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THEMIS multi-spacecraft observations of magnetosheath plasma penetration deep into the dayside low-latitude magnetosphere for northward and strong B_y IMF

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[1] On 2007-06-03 the five THEMIS spacecraft consecutively traversed the dayside (13.5 MLT) magnetopause during northward IMF with strong B_y. While one spacecraft monitored the magnetosheath, the other four encountered an extended region of nearly-stagnant magnetosheath plasma attached to the magnetopause on closed field lines. This region was much denser than, but otherwise similar to, the nightside cold-dense plasma sheet. At two points in time this region was bordered by two spacecraft, revealing that its thickness grew from 0.65 R_E to 0.9 R_E in ~25 minutes. There was no evidence for Kelvin-Helmholtz waves nor diffusion at the local magnetopause. Our observations suggest that even when the IMF clock angle was as large as 60°, substantial solar wind entry across the dayside magnetopause occurred due to reconnection either poleward of both cusps or poleward of one cusp in one hemisphere and equatorward-of-the-cusp in the other. **Citation:** Øieroset, M., T. D. Phan, V. Angelopoulos, J. P. Eastwood, J. McFadden, D. Larson, C. W. Carlson, K.-H. Glassmeier, M. Fujimoto, and J. Raeder (2008), THEMIS multi-spacecraft observations of magnetosheath plasma penetration deep into the dayside low-latitude magnetosphere for northward and strong B_y IMF, *Geophys. Res. Lett.*, *35*, L17S11, doi:10.1029/2008GL033661.

1. Introduction

[2] It is commonly believed that the dominant process by which the solar wind enters the Earth's magnetosphere is via dayside and nightside reconnection during southward IMF [*Dungey*, 1961]. In such a scenario, the magnetosphere is thought to be more closed to the solar wind during northward IMF, and one might expect that density of solar wind-sourced material in the plasma sheet would decrease during northward IMF.

[3] Surprisingly, however, the opposite behavior is observed. The plasma density in the near-Earth nightside plasma sheet during northward IMF is ~1 cm^{-3}, three times that observed during southward IMF. The plasma temperature is lower during northward IMF [e.g., *Fujimoto et al.*, 1996; *Terasawa et al.*, 1997]. This cold and dense plasma sheet (CDPS) has been detected deep inside the magnetosphere and often consists of a mixture of magnetosheath and magnetospheric plasma [e.g., *Fujimoto et al.*, 1996; *Fuselier et al.*, 1999; *Nishino et al.*, 2007]. The CDPS could have significant impact on inner-magnetospheric dynamics during strong convection times as the earthward injection of the denser plasma contributes to the development of an enhanced ring current [e.g., *Thomsen et al.*, 2003]. Determining the processes by which the CDPS is formed is thus one of the key challenges in magnetospheric physics.

[4] Several processes have been suggested including (1) slow diffusion of solar wind plasma across the flank low-latitude boundary layer (LLBL) [*Terasawa et al.*, 1997], (2) capture of solar wind plasma by non-linear Kelvin-Helmholtz instabilities on the flank magnetopause [e.g., *Hasegawa et al.*, 2004], and (3) capture of magnetosheath plasma by poleward-of-cusp reconnection in both hemispheres [*Song and Russell*, 1992; *Raeder et al.*, 1995]. However, the relative importance of these processes and the locations where they dominate are still unknown, largely because of the lack of simultaneous multi-point observations at the key entry sites.

[5] In this letter, data from the multi-spacecraft THEMIS coast phase is used to investigate the transfer of solar wind plasma into the dayside magnetosphere during a prolonged interval of northward IMF with strong B_y. We report the first direct measurement of the thickness of the dayside CDPS and investigate the temporal evolution of the thickness of the CDPS and the particle distributions in this layer.

2. Orbits and Instrumentation

[6] On June 3, 2007, between 15:22:00 and 17:11:00 UT, the five THEMIS spacecraft [*Angelopoulos*, 2008] traversed the dayside (13.5 MLT) magnetopause. They were in the same 14.7 R_E apogee orbit with the leading (TH-B) and trailing (TH-A) spacecraft separated by ~2 R_E (Figure 1). 3-s resolution data from the fluxgate magnetometer [*Auster et al.*, 2008] and the electrostatic plasma analyzer [*McFadden et al.*, 2008] are used. ACE data, propagated to Earth by comparing with TH-B magnetosheath observations, was used to monitor the solar wind conditions.

3. THEMIS-A Single Spacecraft Observations

[7] In this section we present single spacecraft observations of the dayside cold-dense plasma sheet to illustrate in detail its properties. Similarities and differences in the

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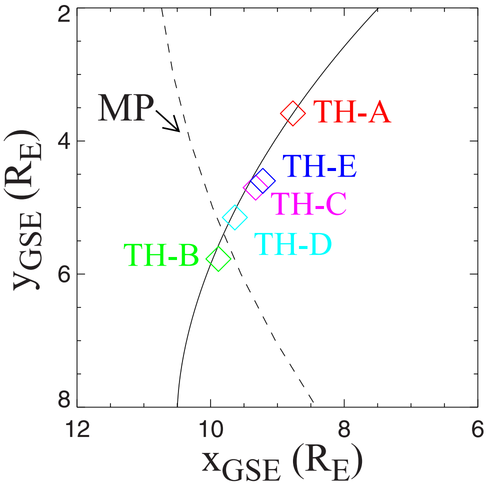

Figure 1. THEMIS orbit and spacecraft locations on June 3, 2007 in the vicinity of the 13.5 MLT magnetopause.

CDPS properties observed by the various spacecraft will be discussed in the next section.

[8] Figure 2 shows the outbound pass by TH-A. The spacecraft was initially located in the magnetosphere proper where only single energetic ion (Figure 2c) and electron (Figure 2d) populations were observed, and ended up in the magnetosheath where the flow speed was > 100 km/s. Between the hot ($T_i \sim 5$ keV) and tenuous ($N_i \sim 0.2$ cm^{-3}) magnetosphere and the magnetosheath, TH-A observed, for more than half an hour (from 16:31:10–17:05:10 UT marked by the horizontal dark blue bar in Figure 2c), a nearly stagnant (Figure 2g) and mixed population of both magnetospheric and heated magnetosheath ions with density and temperature intermediate between magnetospheric and magnetosheath values. There was a gradual density gradient toward the magnetopause, with the ion density increasing from $\sim$1 cm^{-3} at the inner edge of the mixed ion region (at 16:31:10 UT) to 3.8 cm^{-3} (at 17:05 UT) near the magnetopause, the average density being $\sim$3.3 cm^{-3}. The magnetic field in this region was extremely

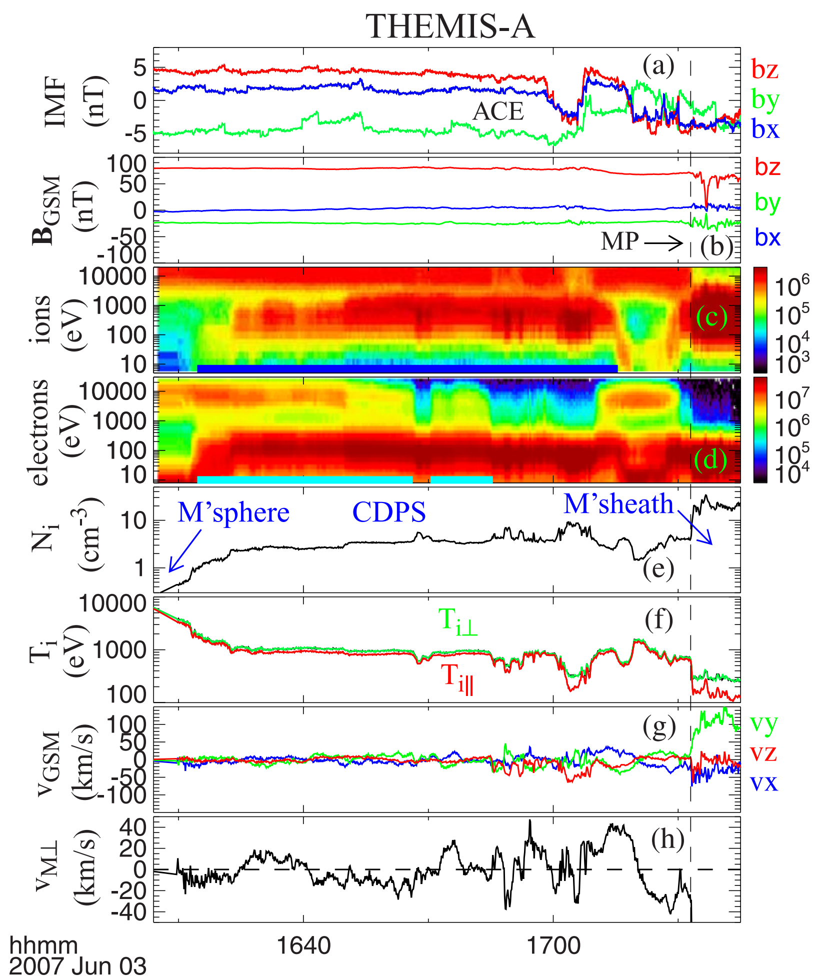

Figure 2. (a) The time-shifted IMF measured by ACE. (b–h) TH-A measurements of the magnetic field, ion and electron energy spectrograms (in eVs^{-1}cm^{-2}ster^{-1}eV^{-1}), ion density, temperature and velocity, and the M component of the velocity tangential to the magnetopause and perpendicular to the magnetic field, respectively. In the LMN boundary coordinate system N lies along the model magnetopause normal and the L-M plane is tangential to the magnetopause with M approximately due west. The horizontal dark blue bar in Figure 2c marks the CDPS region. The light blue bar in Figure 2d denotes the region of mixed magnetosheath and magnetospheric electrons.

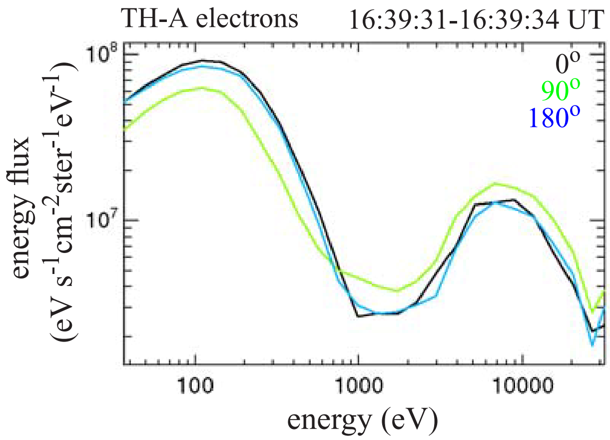

Figure 3. TH-A electron pitch-angle distribution measured in the mixed electron region of the CDPS.

smooth. The plasma and field properties of this region are similar to those of the CDPS commonly observed further downtail and in the nightside plasma sheet during northward IMF, except that the density in this dayside CDPS is 3 times higher than in the typical nightside CDPS. Figure 2h shows that the velocity component tangential to the magnetopause, v_M, was low (<40 km/s) and its direction was highly variable showing no systematic tailward or earthward flow. The nearly-stagnant plasma and smooth magnetic field in this CDPS stand in contrast to the flowing and more turbulent Low-Latitude Boundary Layer (LLBL).

[9] The CDPS interval was interrupted by a ~1 minute interval near 17:02 UT with $N_i > 10$ cm^{-3} and $T_i \sim 100$ eV, indicating a brief excursion into the magnetosheath. Between the end of the CDPS at 17:05:00 UT and the magnetopause crossing at 17:11:10 UT, TH-A re-encountered the single-population hot magnetosphere. Although the CDPS appears to be detached from the magnetopause, this may not be a spatial effect as will be discussed later.

[10] In addition to the mixed ion populations, Figure 2d shows the presence of mixed magnetospheric and heated magnetosheath electrons during the earlier part of the CDPS (marked by the light blue bar in Figure 2d). Figure 3 shows an electron pitch-angle distribution sampled at 16:39:32 UT inside the mixed electron region. The field-aligned and anti-field-aligned electron fluxes of both (high-energy) magnetospheric and (low-energy) magnetosheath origin are well balanced. In the outer CDPS where there was only a single heated magnetosheath electron population, the field-aligned and anti-field-aligned electron fluxes were also well balanced. These electron behaviors indicate that the entire CDPS was on closed field lines. Note that the presence of energetic magnetospheric electrons inside the mixed-ion CDPS have rarely been reported in previous CDPS events. In the present event, the thickness of this mixed electron layer appears to evolve with time as will be discussed in the next section.

[11] The CDPS observed by TH-A occurred during a period of relatively steady northward and dawnward IMF, except for a brief 3-min interval (17:00–17:03 UT) when the IMF had a southward component.

4. Solar Wind and Five-Spacecraft THEMIS Observations

4.1. Solar Wind and IMF Conditions

[12] Figures 4a–4c display the time-shifted solar wind data from ACE. At the beginning of the interval the IMF was southward-directed ($\theta_{IMF} = \tan^{-1}[B_{z,GSM}/|B_{y,GSM}|] \sim -90°$). At 15:25 UT, the IMF abruptly turned to dominantly duskward ($\theta_{IMF} \sim 0°$). Over the next 35 minutes, the IMF became increasingly more northward, with θ_{IMF} varying linearly from 0° to ~ 70° during that interval. This interval was followed by one hour (16:00–17:00 UT) of relatively steady northward and dawnward IMF, with θ_{IMF} varying between 30°–70°. At 17:00 UT the IMF turned southward for 3 minutes followed by a brief interval of northward IMF before becoming dominantly southward after 17:07 UT. The varying but well-defined IMF orientation during the two hours of interest provided important information on the IMF condition for the occurrence of the CDPS. Finally, the solar wind dynamic pressure varied between 1.5 nPa and 3.5 nPa during the two-hour interval.

4.2. THEMIS Five-Spacecraft Observations

[13] Figures 4d–4r show observations from all five THEMIS spacecraft as they traversed one after another the regions surrounding the magnetopause (MP). TH-B (Figures 4d, 4i, and 4n) was the leading spacecraft and encountered the magnetopause at 15:22:00 UT, while the IMF was southward-directed. The duration of the MP/LLBL crossing was only ~1 minute, in contrast to the duration of the TH-A crossing of the CDPS (>30 minutes). The TH-B crossing occurred during a period of stable solar wind ram pressure (Figure 4a) and did not coincide with the sudden increase of the ram pressure that accompanied the northward turning of the IMF 3 minutes later. The 1-min duration of the crossing must therefore imply a thin MP/LLBL during southward IMF. After the crossing, TH-B served as the magnetosheath monitor and was used to determine the exact time lag for the ACE data.

[14] Before the IMF turned northward at 15:25:00 UT, the remaining four spacecraft (D, C, E, and A) were located inside the hot magnetosphere. Starting at 15:51:00 UT all four spacecraft consecutively encountered the CDPS marked with the dark blue bars in Figure 3. In fact, TH-D started to intermittently encounter the CDPS when $\theta_{IMF} \sim 11°$, at 15:29:22 UT, prior to detecting the CDPS in a more continuous fashion. The magnetosheath-like plasma encountered by TH-D, C, and E had similar properties as the CDPS observed by TH-A (section 3), i.e., it was stagnant, with stable magnetic field, heated magnetosheath ions and electrons, and field-aligned and anti-field aligned electron fluxes that were well balanced at all energies (not shown), indicating that this region was on closed field lines. TH-E observed the highest average CDPS density of 6.7 cm^{-3}, while the average densities at TH-D and TH-C were 4.6 and 5.6. cm^{-3}, respectively, all of which are much higher than the density in the nightside CDPS. Combining all four spacecraft, the CDPS

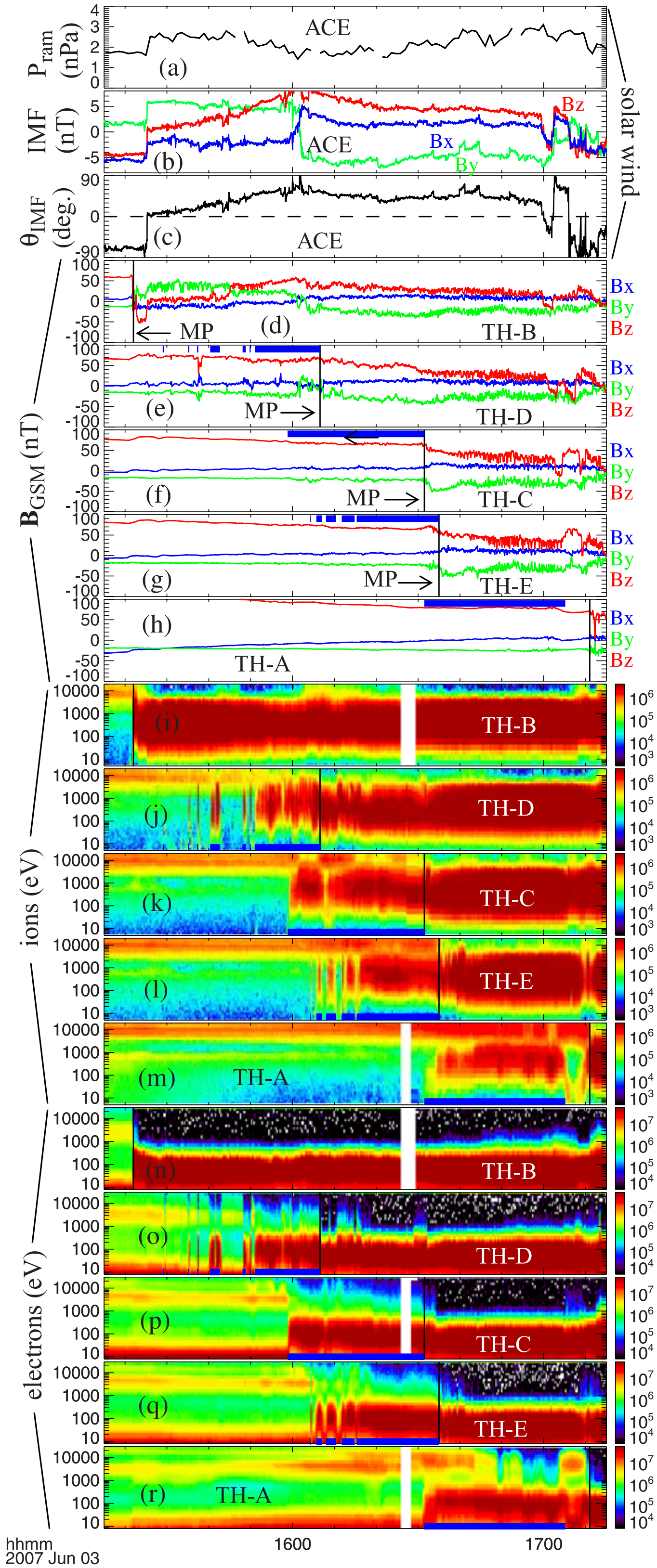

Figure 4. (a–c) ACE solar wind ram pressure, magnetic field, and magnetic field theta angle ($\theta_{IMF} = \tan^{-1}[B_{z,GSM}/|B_{y,GSM}|]$). (d–h) magnetic field components, (i–m) ion spectrograms, and (n–r) electron spectrograms from TH-B, D, C, E, A respectively. Horizontal dark blue bars mark the CDPS intervals. The magnetopause marked by a vertical black line, corresponds to the open/closed field boundary deduced from the electron pitch angle distributions.

was observed continuously from 15:51:00 UT (TH-D) to 17:05:10 UT (TH-A). Thus the CDPS was a persistent spatial region over 74 minutes, during which time θ_{IMF} varied between 30° and 70°.

[15] Although TH-D, TH-C, and TH-E detected a CDPS with similar properties to the one encountered later by TH-A there were some notable differences. Unlike TH-A, which observed a mixture of magnetospheric and heated magnetosheath ions, the plasma observed by TH-D was for the most part not mixed, with the magnetospheric component being absent or weak. The magnetospheric ions were clearly present in more than half of the TH-C CDPS samples, and they were present throughout the TH-E CDPS observations. Thus the magnetosheath-sourced CDPS ions appeared to become more mixed with increasingly higher fluxes of hot magnetospheric ions as time progressed.

[16] The electrons display a similar feature. At the beginning of the CDPS interval TH-D, C, and E observed single population electrons with peak energies of 100 eV, i.e., heated magnetosheath electrons, while hot (5–10 keV) magnetospheric electrons were absent. Towards the end of the CDPS interval, however, TH-A observed both cold and hot electrons inside the CDPS 75% of the time (marked by the light blue bar in Figure 2d).

[17] Unlike TH-A, TH-D, C, and E all observed the CDPS to be attached to the magnetopause. The difference between the TH-A observations and the other probes may be related to the southward turning of the IMF at 17:00:00 UT, as observed by TH-B and ACE. The magnetopause crossings by TH-D, C, and E occurred during northward IMF and were all single crossings, indicating that there were no surface waves present at 13.5 MLT.

[18] The large variation in the solar wind dynamic pressure meant that we could not reliably determine the CDPS thickness using single spacecraft measurements, nor could the evolution of the CDPS thickness be determined from the relative CDPS durations. However, at around 16:30 UT TH-C crossed the magnetopause (outer edge of the CDPS) while TH-A entered the CDPS. Thus the two spacecraft bordered the CDPS; the thickness was found to be 1.1 R_E along the spacecraft track, or ~0.9 R_E normal to the magnetopause. The thickness of the CDPS could also be estimated 25 minutes earlier (at ~16:07 UT) when TH-D crossed the magnetopause and TH-E was close to the inner edge of the CDPS. The CDPS thickness was ~0.8 R_E along the spacecraft track or ~0.65 R_E normal to the magnetopause. This suggests that the CDPS grew in thickness by ~0.25 R_E in less than half an hour.

5. Discussion

[19] The event presented here shows the presence of a thick (0.65–0.9 R_E) dayside CDPS of magnetosheath-like but nearly-stagnant plasma immediately earthward of the magnetopause at 13.5 MLT, observed continuously for $30° < \theta_{IMF} < 70°$ (or IMF clock angle between 60° and 20°). The multi-spacecraft observations also revealed the increasing presence of hot magnetospheric ions and electrons in the CDPS with time. We now discuss these observations in relation to the candidate solar wind entry processes.

[20] Even though there was a slight density gradient from the inner edge of the CDPS to the MP, which could be consistent with diffusive entry, the CDPS was observed on extremely smooth magnetic field with no notable wave activity. Thus local diffusion is unlikely to be important. There was also no evidence for Kelvin Helmholtz (K-H) activity at the local magnetopause since no boundary waves were observed, although the absence of K-H waves at 13.5 MLT under normal solar wind condition is not unexpected.

[21] It is also unlikely that the observed CDPS is the result of plasma entry via diffusive entry or K-H further downtail and subsequent sunward convection. Such a scenario is not expected to result in a thin (0.9 R_E) CDPS attached to the magnetopause on the dayside and furthermore, no systematic sunward flow was observed.

[22] A possible CDPS formation scenario is the capture of magnetosheath plasma by poleward-of-cusp reconnection in both hemispheres [*Song and Russell*, 1992; *Raeder et al.*, 1995]; the key evidence is the presence of counter-streaming and heated magnetosheath electrons on CDPS field lines. Such electrons have previously been observed in the magnetosheath boundary layer just outside the magnetopause and interpreted as newly closed field lines resulting from dual-lobe reconnection during northward IMF [*Onsager et al.*, 2001; *Lavraud et al.*, 2006]. The fact that the CDPS is seen at 13.5 MLT for $30° < \theta_{IMF} < 70°$ degrees implies not only that reconnection occurred on the same field lines in both cusps, but that this resulted in the addition of magnetic flux to the subsolar magnetosphere, even when the IMF had a strong B_y component. More importantly, this scenario led to substantial and persistent entry of the solar wind across the dayside magnetopause as evidenced by the uninterrupted (for 74 minutes) encounter of a rather thick CDPS that was attached to the magnetopause until the IMF turned southward.

[23] Although the dual-lobe reconnection scenario enables the capture of magnetosheath plasma, it does not immediately explain the simultaneous presence of 10 keV magnetospheric ions and 5–10 keV electrons. The fact that these energetic particles in the CDPS have the same energy as (and their flux levels are similar to or lower than) those observed in the adjacent (hot) magnetosphere suggest a local source which penetrates via magnetic gradient and curvature drifts. The fact that the intensity and the depth of penetration of the energetic ions and electrons into the CDPS increase with time seems consistent with this scenario.

[24] Another possible CDPS formation scenario is the capture of magnetosheath plasma onto closed field lines by tailward-of-the-cusp reconnection in one hemisphere and equatorward-of-the-cusp reconnection in the other hemisphere (Figure S1 in auxiliary material[1]). The latter would occur at the low (<60°)-shear magnetopause [e.g., *Paschmann et al.*, 1993]. This scenario would readily account for the presence of magnetospheric electrons if reconnection first occurred tailward of the cusp. Magnetospheric electrons would stream onto the newly captured magnetosheath field lines via subsequent equatorward-of-the-cusp reconnection.

[25] It is important to establish whether the dayside CDPS could be the source of the much thicker nightside

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033661.

CDPS as has been suggested by global simulations [*Raeder et al.*, 1995; *Li et al.*, 2005]. The fact that the density in this dayside CDPS is 3–6 times higher than the typical value observed in the nightside CDPS is consistent with the expected increase of the magnetic flux tube volume associated with the transport of CDPS flux tubes from the dayside to the nightside. However, the observed tangential flow velocity did not show a systematic tailward flow which might be expected under this scenario. Instead THEMIS observed alternating sunward and tailward slow (10–40 km/s) flows in the CDPS. This could imply that the transport is slow and not laminar. The slow transport may be consistent with previous studies showing that the CDPS is observed in the magnetotail only several hours after a northward IMF turning [*Terasawa et al.*, 1997; *Øieroset et al.*, 2005].

[26] To fully solve this problem, the present THEMIS observations need to be put in a more global context. Comparisons with Geotail observations on the dawn flank and with global simulations could shed light on the question regarding plasma transport as well as the relative importance of the different candidate solar wind entry processes at different magnetopause locations, since it is possible that several processes may be active at the same time but dominant at different magnetopause locations.

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