopause and it is possible that the bow shock is displaced differently. For example it is possible that the reconnected flux pushes the bow shock in the antisunward direction.

[34] Since THEMIS D was deeply in the magnetosheath most of the time it shows the magnetic field changes but shows no changes in the plasma density.

7. Summary and Conclusions

[35] We examined two cases of magnetosphere boundary crossing of the THEMIS cluster one on 12 August and on

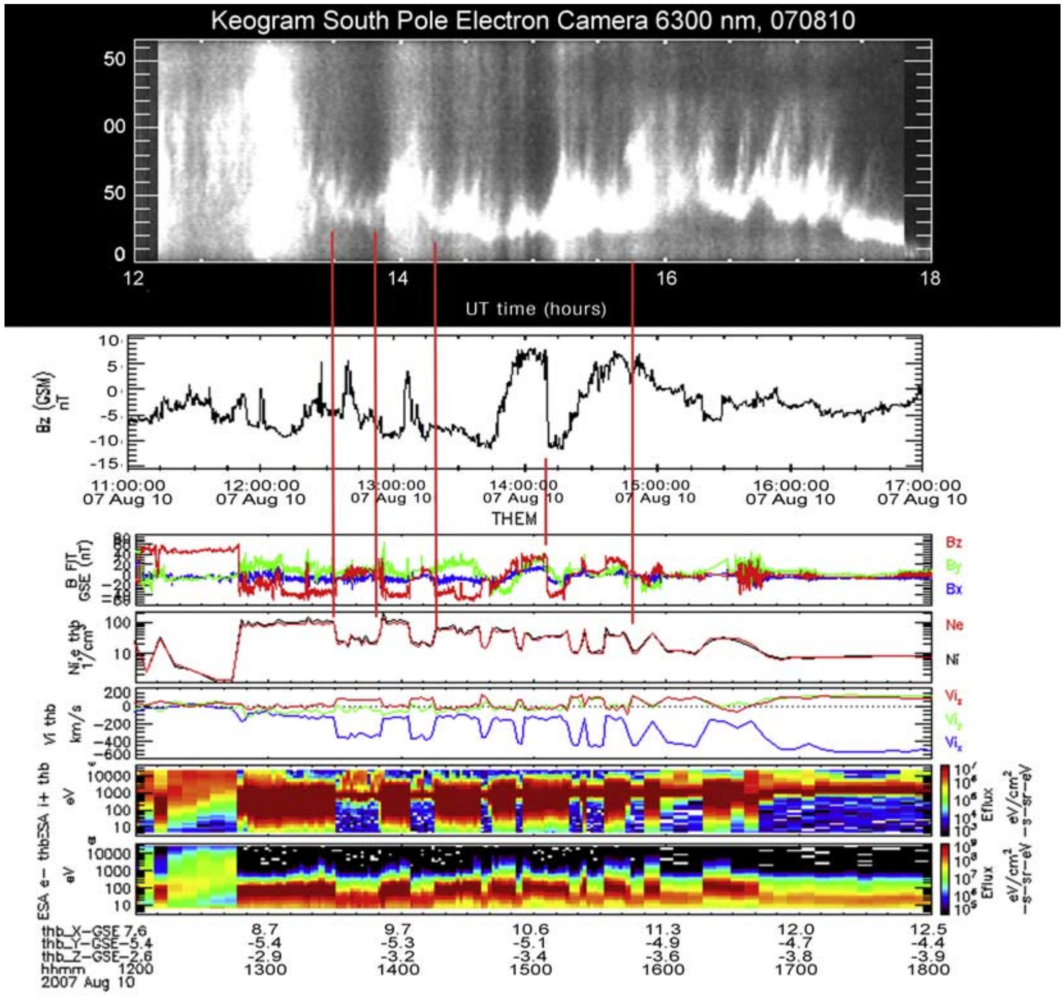

Figure 9. Similar to Figure 3 representing THEMIS B data but for 10 August 2007. We have added the ACE B_z data suitably delayed. Vertical red lines were drawn at various times of interest. See text for explanation. The *y* axes on the keograms are zenith angle in degrees, where 80 is the local zenith.

10 August 2007. Simultaneous auroral images were available from South Pole station and AGO P1, which show the aurora at the foot of the field line relevant to the point of entry or exit of the magnetosphere. The two crossings are summarized in Figure 11.

[36] In the first case (12 August 2007) the satellites were entering the magnetosphere and the IMF was weakly northward during the preceding period. The magnetosphere was inflated and the auroral region was located poleward (between AGO-1 and South Pole) and the auroral regions mapped to relatively distant field lines. The THEMIS satellites traveled from the magnetosheath, intersected the magnetopause (Figure 11, red circle on the right) to enter the magnetosphere. During this period radial motion of magnetopause motions best correlated with the inner boundary of the aurora.

[37] In case of IMF B_z positive we expected reconnection to occur on lobe field lines and the THEMIS satellites located near the subsolar magnetopause should not see any directly correlated phenomena. However, the satellites are well located to observe the subsolar boundary of the closed magnetospheric field lines. This inner edge would be expected to respond directly to pressure pulses, to move equatorward owing to closed field line erosion or poleward as a delayed result of lobe field line reconnection. This observation therefore suggests that during positive B_z the inner edge of the auroral oval represents the boundary of the closed field lines. The outer edge where the PMAFs are found is probably connected to the region of lobe reconnection.

[38] In the second case 10 August 2007 during a period of B_z negative the satellites were exiting a shrunk and somewhat smaller magnetosphere. The auroral oval was located at lower latitude and could be seen fully from South Pole station. Because of the reduced size magnetosphere the THEMIS satellites spent more time in the magnetosheath and in the solar wind and in crossing the bow shock (Figure 11, red circle on the left). In the B_z negative case reconnection should have occurred near the subsolar magnetopause close to where the THEMIS satellites were located. There were several southward turnings of the IMF B_z seen by the Geotail and THEMIS satellite magnetometer each causing enhanced reconnection and producing a corresponding large poleward expansion of the aurora thus

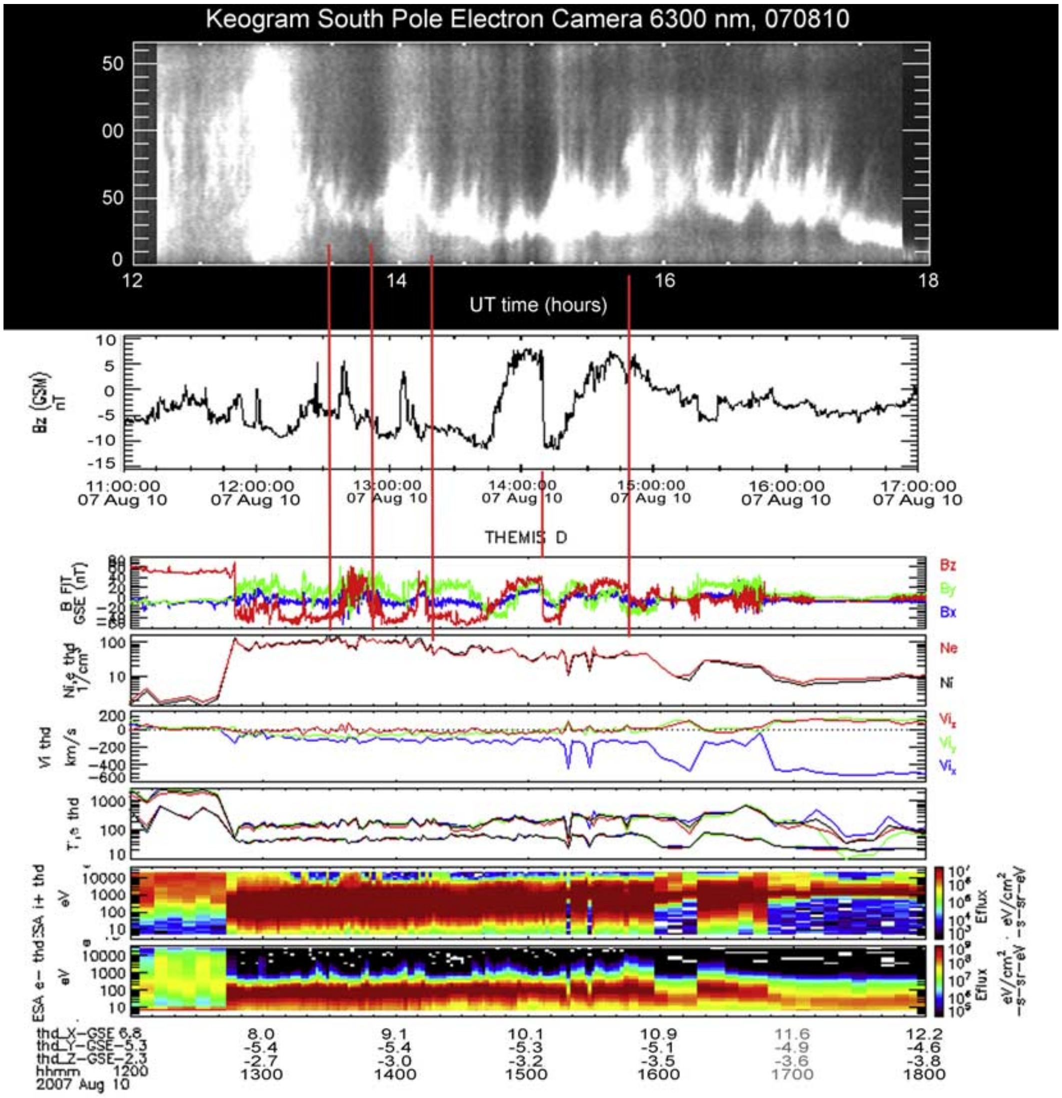

Figure 10. South Pole keogram: ACE B_z component and THEMIS D satellite data.

creating a kind of super PMAF. From THEMIS B plasma density we would conclude that these southward turnings and correlated poleward auroral boundary expansions were accompanied by outward radial motion of the bow shock.

[39] During the 12 August observation period we have seen that PMAFs were quite ubiquitous regardless of the orientation of the IMF B_z. In the literature they have been extensively associated with sudden pulsed reconnection or FTE events. However, on 12 August during the entire THEMIS satellites were able to discern only one FTE event that occurred at 1729 UT (1600 MLT at our South Pole ground-based observing site). As discussed above, PMAFs are likely to be a poleward boundary phenomena and during positive B_z they are associated with lobe reconnection therefore not expected to occur in the vicinity of the THEMIS satellites. We did not see any specific one to one correlation of the observed PMAFs with either plasma or magnetic field observations on the THEMIS satellites.

[40] Although it is not conclusive the data suggests that PMAFs are likely to be an ongoing feature of the aurora even when the magnetosphere is quiet whether the IMF B_z field is positive or negative and reconnection takes place either near the subsolar region or at the tail lobes.

[41] The latitude of the aurora and the recurrent PMAF events on 12 August when B_z was slightly positive was consistent with the observations of the *Frey et al.* [2002, 2003] positive B_z high-latitude auroral patch is formed near noon. We can therefore interpret the P1 observations as the "foot prints" of B_z positive lobe reconnection. Since this has important association with the question of "steady state" reconnection it is important to note that these auroras are quite dynamic producing a continuous stream of poleward moving arc structures pealing out from the equatorward lying more intense aurora. Thus although the lobe reconnection foot print auroras may appear as steady diffuse spots with the spatial and temporal resolution of IMAGE FUV system [*Mende et al.*, 2000], they can be resolved with the finer-scale resolution of the PENGUIN Antarctic imagers as a dynamic set of poleward moving arcs.

[42] As a minor finding we should note that predictions of satellite entries into the magnetosphere using models such as the Tsyganenko 89C model [*Tsyganenko*, 1989] as used

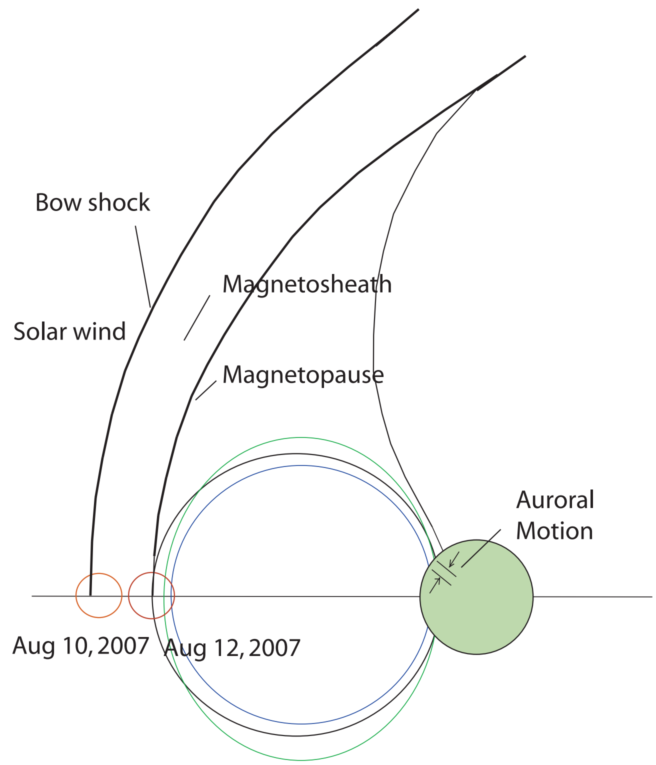

Figure 11. Because of the difference in the IMF B_z direction on 12 August, the magnetosphere was inflated and the THEMIS satellites entered from the magnetosheath and crossed the magnetopause at the location indicated by the red circle on the right, while on 10 August the magnetopause was eroded and the satellites passed through the bow shock into the solar wind, indicated by the red circle on the left. The illustration also depicts the last closed subsolar field line (black). This can be either compressed by a pressure pulse (green) or eroded, and the last closed field line appears at a new (blue) position. Auroras located near the open closed field line boundary should show configuration change owing to field line erosion but not to pressure pulses.

in the SPDF GSFC Web site were found inaccurate. According to the predictions THEMIS B and THEMIS A should have arrived at 1533 and 1749 UT, respectively, from the SPDF Web site, which routinely uses Tsyganenko 89C with Kp = 3. The actual spacecraft measurements indicated that the satellite entry took place between 1410 and 1530 for THEMIS B and no later than 1700 for THEMIS A.

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V. Angelopoulos, Institute of Geophysics and Planetary Physics, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095, USA.

C. W. Carlson, H. U. Frey, J. McFadden, and S. B. Mende, Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720, USA. (mende@ssl.berkeley.edu)

K.-H. Glassmeier, Institute for Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, Braunschweig, D-38106 Braunschweig, Germany.

D. G. Sibeck, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

A. Weatherwax, Department of Physics, Siena College, 515 Loudon Road, Loudonville, NY, 12211, USA.