Structure of plasmaspheric plumes and their participation in magnetopause reconnection: first results from the THEMIS spacecraft


Abstract

New observations by the THEMIS spacecraft have revealed dense (>10 cm⁻³) plasmaspheric plumes extending out to the MP. The large scale radial structure of these plumes are revealed by the multipoint 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.

Introduction

The relative importance of solar wind and ionospheric input to the magnetosphere’s plasma has been a subject of study and debate for decades [refs]. 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 have 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.

THEMIS is not the first satellite to measure cold plasma in the dayside magnetosphere. Plasmaspheric plumes were sampled and characterized at low altitudes by the Dynamics Explorer spacecraft [refs]. The Cluster spacecraft measured cold ions near the high latitude magnetopause when solar wind dynamic pressure changes revealed the cold ions [Sauvaud et al., ??]. In addition, the IMAGE spacecraft was able to capture the formation and loss of plasmaspheric plumes during magnetic storms [Goldstein et al., 2007]. The THEMIS mission provides a much more detailed and expansive data set of cold plasma observations within plasmaspheric plumes and at the reconnecting magnetopause. In particular these first results demonstrate radial and small scale structure in plasmaspheric plumes and reveal cold plasma capture during reconnection.

THEMIS Mission and Instruments

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 et al., 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 magnetopause, the inner three probes were spaced by ~1000 km and the leading and trailing probes spaced by ~3000 km. This orbit and satellite configuration provided near-radial separation of the spacecraft at the dayside magnetopause.

The “coast phase” configuration provided one or two passes through the plasmaspheric plume each day for several months, followed by pre-noon observations of cold plasma outside the plumes. 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 can overcome the potential barrier caused by spacecraft charging. This generally restricts cold ion detection to regions near the magnetopause where solar wind dynamic pressure changes result in plasma 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 [McFadden et al., 2008].

The third method of detecting cold plasma is by monitoring the spacecraft potential, which depends on the plasma density [Pederson et al., 19??, Scudder et al., 19??]. Cross-correlation between measured densities and spacecraft potential, as determined from the EFI Langmuir probes [Bonnell et al., 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 magnetopause since the flows are generally too small for detection of cold ions and since the combination of small spacecraft potentials and cold electrons result can result in most electrons being at energies below the lowest energy sampled by the electron sensor.

Observations

Figure 1 illustrates the 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 magnetopause near ~1330 LT (2300 UT) at a distance of ~11 Re. Panel a shows the magnetic field which dominates the total pressure.
throughout the interval inside the MP. The ion spectrogram (panel b) 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. Panel c shows that hot (5-10 keV) electron plasma was present over most of this outbound pass. However, a transition to a cooler (~1 keV) electron plasma occurs between 2220 and 2226 UT, coinciding with the disappearance of cold ions (panel b). This transition also corresponds to the increase in spacecraft potential (black line, panel c), indicating a drop in density.

Figure 1: a) Magnetic field, b) ion spectrogram, c) electron spectrogram, and d) density plots from THC probe. The density plot includes measured ion (black) and electron (red) densities, along with the inferred density from spacecraft potential (green). d) Ion spectrogram and e) electron spectrogram from the THA probe. The plasmaspheric plume is revealed with the inferred density (panel d). THA observations are used to demonstrate the drop in plume density near the magnetopause, that is accompanied by cool (~1 keV) electrons, is a spatial feature of the large scale plume structure.

Figure 1, panel d 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 ($\Phi_{sc}$~4-5 V), an electron energy sweep cutoff at 7 eV, and the presences of very cold (~1 eV), dense, ionospheric electrons. The best estimate of plasmaspheric plume structure comes from the spacecraft potential inferred density (panel d, 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 (2326 UT) was a spatial
feature that extend to ~10.7 Re before abruptly ending leaving a ~0.6 Re gap in cold plasma just inside the MP.

To determine that the abrupt drop in plume density at 2226 UT was a radial spatial boundary rather than an azimuthal boundary convecting across the spacecraft required the examination of 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 provided the needed measurements. Panels e and f (ion and electrons) show that THA passed through the same spatial region as THC with a one hour delay. Cold ions (panel e) were observed from ~8.6 to ~10.4 Re followed by a dropout in cold ions that is simultaneous with the appearance of a cool (0.2-0.5 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.

For completeness we mention that significant small scale spatial and temporal variations were also present within the plume of Figure 1. For example, the sheath-like plasma measured by THA at the day boundary is not a MP encounter. Instead this is a brief appearance of trapped sheath plasma, similar to that observed on THC, indicating a low entropy flux tube that has sunk into the magnetosphere. This encounter is also preceded by a brief appearance of cold ions (2357-2359.5 UT), and dropout in cool electrons, indicating that the magnetosphere expanded and that THA re-entered the plume. During this period a slow decrease in total pressure (magnetic and plasma) was observed at THA indicating a drop in dynamic pressure caused this expansion of the magnetosphere. However, to better illustrate small scale spatial and temporal variations we consider another event described below.

Figure 2 illustrates the small scale structure and temporal variations that can be found in plasmaspheric plumes at the MP. The top 4 panels show observations from the THD probe during 14 MP contacts spanning 20 minutes. Cold plasma is easily identified in the ion spectrogram (panel a) prior to 9:38 UT as a low energy, nearly mono-energetic component. Charge neutrality is provided by an accompanying cold (10-20 eV) electron component (panel b). Panel c 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 ~9:40 UT, the total density remains relatively constant across ten MP crossings indicating the magnetosheath and cold plasma densities are about the same. However at 9:41:30 and 9:48 UT, the cold plasma has decreased significantly, leaving primarily hot plasma adjacent to the MP. Such a rapid change in magnetospheric mass loading will cause significant changes in ion outflow velocities at a reconnecting MP. For completeness we note that a thick LLBL of trapped magnetosheath plasma is also present at the MP between 9:36 and 9:45:30 UT, which formed during a brief period of northward IMF (determined from THA). This
LLBL has about half the sheath density and disappeared by the >9:46 UT MP crossings by THD (panel a).

**Figure 2:** For the THD probe: a) Ion spectrogram, b) electron spectrogram, c) ion (black), electron (red) and inferred density from spacecraft potential (green). For the THB probe: d) Ion spectrogram, e) electron spectrogram, f) ion (black) and electron (red) densities, g) ion parallel (green) and perpendicular (red) velocities, h) ion velocities in boundary normal coordinates. For THB, spacecraft potential (black line, panel e) was estimated from electron spectra. Plot reveals both significant cold plasma (N~10 cm-3) and temporal variations in cold plasma at the magnetopause.

Panels d-h of Figure 2 show observations from the THB spacecraft located ~3000 km Earthward that provide a better picture of the magnetospheric changes. The decrease in magnetospheric density clearly occurs at ~9:39 UT with a factor of ~5 drop in cold plasma density (panel f). A tenuous (~0.1-0.2 cm⁻³) cold component remains at THB throughout this period, however cold ions have nearly disappeared closer to the MP at THD by ~9:48 UT (panel a). If MP motion was the only flow driver, one would expect periodic dropouts in measured cold ions as the MP reversed its motion. The 10 minute
interval (9:34-9:44 UT) in panel d, where cold ions are observed without dropouts while the MP reverses motion at THD, demonstrates additional flows must be present. Panel g 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. Panel h 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.

Figure 3: a) Magnetic field, b) ion and c) electron spectrograms, d) density and e) ion velocity during several encounters by THEMIS probe C with the magnetopause. The cold plasma dominated magnetosphere has about the same density as the magnetosheath. Cold plasma is observed on newly reconnected field lines as determined from the loss of hot electrons (panel c) and from reconnection flow jets (panel d).

The presence of cold plasma at the MP should impact reconnection flows and perhaps reconnection rates. Figure 3 demonstrates for the first time that cold plasma plumes, with densities comparable to the magnetosheath densities, participate in reconnection. The figure 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 panel d 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.

The signature for newly reconnected flux tubes, as revealed in panel c, 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 in panel e where we plot ion velocity in boundary normal coordinates. These plume ions should remain cold until they cross the current sheet where they would be accelerated to twice the Hoffmann-Teller velocity.

As a final note 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.

**Conclusion**

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

**References - TBD**


Sauvau et al …

Goldstein et al., …

Pederson et al., 19??,

Scudder et al., 19??

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