Structure of the subsolar magnetopause regions during northward IMF: first results from THEMIS

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Abstract

THEMIS observations at the sub-solar magnetopause reveal the structure of the low latitude boundary layer (LLBL) and magnetosheath boundary layer (MSBL) during northward IMF. Unlike previous single spacecraft observations of this region, four of the five THEMIS spacecraft were able to capture the transition of magnetosheath plasma with no electron heating to uni-directional heated electrons followed by bi-directional heated electrons, demonstrating that this electron structure is spatial. Furthermore, the sequence of these transitions shows that the bi-directional heated electrons appear at the outer edge of the weak magnetopause current sheet. Since heated magnetosheath electrons outside the magnetopause current layer are used as an indicator of lobe reconnection in the hemisphere radiating these electrons, reconnection in both lobes is observed before the flux tubes cross the magnetopause. In essence, these observations provide convincing evidence that the LLBL was formed by dual-lobe reconnection.

1. Introduction

The possibility of dual-lobe reconnection during northward IMF was recognized early by Dungey (1961) and later used by Song and Russell (1992) to explain the formation of the low-latitude boundary layer (LLBL). Gosling et al. (1990) was the first to recognize the existence of a layered magnetopause and Le et al. (1996) used ISEE ion observations of this layering to support the dual-lobe reconnection model. However, significant IMF Bx or By might be expected to result in a geometry where lobe reconnection in one hemisphere is not followed by reconnection in the other hemisphere. A comprehensive attempt to understand reconnection geometries during northward IMF was presented by Fuselier et al. (1995) who used AMPTE/CCE data to investigate the structure of the sub-solar magnetopause (MP) and LLBL. They defined a new layer, the magnetosheath boundary layer (MSBL), as that region just outside the MP current sheet. They reported that magnetosheath electrons outside the current sheet showed uni-directional heating and that magnetosheath electrons inside the current sheet showed bi-directional heating. Using these observations, Fuselier et al. (1995) proposed an open-MSBL model which describes a MP geometry where the MSBL exists exclusively on open field lines during northward IMF. As these field lines pass through the MP, they remain open as they become part of the LLBL. They leave open the possibility that LLBL field lines could close in the second hemisphere at some later time. Electron heating is assumed to occur at the MP current sheet in this model. Inside the MP the entering magnetosheath electrons are heated while crossing the current sheet, then mirror in the Earth's dipole field producing a bi-directional heated electron signature. Outside the MP, the mirrored electrons produce the uni-directional signature of electrons streaming away from the MP.

When no obvious current sheet could be observed (nearly pure northward IMF), they defined the MP as the transition between uni-directional and bi-directional electrons.

Lobe reconnection and reconnection geometries during northward IMF gained interest with the launch of the Polar and Cluster satellites. Onsager et al. (2001) used Polar data from an extended period of northward IMF (29 May 1996) and showed that the majority of the MSBL field lines were closed. These high latitude data allowed much better identification of the MP current sheet and showed only brief periods of uni-directional electrons outside the MP. The majority of the Polar data showed bi-directional heating in the MSBL indicating dual-lobe reconnection. Cluster observations have added to the lobe-reconnection picture. Twitty et al. (2004) reported that lobe reconnection occurs ~90% of the time in the measured hemisphere when the IMF has a northward component. This result doesn't prove that dual-lobe reconnection is occurring, but rejects models where lobe reconnection is confined to a single hemisphere. Lavraud et al. (2005, 2006) and Bogdanova et al. (2005) report high latitude MSBL observations with bi-directional heated electrons, supporting the picture that the MSBL is primarily on closed field lines.

Below we present multi-satellite THEMIS observations that demonstrate the transition from uni-directional to bi-directional heated electrons is spatial feature of the sub-solar MP. In addition, we show that this transition occurs at the outer edge of the MP current indicating the heating is not caused by the passage of magnetosheath electrons through a weak current sheet. We conclude the paper with a comparison of observations with the dual-lobe reconnection model and the open-MSBL model.

Observations are presented from four of the five THEMIS satellites (Angelopoulos et al., 2008) during the early mission "coast phase". This period kept the satellites in close proximity in a string-of-pearls orbit with apogee and perigee of 14.7 Re and 1.16 Re, respectively. The spacecraft are identified by letters and were ordered B-D-C-E-A, starting with the leading probe. Near the sub-solar MP the separations were mostly radial, with the B leading C-D by ~3650 km, C-D closely spaced (~250 km), E trailing C by ~1000 km, and A distantly trailing E by ~10,000 km. We confine our analysis to data from the fluxgate magnetometer (Auster et al., 2008) and the ion and electron plasma instruments (McFadden et al., 2008) on probes B, D, C and E. Data from probe A is not presented since it was in a low rate mode that could not resolve field-aligned electron structure.

2. Observations

Figure 1 shows the magnetic field and plasma observations for the THEMIS-E (THE) probe as it crossed near the sub-solar MP (11.6,-1.2,3.0 Re, GSM). Panel a is the interplanetary magnetic field (IMF) measured by Wind MFI and shifted in time by 57 minutes to align it with the THEMIS upstream observations. The IMF was strongly northward during this period, with a clock angle of ~30^{o}. Panel b is the magnetic field measured by THE in GSM coordinates illustrating the weak MP current sheet (05:37:50-05:39:50 UT) seen in the By component and indicated by vertical solid lines. Panel c shows that the plasma density (N_i-black, N_e-red) gradually decreases over an extended region near the MP. Ion velocity in panel d shows only weak flows in the MP consistent with the absence of low-latitude reconnection during northward IMF. It is interesting to note that the location of the abrupt change in the ion temperature and temperature anisotropy (panel e), often used in previous studies to identify the low magnetic shear MP (e.g., Phan et al., 1994), coincides with the outer edge of the MP current layer. Panel f presents the plasma (ion-green, electron-red), magnetic (blue), and combined (black) pressure showing that total pressure across the MP is constant. A plasma depletion layer has formed at this time as indicated by much higher magnetic pressure than plasma pressure in the magnetosheath outside the MP.

The layered structure in and around the MP is best illustrated by the spectrograms in panels g through k. As will be shown shortly, this structure is repeated on the crossings by four spacecraft and therefore represents a spatial layering. For purposes of analysis, we describe the evolution of flux tubes from right to left as magnetosheath plasma traverses the MP. 05:43:08 UT (dashed line) marks the outer boundary of the MSBL where anti-parallel electrons (panel g) transition from nominal upstream magnetosheath electrons to electrons with a heated component in the anti-parallel direction (enhanced flux >200 eV). Panel h at 05:39:47 UT shows a similar change in the parallel electrons, thus marking the transition from uni-directional to bi-directional heated electrons. Remarkably, this latter boundary coincides with the outer edge of the MP current. Lastly, the LLBL consists of those flux tubes inside the MP current sheet with either trapped magnetosheath plasma (05:33:30-05:38 UT) or a mixture of hot plasmasheet and trapped magnetosheath plasma (05:30:30-05:33:30 UT) as seen in panels g-k.

The ion spectrograms exhibit signatures similar to the electrons, with anti-parallel ion beams (1-20 keV) observed sunward (05:42:20 UT) of the parallel ion beams (05:39.53 UT). Assuming the anti-parallel ion beams and heated electrons are both produced in the high latitude MP current layer during lobe reconnection, the observation of heated electrons sunward of the ion beams is consistent with velocity dispersion within flux tubes convecting toward the MP. However, some parallel ions (panel k, >10 keV) were observed slightly sunward (two spins) of the parallel-heated electrons indicating that simple dispersion from a single source is inadequate to explain the measurements. We leave further discussion of this inconsistency to the next section.

Figure 2 shows the magnetic field and field-aligned particles for the THC and THD crossings of the MP. These satellites were only separated by ~250 km and observed nearly identical crossings. These transitions were faster, taking about half the time to cross the uni-directional heated electrons and current sheet. Again the anti-parallel heated electrons were observed sunward of the parallel heated electrons, and the transition from uni-directional to bi-directional heating occurred at the outer edge of the MP current sheet.

Figure 3 shows the MP crossing by THB, which occurred about 15 minutes before THC/D and 19 minutes before THE. Panel a shows the IMF was northward. The MP can be clearly identified in panel e using the change in ion temperature and anisotropy to identify the primary rotation of the magnetic field between 05:20:20 and 05:21:30 UT. Anti-parallel heated electrons are again observed sunward of the parallel heated electrons, and anti-parallel ion beams are also observed sunward of the parallel ion beams. The transition from uni-directional to bi-directional heated electrons is less well defined in this case. Bi-direction streaming is observed briefly on some field lines well upstream of the current sheet, whereas the final transition to bi-directional streaming occurs just inside the outer edge of the MP current sheet. Anti-parallel electrons were observed sunward of anti-parallel ions, consistent with dispersion. However, parallel ions and electrons show no consistent simple dispersion, both being sporadically observed sunward of the MP. Density, velocity and pressure changes across the MP are similar to those observed on THE (Figure 1), with moderate flows and a magnetic pressure dominated plasma depletion layer upstream of the MP.

3. Discussion

The primary question addressed by this paper is whether the THEMIS sub-solar MP observations support the open-MSBL model of Fuselier et al. (1995) or the dual-lobe reconnection model of Song and Russell (1992). Both models would predict lobe reconnection in the northern hemisphere before the southern hemisphere, as is indicated by the anti-parallel heated electrons in the MSBL. This is expected since the IMF Bx is relatively small and since the dipole tilt places the northern lobe closer to the subsolar region, both producing a geometry where draping at the lobes will occur first in the northern hemisphere. To distinguish the two models, the key observation is the location of the transition to bi-directional heated electrons in relation to the current sheet.

The open-MSBL model posits that electron heating occurs in the current sheet. In the open-MSBL model, the transition from uni-directional to bi-directional heating occurs when a spacecraft moves Earthward of the current sheet, with magnetosheath electrons heated while crossing the current sheet and bi-directional flow caused by electrons mirroring in the Earth's magnetic field. Since the observations clearly show that this transition is at the outer edge of the current sheet, and sometimes outside of the current sheet, where earthward flowing heated electrons have not had time to interact with the current sheet, the THEMIS observations are not consistent with the open-MSBL model. We note that the AMPTE/CCE observation in Figure 4 of Fuselier et al. (1995) also has the current sheet earthward of the transition to bi-directional heating.

In contrast, the dual-lobe reconnection model predicts the current sheet should lie inside the transition to bi-directional heated electrons. Heated electrons are expected to be produced at the high latitude current sheets where flux tubes cross a high shear MP. Bi-directional heated electrons indicate the flux tube has reconnected in both lobes. No longer connected to the solar wind, a dual-lobe reconnected flux tube will relax to a dipolar geometry, then spread along the MP via the interchange instability (Song and Russell, 1992). The MP current sheet is a field aligned current between hemispheres that identifies the relaxation to a dipole geometry. The IMF By initially imposed by the solar wind on magnetosheath flux tubes results in tilted flux tubes after reconnection. The tilt of the flux tube is associated with ionospheric footpoints that are mismatched in local time because lobe reconnection locations were asymmetric with respect to GSM-Y. The stresses due to this geometry drive ionospheric flows that move the footpoints to the same local time. The ionospheric flows have associated Pedersen currents that close through field-aligned currents. One of these relaxation current sheets is between hemispheres and forms the MP current sheet. THEMIS observes this stress relief, or field line relaxation, just inside the transition to bi-directional heating as expected for dual-lobe reconnection.

We note that the boundaries of the MP current sheet, as determined from By, are not as well defined as the electron transitions from uni-directional to bi-directional heating. Electron transitions are local whereas By represents a weighted average of the field-aligned currents across the MP. We should expect non-uniformities in dual-lobe reconnection to result in some single-lobe reconnected flux tubes appearing slightly earthward of the outer edge of the current sheet before reconnecting in the other hemisphere, and some dual-lobe reconnected flux tubes appearing sunward of the current sheet. Therefore we should look at the average relative location of the current sheet and electron transitions and not dwell on small variations from these averages. Figure 3 shows an example of “fuzzy” boundaries with some bi-directional heated electrons well outside the MP current sheet and the final transition to bi-directional heating (where time averaging over the spin period does not dilute the heating signature) occurring just inside the outer edge of the current sheet. We conclude that, on average, the low-latitude transition from uni-directional to bi-directional heated electrons occurs at the outer edge of the MP current sheet, consistent with dual-lobe reconnection.

A second contributor to “fuzzy” boundaries arises from the nature of the reconnection acceleration mechanism and can explain how parallel ions may arrive slightly sunward (2 spins) of parallel heated electrons as in Figure 1. Ions and electrons on a newly reconnected field line will no longer be on the same field line after they cross the current sheet. This is because ions are energized by drifting along the reconnection electric field. For a few mV/m reconnection electric field, the ion will have to drift ~1000 km to gain a few keV. Electron energization is still not understood, but it is clear that electrons don’t move with the ions otherwise there would be no current sheet. Out of plane variations on ~1000 km scales in roughly 2-D reconnection geometry could explain small differences in the arrival locations of energized electrons and ions from the same hemisphere. Only for a purely symmetric, 2-D geometry would one expect simple layering with heated electrons always appearing sunward of energized ions. We conclude that the small variation in expected ordering of parallel ion and electron layers seen in Figure 1 suggests 3-D structure is present at the southern hemisphere dual-lobe reconnection site.

Last of all we address an aspect the open-MSBL model that assumes that electron heating takes place even in weak current sheets. When no clear magnetic signature was observed in the AMPTE/CCE data, indicating a very weak MP current, the uni-directional to bi-directional heating signature was used to determine the MP location (Fuselier et al., 1995). It is difficult to understand what mechanism could heat electrons at such weak current sheets since even ion acceleration at such current sheets is negligible. In contrast, the dual-lobe reconnection model produces electron heating at high-latitude high-shear current sheets, where ion acceleration is observed. Heated magnetosheath electrons will have crossed the current sheet twice before being observed at low latitudes. The sudden appearance of bi-directional fully-heated electrons at the outer edge of the current sheet (see Figure 1) not only provides evidence for the dual-lobe reconnection model, but implies that electron energization need only occur at high-shear current sheets, as is observed for ion energization.

In summary, the THEMIS sub-solar observations of the MSBL and LLBL are consistent with the high latitude MSBL observations of Polar (Onsager et al., 2001) and Cluster (Lavraud et al., 2005, 2006; Bogdanova et al., 2005). All three data sets show bi-directional heated electrons outside or on the outer edge of the MP current sheet. All three data sets are inconsistent with the open-MSBL model of Fuselier et al. (1995) which predicts bi-directional heated electrons inside the current sheets. These observations provide additional evidence that dual-lobe reconnection plays a major role in magnetospheric dynamic. They also support previous observations (Lavraud et al., 2006) that demonstrate dual-lobe reconnection, and the capture of magnetosheath plasma to form the LLBL, is not confined to purely northward IMF, but will occur over a broad range of clock angles including By~Bz/2 as is observed in these data.

Acknowledgements

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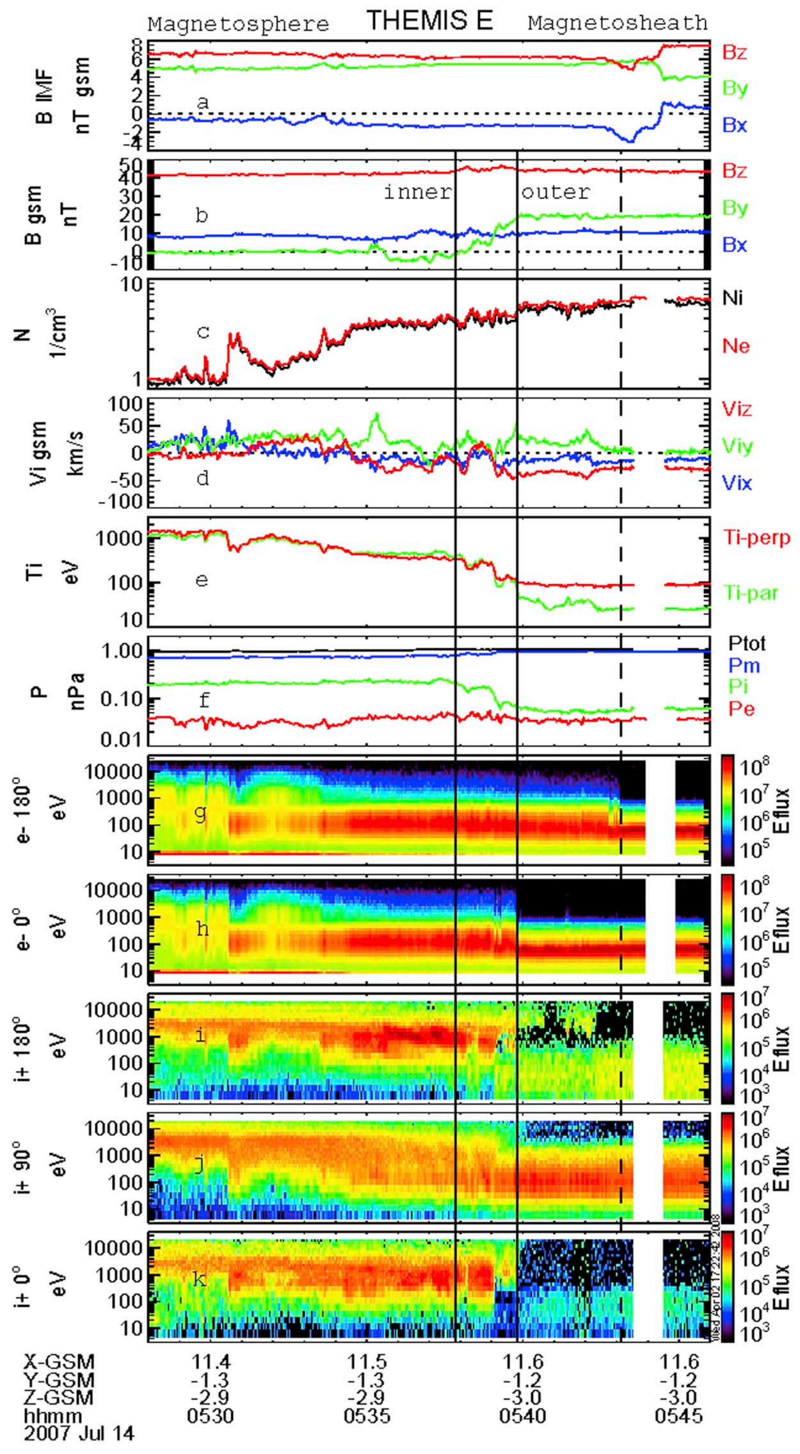
Figure Captions

Figure 1. Wind IMF and THEMIS probe THE observations of the subsolar MSBL and LLBL. The MP current sheet, indicated by solid vertical lines, lies earthward of the transition to bi-directional heated electron seen in Panel h. Dashed line indicates outer edge of MSBL.

Figure 2. THEMIS probe THC (upper 5 panels) and THD (lower 5 panels) during a subsolar MP crossing. The probes are separated by only 250 km. The layered structure of the MP is the same as seen by the other probes indicating these are spatial features. The MP current sheet is indicated by vertical lines.

Figure 3. Wind IMF and THEMIS probe THB observations of the subsolar MSBL and LLBL, similar to Figure 1. The MP current sheet is indicated by vertical lines.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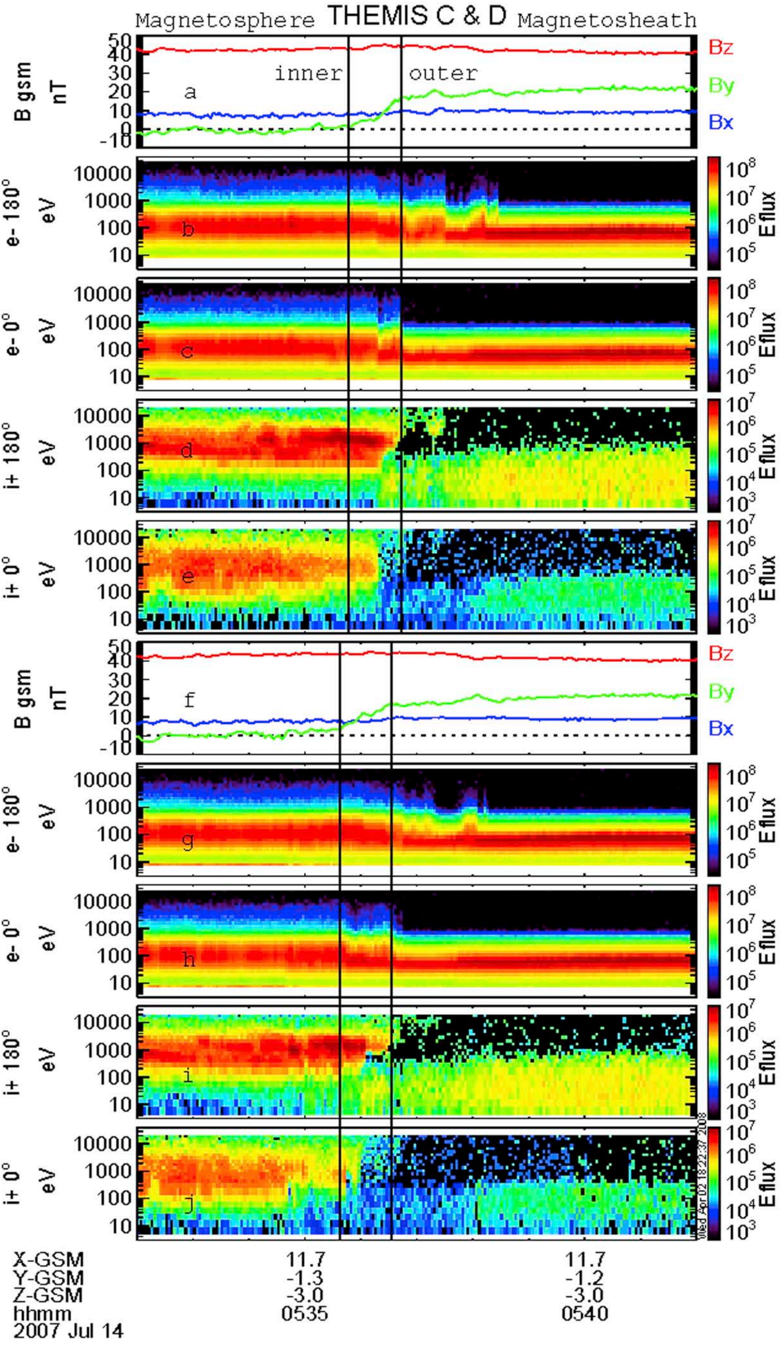

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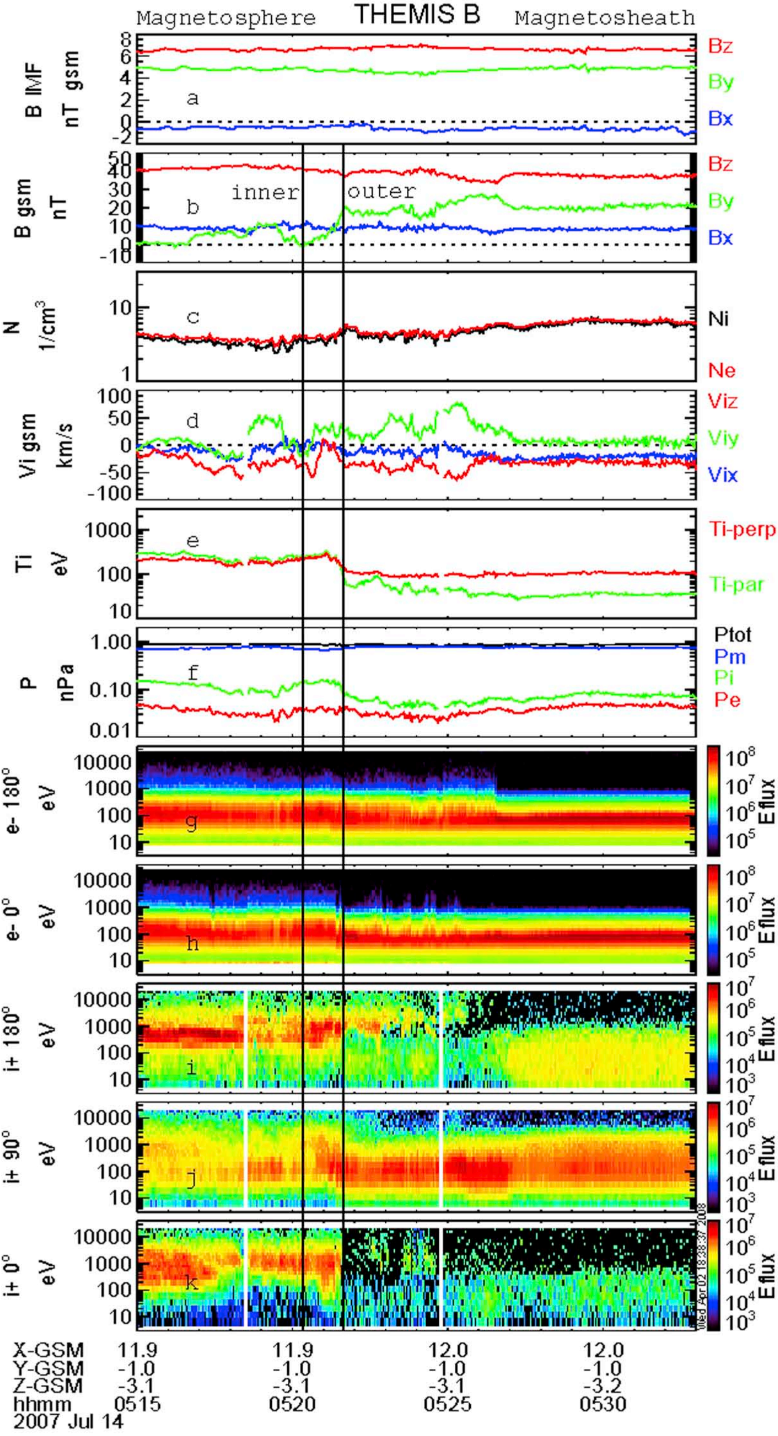

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