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Structure of plasmaspheric plumes and their participation in magnetopause reconnection: First results from THEMIS

J. P. McFadden,[1] C. W. Carlson,[1] D. Larson,[1] J. Bonnell,[1] F. S. Mozer,[1] V. Angelopoulos,[1,2] K.-H. Glassmeier,[3] and U. Auster[3]

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[1] New observations by the THEMIS spacecraft have revealed dense (>10 cm^{-3}) plasmaspheric plumes extending to the magnetopause. The large scale radial structure of these plumes is revealed by multi-spacecraft measurements. Temporal variations in the radial distribution of plume plasma, caused by azimuthal density gradients coupled with azimuthal flow, are also shown to contribute to plume structure. In addition, flux tubes with cold plume plasma are shown to participate in reconnection, with simultaneous observations of cold ions and reconnection flow jets on open flux tubes as revealed by the loss of hot magnetospheric electrons. **Citation:** McFadden, J. P., C. W. Carlson, D. Larson, J. Bonnell, F. S. Mozer, V. Angelopoulos, K.-H. Glassmeier, and U. Auster (2008), Structure of plasmaspheric plumes and their participation in magnetopause reconnection: First results from THEMIS, *Geophys. Res. Lett.*, *35*, L17S10, doi:10.1029/2008GL033677.

1. Introduction

[2] The relative importance of solar wind and ionospheric input to the magnetosphere's plasma has been a subject of study and debate for decades. The cold plasma content of the magnetosphere is often ignored due to difficulties in its measurement. If we neglect the distant magnetotail (>100 Re), then cold plasma clearly dominates the total plasma content of the magnetosphere, with the plasmasphere often containing an order of magnitude more plasma than the <100 Re magnetotail. As demonstrated below, dusk-side plasmaspheric plumes generally contain 10–100 times more cold plasma than hot plasma. In this paper we present THEMIS observations of cold plasma in the near-equatorial dayside magnetosphere, illustrating the important role cold plasma plays in the dayside magnetosphere including reconnection dynamics.

[3] THEMIS is not the first satellite to measure cold plasma in the dayside magnetosphere. Plasmaspheric plumes were sampled by Ogo 5 [*Chappell*, 1974], by ISEE 1 and 2 [*Gosling et al.*, 1990], and by the Dynamics Explorer spacecraft [*Craven et al.*, 1997]. The eruption and structure of plasmaspheric plumes at geosynchronous orbit during active times has been observed using the MPA instruments on the LANL Geosynchronous satellites [*Su et al.*, 2001]. The participation of cold plasma in reconnection at the magnetopause has also been inferred by *Gosling et al.* [1990] from low latitude boundary layer measurements, and by *Su et al.* [2000] at geosynchronous orbit during times of high solar wind dynamics pressure. The Cluster spacecraft measured cold ions near the high latitude magnetopause (MP) when solar wind dynamic pressure changes revealed the cold ions [*Sauvaud et al.*, 2001]. Similar but higher density cold plasma measurements (up to 70 cm^{-3}) at the equatorial magnetopause were reported by *Chandler and Moore* [2003]. In addition, the IMAGE spacecraft was able to capture the formation and loss of plasmaspheric plumes [*Goldstein et al.*, 2004]. The THEMIS mission provides a much more extensive, detailed, high resolution data set of cold plasma observations within plasmaspheric plumes and at the magnetopause during reconnection. In particular these first results demonstrate radial and small scale structure in plasmaspheric plumes, and reveal cold plasma capture during reconnection at the MP during nominal solar wind conditions.

2. THEMIS Mission and Instruments

[4] THEMIS is a five satellite mission whose prime science objective is to measure the time sequences of substorm dynamics. The first seven months of the mission consisted of a "coast phase" that kept the satellites in close proximity in preparation for their final injections into the prime-mission orbit configurations [*Angelopoulos*, 2008]. This close separation allowed cross-calibration of the instruments and meso-scale studies of the dayside magnetosphere. In particular the spacecraft were oriented in a string-of-pearls configuration whose orbit had apogee (perigee) of ~14.7 Re (~1.16 Re), with the initial line-of-apsides near dusk. The spacecraft are identified by letters and were ordered B-D-C-E-A starting with the leading probe. In the vicinity of the MP, the inner three probes were spaced by ~1000 km and the leading and trailing probes spaced by ~3000 to ~10000 km. This orbit and satellite configuration resulted in spacecraft separations that were aligned within ~35° of the MP normal.

[5] The "coast phase" configuration provided one or two passes through the nominal plasmaspheric plume region (12–18 LT) each day for several months, followed by pre-noon observations of cold plasma outside the plume region. Cold plasma is difficult to detect and quantify so we use a combination of three different instruments on THEMIS to make this measurement. An ion plasma sensor detects cold plasma when convection flows overcome the potential barrier caused by spacecraft charging. This generally restricts cold ion detection to regions near the MP where solar wind dynamic pressure changes result in plasma

[1]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[2]IGPP, University of California, Los Angeles, California, USA.
[3]Technische Universität Braunschweig, Germany.

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motion. Since spacecraft charging generally allows detection of all electrons, comparisons of ion and electron densities can also reveal a missed cold ion component. However the electron measurement is also difficult since cold ions are normally charge-balanced by cold electrons, which are hard to separate from spacecraft photo-electrons. Both plasma sensors are electrostatic analyzers that make 3-D plasma measurements with ~3s resolution. The relative calibration of electron and ion plasma sensors is better than 5%, and the uncertainty in the absolute calibration is 10% (J. P. McFadden et al., The THEMIS ESA plasma instrument and in-flight calibration, submitted to *Space Science Reviews*, 2008).

[6] The third method of detecting cold plasma is by monitoring the spacecraft potential, which depends on the plasma density [*Pederson et al.*, 1998; *Scudder et al.*, 2000]. Cross-correlation between measured densities and spacecraft potential, as determined from the EFI Langmuir probes (J. Bonnell et al., The THEMIS electric field instrument, submitted to *Space Science Reviews*, 2008), provides a relation between density and potential. For a given spacecraft geometry, this relation is not constant and depends on the plasma distribution and the bias currents and voltages applied to the Langmuir probes. At the time of this paper, the potential versus density relationship has not been well quantified for all these changes. Instead we use a simple functional relation (3 exponentials) with an adjustable parameter that allows us to tailor the algorithm to obtain a good fit in regions where cold plasma is measured by other instruments. Density inferred by spacecraft potential is especially useful within plasmaspheric plumes far from the MP since the flows are generally too small for detection of cold ions and since the combination of small spacecraft potentials and cold electrons can result in most electrons being at energies below the lowest energy sampled by the electron sensor. The difference between inferred and measured density can be easily adjusted to <10% for a particular case, however if the electron spectra change dramatically from the fit region, ~30% errors are possible.

3. Observations

[7] Figure 1 (8 June 2007) illustrates the typical large scale structure found in and around plasmaspheric plumes. During this interval the THC probe traveled outward from local noon starting at ~5 Re and eventually crossed the MP near ~1330 LT (2300 UT) at a distance of ~11 Re. Figure 1a shows the magnetic field which dominates the total pressure throughout the interval inside the MP. The ion spectrogram (Figure 1b) shows tenuous hot plasma extending out to the MP, and occasionally displays cold ions (<100 eV) between 2100 and 2225 UT. There is also a brief appearance of trapped sheath plasma at ~2220 UT which appears to be a low entropy flux tube that has sunk into the magnetosphere. Figure 1c shows that hot (5–10 keV) electron plasma was present over most of this outbound pass. However, a transition to a warm (~1 keV) electron plasma occurs between 2220 and 2226 UT, coinciding with the disappearance of cold ions (Figure 1b). This transition also corresponds to the increase in spacecraft potential (black line, Figure 1c), which indicates a decrease of plasma density (green line, Figure 1d).

[8] Figure 1d shows the measured ion (black) and electron (red) densities, along with the inferred total density (green) using an algorithm based on spacecraft potential. Parameters in the algorithm were adjusted for a good fit during periods when both cold and hot plasma were well measured. Prior to 2220 UT, cold ions were only occasionally and incompletely measured due to very weak flows (<30 km/s). Electrons were also poorly measured prior to 2220 due to a combination of small spacecraft potentials ($\Phi_{sc} \sim 4-5$ V), an electron energy sweep cutoff at 7 eV, and the presence of very cold (~1 eV), dense, ionospheric electrons. The best estimate of plasmaspheric plume structure comes from the spacecraft-potential-inferred density (Figure 1d, green). The inferred density allows identification of a plasmapause at ~1840 UT, where the density drops from ~400 cm^{-3} to ~20 cm^{-3}, and shows a plume that varied in density from ~20–80 cm^{-3}. As we demonstrate below, the outer boundary of the plume (2226 UT) was a spatial feature that extended to ~10.7 Re before abruptly ending leaving a ~0.6 Re gap in cold plasma just inside the MP.

[9] To determine that the abrupt decrease in plume density at 2226 UT on THC was a radial spatial boundary rather than an azimuthal boundary convecting across the spacecraft required the examination of data from additional spacecraft. Probes THD and THE were in close proximity to THC, exhibiting similar temporal profiles for density that provide little information to separate large scale spatial and temporal variations. Probes THA and THB had larger separations but did not have their electric field probes deployed, and therefore could not provide density estimates based on spacecraft potential. Instead their ion and electron spectrograms provide the needed measurements. Figures 1e and 1f (ion and electrons) show that THA passed through the same spatial region as THC with a one hour delay. Cold ions (Figure 1e) were observed from ~8.6 to ~10.4 Re (2200 to 2330 UT) followed by a dropout in cold ions that is simultaneous with the appearance of a warm (~1 keV) electron component. In addition, THB (not shown) which led THC by ~1 hr, also showed a similar radial layering. Therefore the THEMIS probes reveal the large scale radial structure of this plume, which appears to be confined inside a thin (~0.6 Re) layer with no cold plasma.

[10] For completeness we mention that significant small scale spatial and temporal variations were also present during this period. For example, the sheath-like plasma measured by THA at the day boundary (0000 UT) is not a MP encounter. Instead this is a brief appearance of trapped sheath plasma at the boundary between the plume and warm electrons, similar to that observed on THC at 2226 UT. This encounter was preceded by a brief appearance of cold ions (2357–2359.5 UT) showing the plume was momentarily re-entered. During this period a slow decrease in total pressure (magnetic and plasma) was observed at THA indicating that a drop in dynamic pressure caused this expansion of the magnetosphere.

[11] It is of interest whether large scale plumes, as seen in Figure 1, are typical of the post-noon sector. Using the spacecraft potential to infer density, we found cold plasma with density >2/cm^3 was present at distances >8 Re on all THC outbound and inbound passes in the post-noon sector during June 2007. These densities are an order of magnitude

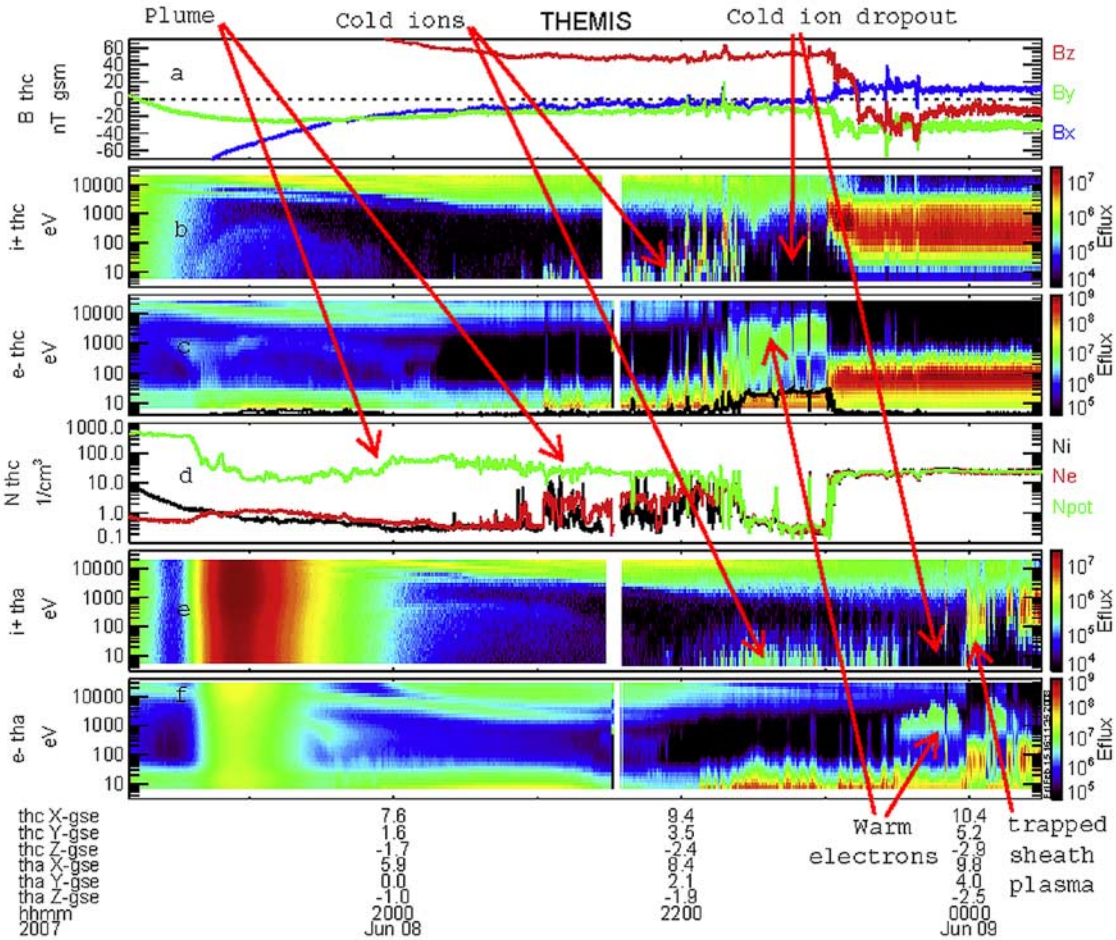

Figure 1. For the THC probe, (a) magnetic field, (b) ion spectrogram, (c) electron spectrogram, and (d) density. The density plot includes measured ion (black) and electron (red) densities, along with the inferred density from spacecraft potential (green). For the THA probe, (e) ion and (f) electron spectrograms. The plasmaspheric plume is revealed with the inferred density (green line, Figure 1d). THA observations are used to demonstrate that the drop in plume density near the magnetopause associated with warm (~1 keV) electrons, is a spatial feature of the large scale plume structure.

larger than the typical hot plasma density. In addition, about one third of these passes had densities >10/cm^3 at distances >8 Re. Not all of these plumes extended to the magnetopause, however cold plasma dominated the density at the MP on about half of the passes.

[12] To better illustrate small scale spatial and temporal variations we consider the 7 August 2007 event. Figure 2 illustrates the small scale structure and temporal variations that can be found in plasmaspheric plumes at the MP. Figures 2a–2e show observations from the THD probe during 14 MP contacts spanning 20 minutes. Cold plasma is identified in the ion spectrogram (Figure 2b) prior to 9:38 UT as a narrow-band, low-energy component interspersed between sheath plasma (~1 keV). Charge neutrality is provided by an accompanying cold (10–20 eV) electron component (Figure 2c). Figure 2d shows the ion (black) and electron (red) densities, along with the inferred density from spacecraft potential (green). The magnetospheric hot plasma density was ~0.2 cm^{-3} during this period. Between 9:30 and ~9:38 UT, the total density remains relatively constant as the satellite shifts five times between magnetosheath plasma and the magnetosphere with cold plasma. However, Figure 2d shows that between 9:40:40 and 9:42 UT, and again between 9:46:40 and 9:49 UT, the cold plasma decreased significantly, leaving primarily hot plasma adjacent to the MP. This factor of ten decrease in magnetospheric mass loading will cause significant changes in ion outflow velocities during reconnection. For completeness we note that a low latitude boundary layer (LLBL) of trapped magnetosheath plasma starts to form at ~9:36. It is most clearly identified at 9:38 and 9:40 UT from the magnetospheric magnetic field (Figure 2a), sheath like ions (Figure 2b) and electrons (Figure 2c), and weak flows (Figure 2e). It formed during a brief period of northward IMF as determined from THA (not shown). This LLBL had about half the sheath density and is not apparent in the 9:46:30 UT MP crossings (Figure 2a).

[13] Figures 2f–2k, show observations from the THB spacecraft, located ~3000 km Earthward of THD, that provide a better picture of the magnetospheric changes. The decrease in magnetospheric density clearly occurs at ~9:39 UT with an order of magnitude drop in cold plasma density by 9:40 (Figure 2i). A tenuous (~0.1–0.2 cm^{-3}), low-energy (~100 eV) field-aligned component (Figure 2g) remains at THB after 9:40 UT and probably consists of conics that have folded up into a beam. The cold ions are

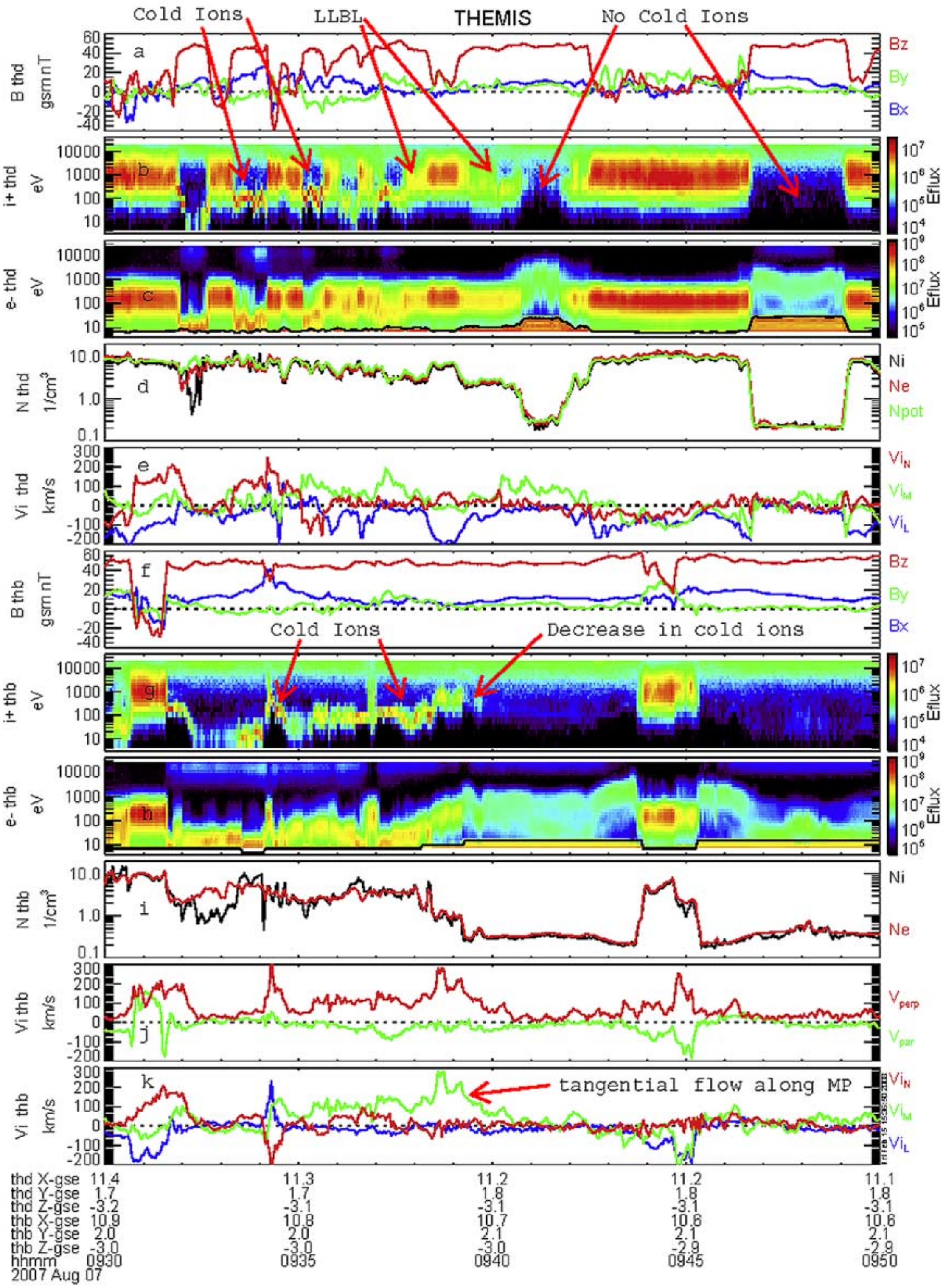

Figure 2. For the THD probe, (a) Magnetic field, (b) ion spectrogram, (c) electron spectrogram, (d) ion (black), electron (red) and inferred density from spacecraft potential (green), and (e) ion velocity in boundary normal coordinates. For the THB probe, (f) magnetic field, (g) ion spectrogram, (h) electron spectrogram, (i) ion (black) and electron (red) densities, (j) ion parallel (green) and perpendicular (red) velocities, and (k) ion velocities in boundary normal coordinates. For THB, spacecraft potential (black line, Figure 2e) was estimated from electron spectra. Plot reveals both significant cold plasma (N$\sim$10 cm^{-3}) and temporal variations in cold plasma at the magnetopause.

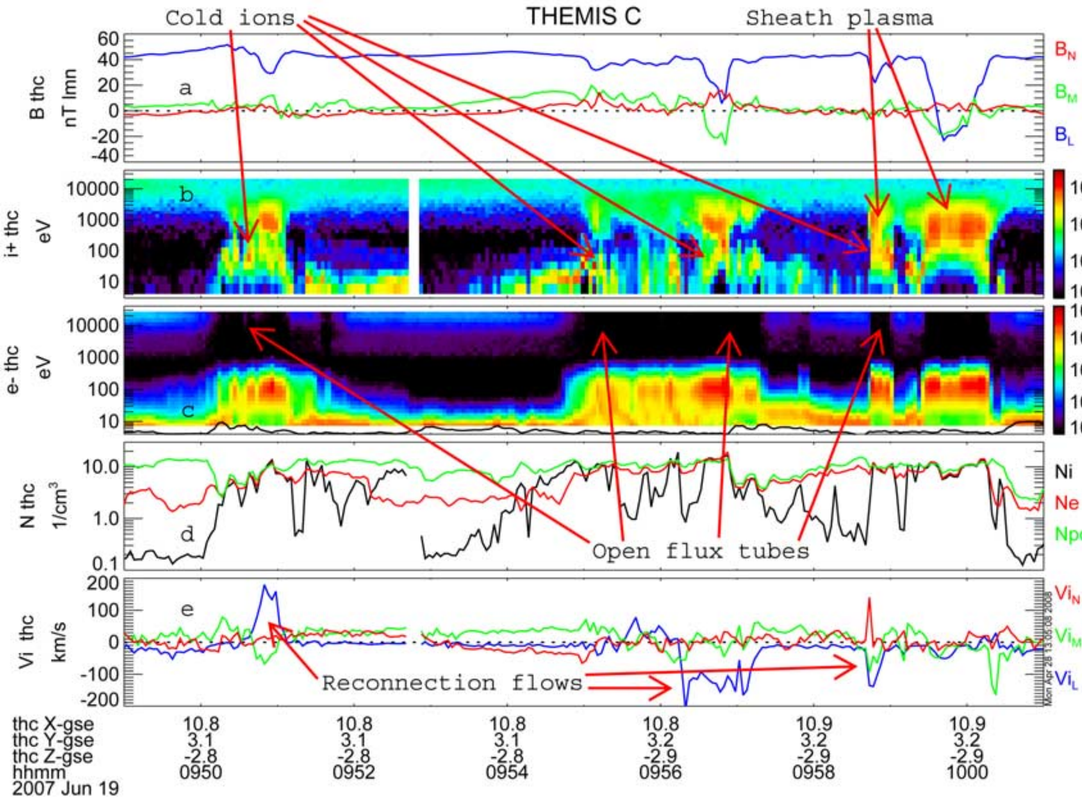

Figure 3. For the THC probe, (a) magnetic field, (b) ion and (c) electron spectrograms, (d) density, and (e) ion velocity during several encounters with the magnetopause. The cold plasma dominated magnetosphere has about the same density as the magnetosheath. Cold ions (spectral peak <200 eV in Figure 3b) are observed on newly reconnected field lines during the periods 0950–0951 UT, 0955–0957 UT, and just before 0959 UT. Reconnection is determined from the loss of hot electrons (Figure 3c) and from reconnection flow jets (Figure 3e).

also missing at THD at ~9:41 UT (Figure 2d). If MP motion was the only flow driver, one would expect periodic dropouts in measured cold ions as the MP reversed its motion. The 6 minute interval (9:34–9:40 UT) in Figure 2d, where cold ions are observed without dropouts while the MP reverses motion at THD, demonstrates additional flows must be present. Figure 2j shows the parallel and perpendicular components of velocity which aid the deduction of these flows. During this period, perpendicular flows are much larger than parallel flows indicating convection is important in revealing the cold ions. Figure 2k shows the velocity in boundary normal coordinates demonstrating a large tangential flow (M-direction) along the MP, predominantly in the –Ygse direction and toward the subsolar region. These observations suggest an azimuthal gradient in the cold plasma plume convected across the spacecraft. Such azimuthal gradients should impact reconnection rates and reconnection flows along the MP when plasma plumes participate in dayside reconnection. Below we present an example of this participation.

[14] Figure 3 (19 June 2007) demonstrates that cold plasma plumes, with densities comparable to the magnetosheath densities, partake in reconnection. Figure 3 shows magnetic field and plasma data for multiple encounters with the MP. The plasma densities from the measured ions (black) and electrons (red) shown in Figure 3d suffer from the same problems discussed earlier. The flow velocities are often too small for complete ion measurements and the spacecraft potential is low enough so that a significant fraction of the electrons are below the electron sensor's energy sweep cutoff. In this case we attempted to compensate for the missed electron plasma by using an algorithm that filled in the electron distribution below this cutoff assuming a constant phase space density below the lowest measured step. Unfortunately the cold electron component is so cold that this method also underestimates electron density. Instead we must again rely on the spacecraft potential inferred density (green). This curve shows that the magnetospheric cold density is about the same as the sheath density for this entire period.

[15] The signature for newly reconnected flux tubes, as revealed in Figure 3c, is the loss of hot magnetospheric plasma and its replacement by cooler sheath plasma. During the intervals 0950–0951 UT, 0955–0957 UT, and just before 0959 UT, cold ions are clearly present on flux tubes that have lost their hot electron component. In addition, reconnection flow jets are seen during each of these encounters as revealed by the appearance of ~1 keV sheath plasma (Figure 3b) simultaneous with large (>100 km/s) ion flows (Figure 3e). These plume ions should remain cold until they cross the current sheet where they would be accelerated to the Alfven speed.

[16] We point out that the dense (~10 cm^{-3}) cold ions seen in Figure 3 were only observed in the region adjacent

to the MP. A short distance Earthward of these MP encounters, the cold plasma density dropped to ~1 cm^{-3}, which was still much greater than the ~0.2 hot plasma density. The fact that this high density plume was confined to thin layer at the MP is similar to the observation in Figure 1, where a thin layer without cold plasma was present at the MP. These observations indicate azimuthal spreading of flux tubes, possibly due to interchange instabilities.

[17] Since the composition of plasmaspheric plumes is of general interest, ion spectra from the THC probe were inspected to determine whether non-proton components were present. A three month period was examined for observations containing high density (>5/cm^3) cold protons measured by the ion ESA. For the majority of events, He+ and O+ spectral peaks could not be resolved. A few events contained He+ peaks with N_{He+}/N_p at a 1%–2% level and with no visible O+ peak. A few brief periods (~2 minutes) with significant (>10%) cold He+ or O+ were found during weak magnetic storms, however the vast majority of data on those days had N_{He+}/N_p < 2% and no O+ peak. The cold plasma N_{He+}/N_p ratio observed by THEMIS is an order of magnitude lower than those reported from IMAGE [*Goldstein et al.*, 2004]. This lack of heavier ions may result from changes in atmospheric scale height associated with solar minimum during the THEMIS observations.

4. Conclusion

[18] In this paper we showed dense (>10 cm^{-3}) plasmaspheric plumes often extend out to the MP and participate in reconnection processes. The large scale radial and temporal (or azimuthal) structure of these plumes was revealed by THEMIS multipoint measurements. These observations suggest that future missions which intend to study the MP should include cold plasma sensors to better quantify the role cold plasma plays in reconnection processes.

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V. Angelopoulos, J. Bonnell, C. W. Carlson, D. Larson, J. P. McFadden, and F. S. Mozer, Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, CA 94720–7450, USA. (mcfadden@ssl.berkeley.edu)

U. Auster and K.-H. Glassmeier, Technische Universität Braunschweig, Sauerbruchstraße 17, D-38116, Braunschweig, Germany.