Boundary layer plasma flows from high-latitude reconnection in the summer hemisphere for northward IMF: THEMIS multi-point observations

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[1] On 2008-07-11, the THEMIS spacecraft, separated both longitudinally and radially, traversed the dayside low-latitude boundary layer (LLBL) under extended northward IMF. They detected southward flows of magnetosheath plasma from magnetopause reconnection poleward of the northern cusp, which were cold-dense, and had southward velocity ~100 km/s and longitudinal extent >3 R_E. These features all agree with a global MHD simulation of the magnetosphere for similar conditions, in which under large geomagnetic dipole tilt, an LLBL forms via poleward-of-the-cusp reconnection first in the summer hemisphere and later in the other. Contrary to the simulation, however, the observed LLBL was mostly magnetically closed, characterized by balanced field-aligned and anti-field-aligned electron fluxes, and was less thick ($\leq$0.5 R_E). The former suggests comparable reconnection rate in both hemispheres, while the latter suggests the actual reconnection rate being lower, and/or the plasma transport toward the magnetotail being faster, than in the simulation.
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1. Introduction

[2] The generation mechanism of the cold and dense plasma sheet (CDPS) that appears for extended northward IMF [e.g., *Terasawa et al.*, 1997] remains a major issue in magnetospheric physics. The CDPS formation requires efficient entry and subsequent transport of solar wind plasma deep into the magnetosphere. Several plasma transport processes have been invoked including (1) poleward-of-the-cusp reconnection in both hemispheres [*Song and Russell*, 1992], (2) nonlinear Kelvin-Helmholtz instabilities (KHIs) on the flank magnetopause [e.g., *Hasegawa et al.*, 2006], and (3) diffusion induced, for example, by kinetic Alfvén waves [e.g., *Lee et al.*, 1994]. However, their relative role is poorly understood, partly because of the lack of simultaneous multi-point measurements in key regions (see, however, *Taylor et al.* [2008]) and partly because these processes may be coupled to each other.

[3] Recent observations by the THEMIS spacecraft showed that a layer of cold-dense magnetosheath plasma can become as thick as 0.9 R_E on the day side for northward IMF [*Øieroset et al.*, 2008]. A global MHD simulation of the magnetosphere conducted for this event on 3 June 2007 (near solstice) shows that a low-latitude boundary layer (LLBL) forms earthward of the dayside magnetopause, via poleward-of-the-cusp reconnection first in the northern (summer) hemisphere and then in the southern (winter) hemisphere [*Li et al.*, 2009]. In the simulation, the outer part of the LLBL contains cold-dense plasma (temperature T < 1 keV and density N > 1 cm^{-3}) streaming southward along the boundary, and is generally on open field lines extending from the northern cusp region. However, such a southward-flow layer was not clearly seen in the THEMIS event, although a region with such a flow was reported for other events [e.g., *Bauer et al.*, 2001]. Therefore, its characters such as its existence/absence, magnetic topology, and spatial extent are largely unknown.

[4] In this report, we examine the structure of the dayside magnetopause and its boundary layers when the IMF was northward for hours and the geomagnetic dipole axis tilted sunward in the northern hemisphere. We show THEMIS observations at longitudinally as well as radially separated points of southward flows from northern high-latitude reconnection for such conditions, and make detailed comparison with the above global simulation. Data from the fluxgate magnetometer [*Auster et al.*, 2008] and the ion and

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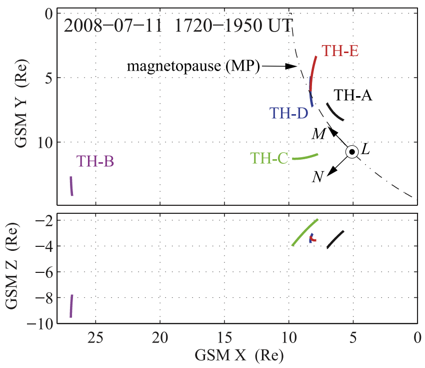

Figure 1. THEMIS orbit and model magnetopause position [*Roelof and Sibeck*, 1993] on 11 July 2008.

electron plasma instruments [*McFadden et al.*, 2008a] are used.

2. Overview of Observations

[5] Figure 1 shows the orbits of the five THEMIS spacecraft for the interval 1720–1950 UT on 11 July 2008. The THEMIS-B (THB) probe was monitoring the upstream solar wind and IMF, while THC was in the duskside magnetosheath. The other three probes were near the postnoon low-latitude magnetopause, separated mostly in the longitudinal direction.

[6] Figure 2 shows THEMIS observations of the IMF, magnetopause, and its surrounding regions. The IMF seen by THB turned northward at ~1400 UT (not shown) and remained northward until ~1940 UT (Figure 2a), except for transient southward IMF periods (before 1720 UT). Figure 2b shows that for the interval under discussion (1720–1940 UT), the IMF was dominantly northward in both the magnetosheath and the solar wind. The magnetopause was traversed first by THD at ~1746 UT, subsequently by THE at ~1848 UT and by THA at ~1918, 1921, and 1943 UT. Here the boundary was defined by changes in ion temperature and velocity (mostly V_L) from their magnetosheath values (Figures 2d–2f), following earlier studies [e.g., *Lavraud et al.*, 2006], since for strong northward IMF it can hardly be identified by rotation of the magnetic field (Figures 2h and 2i). Note that even for 1759–1830 UT when the temperature at THA was often comparable to that at THD situated in the magnetosheath, THA was in the magnetosphere. This will be explained below and is because B_M at THA substantially differed from that at THD (Figure 2i) and the magnetosheath temperature at THA local time must have been lower than at THD that was closer to the subsolar point.

[7] Earthward of the magnetopause, the three inner probes all observed a prominent LLBL, where ions of magnetosheath origin were abundant (Figures 2l and S1 of the auxiliary material) with $N_i \geq 2$ cm^{-3} and $T_i < 1$ keV (Figures 2c and 2d).[1] In this event, even magnetospheric regions lacking the magnetosheath-like ions had a density (>1 cm^{-3}) higher than in typical cases [*Øieroset et al.*, 2008]. This can be explained by the presence of cold plasma of ionospheric origin [e.g., *Sauvaud et al.*, 2001] (Figure S1). We note that the observed LLBL can be decomposed into two parts: outer LLBL (marked by red bars in Figures 2l and S1) characterized by southward flows ($-V_L$ = 50–100 km/s) of dominantly magnetosheath ions ($N_i \sim 10$ cm^{-3}) (Figures 2c and 2e), and inner LLBL (green bars) characterized by apparent coexistence of magnetospheric and magnetosheath ions, lower densities, and lower V_L (Figures 2c, 2e, 2l, 2m, and S1). The inner LLBL is seen to have properties common to the cold-dense plasma layer (CDPL) reported by *Øieroset et al.* [2008] which is, so to speak, the cold-dense part of the dayside LLBL. Other commonalities are that the fluxes of field-aligned and anti-field-aligned electrons were well balanced at all energies (Figures 2j, 2k, and S1), the velocity component along the boundary, V_M, was much lower than in the magnetosheath, and its direction was variable (Figure 2f). These features indicate that the inner LLBL was on closed field lines [*Bogdanova et al.*, 2008; *Øieroset et al.*, 2008].

[8] In the outer LLBL, on the other hand, V_M was comparable to that in the magnetosheath (Figures 2f and 2m) and $|V_L|$ was significantly higher than in the magnetosheath (Figures 2e and 2m) which was monitored by THD just outside the magnetopause for the interval from 1747 UT. Now we characterize this outer layer found for a large dipole tilt angle (~31° at 1830 UT), by detailed comparison with the simulation for similar (northward IMF and large dipole tilt) conditions [*Li et al.*, 2009].

3. Comparison with Simulation

3.1. Similarities

[9] When the dipole axis has a large tilt, northward IMF field lines make contact and can reconnect with high-latitude geomagnetic field lines first in the summer hemisphere (in our case, northern) [*Lavraud et al.*, 2005; *Li et al.*, 2009]. Such high-latitude reconnection generates an electron magnetosheath boundary layer (MSBL) immediately outside the magnetopause but earthward of the separatrix, where unidirectional field-aligned fluxes of magnetosheath electrons heated through reconnection are observed [*Lavraud et al.*, 2005; *Bogdanova et al.*, 2008; *McFadden et al.*, 2008b]. Such electron MSBLs were indeed encountered by all the three probes (blue bars in Figures 2k and S1). There, heated magnetosheath electrons were streaming in the anti-parallel (southward) direction, while ions as well as the parallel electrons were comparable to the pristine magnetosheath. These features are consistent with the MSBL field lines being reconnected in the northern hemisphere only.

[10] The outer (southward-flow) part of the LLBL had some similarities to that seen in the global simulation [*Li et al.*, 2009]: somewhat heated magnetosheath ions (Figure 2d) had a density comparable to that in the magnetosheath (Figure 2c) and southward bulk velocity $V_L \sim -100$ km/s (Figures 2e and 2m), in agreement with the simulation [*Li et al.*, 2009, Figures 9–11]. These ion signatures are consistent with bulk plasma acceleration by magnetic tension on kinked field lines that exist equatorward of the northern high-latitude reconnection site, and indicate that the flows resulted from northern high-latitude reconnection.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039410.

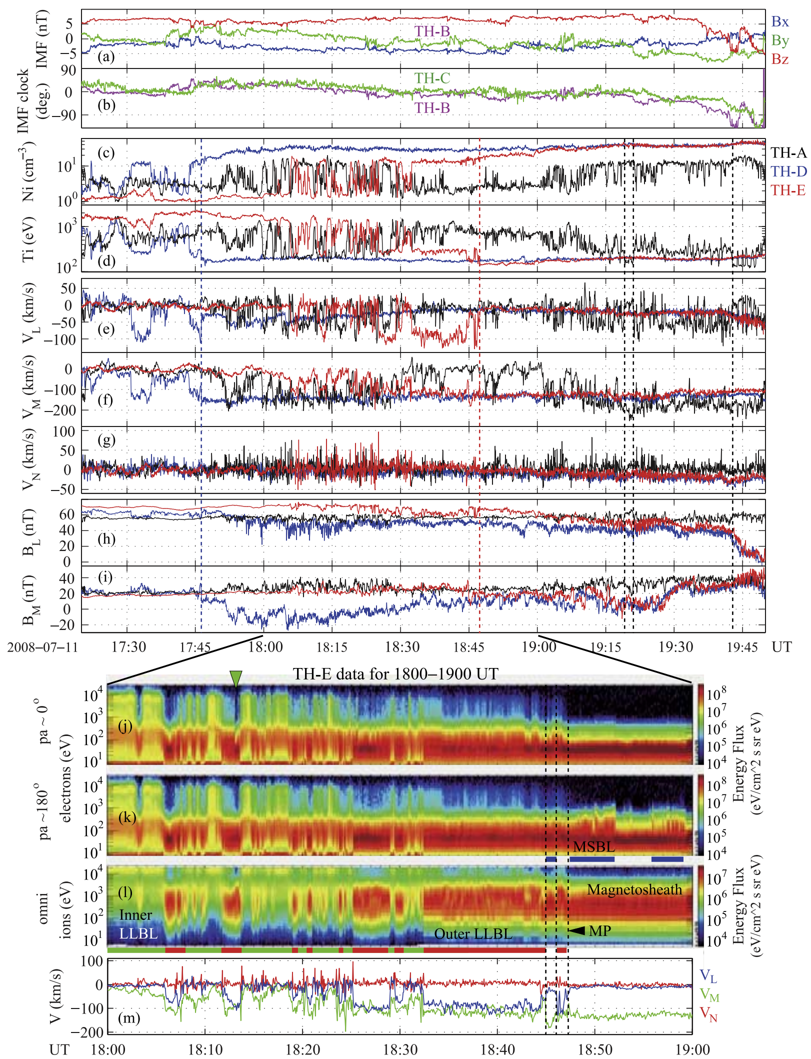

Figure 2. (a) IMF seen by THB, (b) IMF clock angle ($\tan^{-1}[B_{y,GSM}/B_{z,GSM}]$) at THB and THC. (c) Ion densities, (d) ion temperatures, (e–g) LMN components of ion velocity, and (h) L and (i) M components of magnetic field, from THA, THD, and THE. (j–l) Energy-time spectrograms of electrons for pitch angles ∼0° and ∼180° and of ions, and (m) LMN velocity components from THE for a shorter interval. The LMN boundary coordinate system [*Russell and Elphic*, 1978] is determined for each probe, based on the model magnetopause normal (Figure 1). Magnetopause crossings are marked by vertical dashed lines, layers of significant southward flow (outer LLBLs) and inner LLBLs by red and green bars, respectively, at the bottom of Figure 2l, and electron magnetosheath boundary layers by blue bars at the bottom of Figure 2k.

[11] A lower limit of the longitudinal extent of the outer LLBL can be estimated because THA and THE, separated by ∼3.5 R_E in that direction (Figure 1), simultaneously observed the southward flow, e.g., at ∼1827 UT (Figure 2e). Such a large extent (>3.5 R_E) is indeed seen in the simulation [*Li et al.*, 2009, Figures 9 and 10], and suggests that the outer LLBL was continuously formed and convected downtail along the magnetopause with V_M comparable to that in the magnetosheath (Figures 2f and 2m). Continuous formation of the outer LLBL is inferred also from a signature of continuous reconnection poleward of the northern cusp; the southward flows were detected always when either of the three probes traversed the outer LLBL/CDPL, as demonstrated in Figure 3 which shows V_L from the three probes plotted as a function of the temperature for the interval 1720–1940 UT.

3.2. Differences

[12] A striking difference was the observation of an outer LLBL on predominantly closed field lines, contrary to the simulation which showed that the southward-flow part of the LLBL is generally open [*Li et al.*, 2009, Figure 10]. The closed outer LLBL interpretation results from well-balanced parallel and anti-parallel electron fluxes even at energies >1 keV (Figures 2j and 2k), except for short periods (e.g., at ∼1813 UT for THE, marked by a green triangle in Figure 2j). Note that bidirectional heated magnetosheath electrons may not necessarily be a proof of closed field lines [*Fuselier et al.*, 1995], but that the balanced higher-energy electron

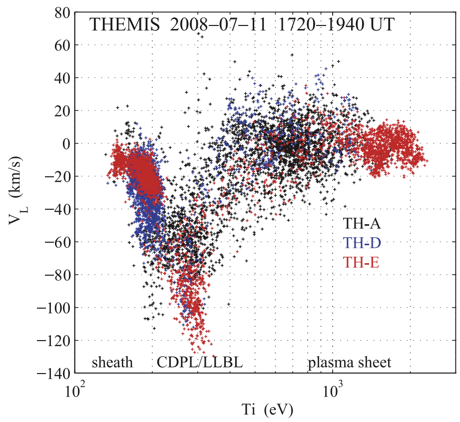

Figure 3. V_L versus ion temperature, showing the persistent presence of southward flows in the outer CDPL/LLBL.

fluxes constitute a proof. This indicates that most of the outer LLBL field lines were reconnected in the southern hemisphere as well. However, effects of southern high-latitude reconnection were not seen in the ion data, probably because of slower speed of ions and of greater distance from the southern reconnection site than from the northern site. We note that the entire LLBL was closed also in the event studied by *Øieroset et al.* [2008], for which the simulation was run. The entire LLBL being mostly closed, despite the continuous formation of the outer LLBL (section 3.1), seems to suggest that the average reconnection rate was roughly equal in both hemispheres.

[13] Since THA was near the inner edge of the LLBL/CDPL when THD and THE crossed the magnetopause at ~1746 UT and ~1848 UT, respectively (Figure S1), the thickness of the CDPL can be estimated; its width along the magnetopause normal was found to be ~0.35 R_E at 1746 UT and ~0.3 R_E at 1848 UT. Moreover, since THE traversed the CDPL when the solar wind dynamic pressure was stable (~2.5 nPa from 1745 UT to 1900 UT), the width at THE also can be estimated; the normal distance between the probe positions when THE crossed the inner edge at ~1806 UT and the magnetopause at ~1848 UT, respectively, was ~0.36 R_E. All these estimates indicate that the CDPL thickness was $\leq$0.5 R_E, smaller than in the *Øieroset et al.* [2008] event and in contrast with the simulations of *Li et al.* [2009] in which it becomes $\geq$1 R_E.

[14] The thickness of the dayside LLBL/CDPL could be controlled by the following factors: (i) the rate of high-latitude reconnection, and (ii) the rate of convective transport of the cold-dense plasma into the magnetotail (and possibly the loss rate of some plasma population into the ionosphere). Higher reconnection rate would generate a thicker LLBL/CDPL, while higher transport rate would lead to a thinner dayside LLBL/CDPL. Thus, our observations of less thick CDPLs seem to suggest that the actual reconnection rate was lower, and/or that the plasma transport toward the tail was faster, than in the simulation.

4. Discussion

[15] Our observations (section 3.2) as well as by *Øieroset et al.* [2008] suggest roughly equal reconnection rate in both hemispheres even under a large dipole tilt, while the global simulation implies higher rate in the summer than in the winter hemisphere [*Li et al.*, 2009]. *Lavraud et al.* [2005] showed no clear dependence on the dipole tilt angle of the occurrence of bidirectional heated electrons in the MSBL, although the dipole tilt determines in which hemisphere a given IMF field line is reconnected first. Their results also seem consistent with no or weak north-south asymmetry in the occurrence frequency or the rate of high-latitude reconnection. We infer that the discrepancy between the observations and the simulation may be explained in terms of the creation of a plasma depletion layer (PDL) outside the dayside magnetopause: the PDL formation makes the magnetosheath Alfvén speed higher and β lower, the conditions favorable for reconnection [e.g., *Twitty et al.*, 2004]. It might be that in the simulation, possibly unrealistically high reconnection rate in the summer hemisphere does not allow the generation of a clear PDL as observed (Figures 2c and 2h) so that reconnection in the winter hemisphere is suppressed (see, however, e.g., *Wang et al.* [2003] for zero dipole-tilt case).

[16] Remarkable in our event is the persistent presence of the cold-dense southward flows over >2 hours (Figure 3). It implies that high-latitude reconnection near the northern cusp was essentially continuous for the analyzed interval, consistent with earlier observations for northward IMF [*Frey et al.*, 2003; *Hasegawa et al.*, 2008]. Note also that along each spacecraft path, the magnetopause was encountered only a few times at most (crossings by THA at ~1945 UT are likely due to enhanced solar wind dynamic pressure), and that V_N was rather small near the boundary (Figures 2g and 2m). These features suggest that the magnetopause position was fairly stable, and may indicate that northern high-latitude reconnection was not only continuous but also quasi-steady.

[17] As information to facilitate further understanding in future of the LLBL/CDPL formation under northward IMF, Table 1 shows upstream solar wind parameters for both the present and *Øieroset et al.* [2008] events. Potentially significant differences between the two events are seen in the IMF B_x and clock angle. It may be worth noting that the LLBL was thinner in the present than in Øieroset et al. event, despite that the clock angle in our event was more favorable for capturing solar wind plasma through double

Table 1. Solar Wind and IMF Conditions in the Present and *Øieroset et al.* [2008] Events[a]

Date	Time (UT)	B_x	B_y	B_z	N_p (cm^{-3})	Clock Angle	Proton β	Alfvén Mach Number
2008–07–11	~1740	−5	1	7	8.5	8°	2.9	6.6
2007–06–03	~1540	2	−5	4.5	9	−48°	2.7	8.3

[a]Data are from the ACE spacecraft and are not time-shifted. The IMF is in unit of nT and GSM.

high-latitude reconnection [*Li et al.*, 2008]. It might be that the IMF B_x component plays some role in controlling the LLBL thickness and in generating significant southward flows as confirmed here.

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