Growth and evolution of a plasmoid associated with a small, isolated substorm: IMP 8 and GEOTAIL measurements in the magnetotail

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Abstract. A tailward-moving plasmoid was observed at the GEOTAIL satellite at a GSM position (–73.3, 18.1, –1.1) R_E on September 16, 1993, at 0417 UT, when the IMP 8 satellite was at (–37.5, –2.5, 1.7) R_E at the midnight plasma sheet/lobe interface. The first indication of the plasmoid formation a few minutes after the negative bay onset of a small, localized auroral substorm was the onset of tailward beams of energetic ions and electrons at GEOTAIL well within the plasma sheet. Earthward-streaming energetic ions observed at IMP 8 a few minutes later suggest that the plasmoid evolved from within the plasma sheet to encompass the flux of nearly the entire thickness of the plasma sheet. The opposite direction of the anisotropies at IMP 8 and GEOTAIL suggest that the particle acceleration region was between $X = -37.5$ and -73 R_E at that time. The isolated substorm associated with this plasmoid started equatorward of 67° latitude at a location which we map to near-Earth nightside plasma sheet ($|X| < 15$ R_E) based on ground observations of a field line resonance. The active electrojet did not expand poleward until at least 10 min after the detection of the acceleration region tailward of IMP 8 and at least several minutes after the core of the plasmoid had moved tailward of GEOTAIL. These observations reinforce by means of in situ, concurrent, multipoint measurements the attitude expressed recently by several researchers that the locations of lobe reconnection and equatorial projection of electrojet intensification during substorm expansion are distinctly different from each other.

1. Introduction

ISEE 3 observations in the distant magnetotail have lent support to earlier theoretical expectations that during geomagnetic substorms part of the plasma sheet mass and magnetic flux is redistributed via the reconnection process into fast, tailward-moving structures termed plasmoids [*Hones*, 1979; *Hones et al.*, 1984]. These are usually accompanied by a bipolar B_z signature and are surrounded by a layer of energetic particle beams [*Richardson et al.*, 1987; *Moldwin and Hughes*, 1993]. Plasmoids often have a strong "core" field region at the polarity reversal of B_z, commonly due to a strong B_y [*Slavin et al.*, 1989]. This large B_y renders plasmoids three-dimensional structures [*Hughes and Sibeck*, 1991]. Although the term "flux rope" is used to stress their three-dimensionality, here we will use the term plasmoid in reference to the original concept of *Hones* [1979], with the proviso that we are allowing for an extended, three-dimensional structure.

Plasmoids correlate with substorms [*Hones et al.*, 1984; *Baker et al.*, 1987; *Slavin et al.*, 1989; *Moldwin and Hughes*, 1993]. Their location and timing are consistent with a near-Earth ejection, roughly at substorm onset. Little emphasis has been placed on the simultaneous monitoring of the near-Earth plasma sheet at substorm times during the ISEE 3 distant tail mission. Depite the lack of such simultaneous observations, there is some evidence that the region of tail reconnection is different from the equatorial projection of the active electrojet [*Lui and Burrows*, 1978; *Samson et al.*, 1992; *Elphinstone et al.*, 1991]. Such evidence has fueled debate on the premise of the near-Earth neutral line model for substorms that plasma sheet/lobe reconnection drives substorms [*Kennel*, 1992].

The recent GEOTAIL mission allows the community to address the above questions using a multipoint measurement approach, by utilizing the IMP 8 satellite to monitor the near-Earth plasma sheet while GEOTAIL was in its distant tail orbit. In this paper we report on such a study. Our findings reinforce the opinion previously based on disparate datasets that the locations of tail lobe reconnection and neutral sheet projection of auroral electrojet intensification during substorm expansion can be quite far from each other.

2. Analysis

We present data from the ion composition sensor (ICS) of the energetic particle and ion composition (EPIC) instrument [*Williams et al.*, 1994] and the magnetic field experiment (MGF) [*Kokubun et al.*, 1994] onboard the GEOTAIL satellite. We have also used data from the charged particle measurement experiment (CPME) [*Sarris et al*, 1976], the energetic particle experiment (EPE) [*Williams*, 1977] and the magnetic field experiment onboard the IMP 8 satellite. Table 1 shows the energy range and temporal resolution of the energetic particle channels used. In addition, we have used data from five ground magnetometer chains: The RGON network (provided by NGDC), the STEP network, the CANOPUS-MARIA network, the Greenland network, and the MACCS network.

2.1 GEOTAIL

On September 16, 1993, at 0400 UT GEOTAIL was at a GSM position (–73.3, 18.1, –1.1) R_E. For ~30 min prior to 0400 UT, the field orientation, its relative steadiness, and the background level of energetic particle fluxes suggest that the spacecraft was in the northern lobe (Figure 1). B_y was large for more than 4 hours, although it decreased at the neutral sheet (around 0415 UT). The average GSM longitude of the field at 0400–0500 UT excluding the neutral sheet encounter (0410–0430 UT) was $B_f = -11°$. Solar wind B_y penetration in the magnetosphere [*Lui*, 1983] would have caused a larger B_y in the plasma sheet than in the lobes, which was not observed. A large Y-component of the solar wind speed could explain the large B_y at GEOTAIL. The solar wind flow angle would then have to be ~7° duskward to result in a field direction at GEOTAIL parallel to the tail axis, allowing for an additional 4° rotation due to aberration.

At 0403 UT B_x started to decrease while the fluxes in E4 and HR0 started to increase above background (see uncertainties in fifth panel from bottom, Figure 1) and to exhibit only a mild, tailward/

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Table 1. Energetic particle channels used.

Channel	Instrument	Temporal Resolution Utilized	Channel Description and Total Energy
ED1	EPIC/ICS (GEOTAIL)	3 s	Electrons > 38 keV
E4	EPIC/ICS (GEOTAIL)	96 s	All ions of 74–89 keV (Mostly H^+)
E5	EPIC/ICS (GEOTAIL)	3 s	All ions of 89–110 keV (Mostly H^+)
HR0	EPIC/STICS (GEOTAIL)	96 s	H^+ of 9–36 keV (Mostly 9 keV)
P1	CPME (IMP 8)	10.22 s	All ions of 290–500 keV (Mostly H^+)
F	EPE (IMP 8)	20.45 s	All ions and electrons > 15 keV

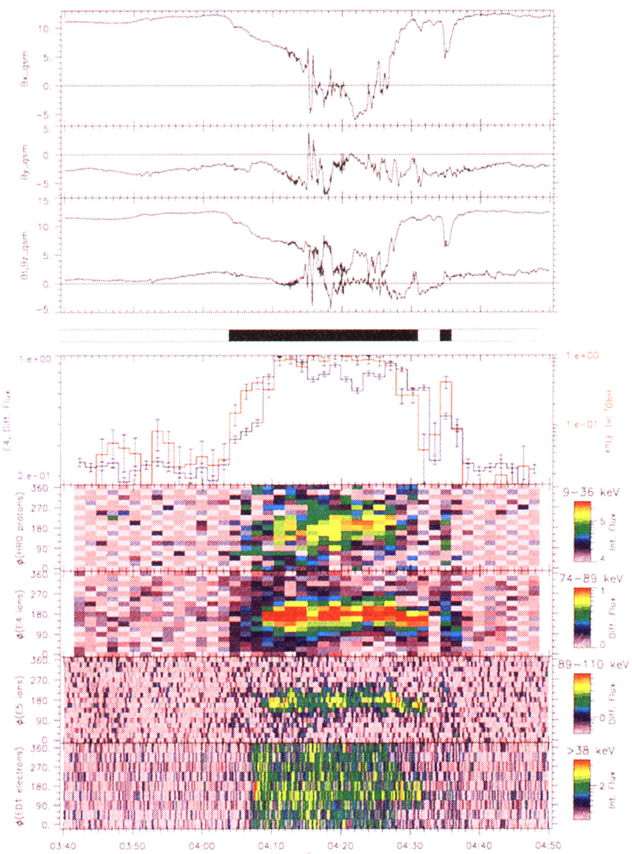

Figure 1. GEOTAIL data during a plasmoid encounter. Top three panels: magnetic field in GSM coordinates and in nanoteslas (3-s resolution). Bottom five panels: energetic particle data measured by the EPIC instrument (spacecraft coordinates very close to GSE) and plotted in angular spectrogram format versus the longitude of the particle direction. Channels plotted are described in Table 1, and their energy is also shown on top of the color bar. The fifth panel from the bottom shows the azimuthal average of the two spectrograms below it (channels E4 and HR0 in blue and red, respectively) normalized to the maximum value during the interval and plotted on different scales (left and right of the panel, respectively). In the horizontal bar below the magnetic field data black corresponds to plasma sheet as determined from the flux increase in the HR0 channel, and white corresponds to all other tail regions (energetic particle separatrix layer or lobe). The core of a plasmoid is centered at 0418 UT when a B_t local maximum mostly due to a B_y component is surrounded by a north-then-south excursion in B_z. The energetic particle beams that are preceding the plasmoid core are seen well within a cold, fairly stationary plasma sheet, when the B_x component is almost half the lobe value and the E4 channel exhibits low intensity, mildly anisotropic fluxes.

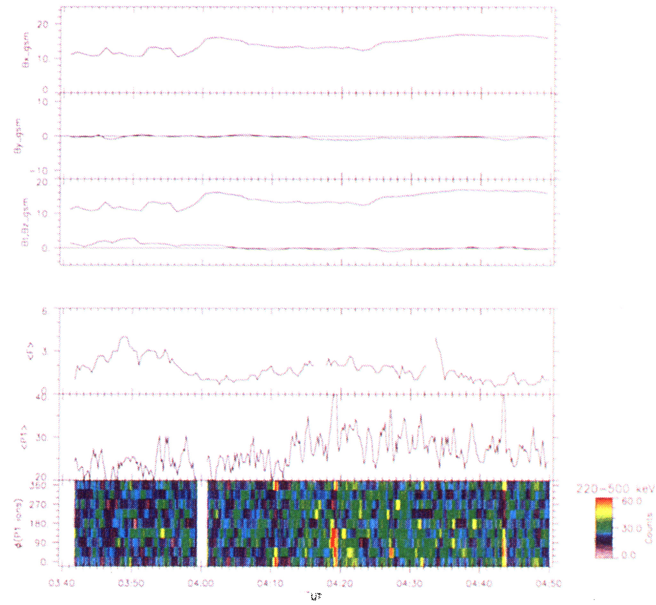

Figure 2. IMP 8 data. Top three traces: magnetic field in GSM coordinates and in nanoteslas (1-min resolution). Bottom three traces: energetic particle data from the CPME instrument. The CPME channels used are shown in Table 1. Rates (counts per second) from channel P1 (mostly protons between 250 and 500 keV) are shown in angular spectrogram format. The median rate of the angular sectors is shown in the panel above the color spectrogram. The median counts of the angular sectors of channel F (i^+ and e^- >15 keV) are also shown above the median rates of channel P1. An earthward beam of energetic particles can be seen at 0411 UT in the angular spectrogram of P1. The beam is narrow in azimuth and cannot be seen in the line plot of the median counts of the P1 sectors. We interpret the earthward beam of energetic particles at IMP 8 as an indication that the acceleration region was tailward of IMP 8 and that its magnetic mapping had reached the plasma sheet boundary by 0411 UT.

duskward anisotropy. We conclude that GEOTAIL entered the thermal plasma sheet, which exhibited only slow streaming. The energetic electrons (ED1) and the higher energy channel ions (E5) did not show significant flux increase at the time. The particle spectrum was presumably quite steep and the fluxes were below the background level for these channels. This suggests that the plasma sheet was fairly cold at the time. B_x reversed sign several times in the next 30 min, indicating multiple neutral sheet crossings, and eventually reached a value consistent with the northern lobe. These neutral sheet encounters suggest that a flapping motion of the plasma sheet (rather than plasma sheet thickening, which would not have led to neutral sheet crossings) brought the spacecraft into and out of the plasma sheet. Based on the above-lobe-level fluxes in the HR0 channel (measuring protons of as low an energy as 9 keV) the entry to the plasma sheet took place between 0404 and 0405:30 UT. No intense energetic electron or ion beams were observed at the lobe/plasma sheet interface.

At ~0407:30 UT, while B_x was about half the lobe value and well after the crossing of the lobe/plasma sheet boundary, a tailward-moving energetic electron beam was observed at GEOTAIL. The beam was fairly collimated along the magnetic field. It was followed by an energetic ion beam in channels E4 and E5. The onset of the ion beam was delayed relative to the electron beam. Following the energetic ion beam, the energetic ion flux in channels E4 and E5 decreased and became less anisotropic; the electron flux also decreased. Such a reduced, tailward anisotropy is consistent with a convective tailward flow of the plasma sheet plasma. These energetic particle signatures are typical during the passage of plasmoids [*Richardson et al.* 1987] with one main difference: the electron and ion beams were first observed well within the plasma sheet (while B_x was nearly half the lobe field) and not at the lobe/plasma sheet interface.

Five minutes after the energetic electron beam onset a bipolar B_z signature with a ~1-min-period field rotation superimposed on it was seen. B_t peaked at 0417:30 UT, while $B_x \sim 0$ and B_z switched from positive to negative; B_y was the dominant component there. We interpret these observations as the magnetic signature of a tailward-moving plasmoid of 6–10 min duration (bounded within the limits of the bipolar B_z signature) and a core of ~2 min (defined by the B_t maximum that surrounds the B_z sign change).

Following the plasmoid core, tailward-streaming of energetic ions persisted for 10 min. GEOTAIL exited the plasma sheet at ~0431 UT (as evidenced by the low flux level in the HR0 channel) while tailward energetic ion beams (E5) and electron beams (ED1) were observed. The proximity of the beams to the exit suggests that by ~0431:30 UT the separatrix of the plasmoid (i.e., the region of energetic particle beams) was on (or very close to) open field lines. This should be contrasted to the energetic particle beams preceding the plasmoid core (~0408 UT), which were streaming well within the plasma sheet (as inferred by the diamagnetic depression of B_t and the increase in the 9–36 keV H^+ channel HR0). The field turned northward at 0435 UT. An ensuing transient crossing of the outer plasma sheet was accompanied by a tailward anisotropy of relatively low fluxes; activity and intense streaming had ceased in the plasma sheet by that time.

2.2 IMP 8

IMP 8 was at a GSM position (–37.5, –2.5, 1.7) R_E at 0400 UT. Magnetic field data prior to 0400 UT (Figure 2) suggest that IMP 8 was in the plasma sheet, exiting toward the northern magnetotail lobe. At 0402 UT B_t started decreasing; a further decrease at 0405 UT, signifies plasma sheet re-entry.

The large B_ϕ observed at GEOTAIL was not seen at IMP 8, where $B_\phi = -2°$ between 0400 and 0500 UT. A magnetotail orientation 7° duskward from its normal position, as inferred from GEOTAIL, would have brought IMP 8 approximately 9 R_E dawnward of the expected location of the tail axis (including aberration of 4°). The magnetic field at IMP 8 would then form an angle of 9° with the tail-aberrated and twisted magnetotail axis, pointing toward the tail center. This angle can be accounted for by flaring [*Tsyganenko et al.*, 1993]. Thus the interpretation of a twisted tail axis due to an inferred large, duskward solar wind flow component at the time is consistent with both the IMP 8 and the GEOTAIL observations.

Energetic protons from channel P1 (220–500 keV) had low, near-background fluxes prior to 0400 UT. Channel F shows high fluxes of ions (>15 keV) in the plasma sheet. At 0411 UT a brief, earthward energetic particle beam was seen at IMP 8; it was followed at 0420 UT by an increase in the fluxes of duskward particles with an earthward component to the (predominantly duskward) particle anisotropy. This anisotropy is consistent with the remote sensing of hot, earthward-streaming particles with gyrocenters ~1 R_E equatorward of IMP 8 (the gyroradius of a proton in channel P1 in a 15-nT field is approximately 1 R_E). There is an overall increase in the count rates of channel P1 after the earthward beam. At the same time the counts of channel F do not increase as much relative to the count level in the plasma sheet prior to 0400 UT. This signifies a hardening of the energetic particle spectrum at 0411 UT relative to the earlier (0330–0400 UT) plasma sheet crossing; this is indicative of plasma sheet heating.

2.3 Ground

Figure 3 shows the total horizontal (H) or the north–south (*X*) component of the magnetic field at auroral stations. The geomagnetic activity was low (also $Kp = 1+$) but for a transient intensification at Kuujjauq (KAQ) at 0320 UT and a longer, more intense (peak ~80 nT) negative bay at Post de la Balaine (PDB) at 0402 UT. The plasmoid core at GEOTAIL was seen ~1 hour after the 0321 onset, a time delay that is atypical for distant tail plasmoids [*Nagai et al.*, 1995]. Thus we discount the KAQ onset as being associated with the plasmoid. The isolated 0402 UT activity at PDB, however, constitutes a reasonable candidate to be associated with the plasmoid. The *Z*-component (positive down) at station PDB is shown in Figure 3. Its sharp increase at 0402 UT was the earliest indicator of substorm onset (first vertical line on top panel). Figure 3 (bottom) also shows low-pass filtered data (5 mHz filter) from the CANOPUS chain. In agreement with the onset time inferred from the *Z*-component of PDB, Pi2 pulsations were observed at CANOPUS stations at 0402 UT.

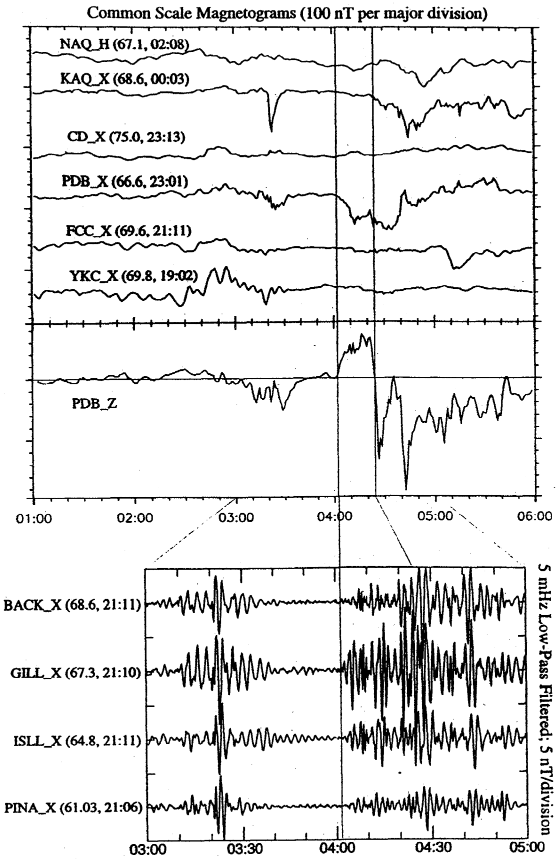

Figure 3. Horizontal (H) and north (*X*) components from high-latitude ground magnetic stations plotted according to their magnetic local time (top to bottom is east to west). Also shown is the *Z*-component of PDB. Magnetic latitude and local time at 0400 UT are shown next to the station abbreviation for each trace. The bottom panel presents 5 mHz low-pass filtered data from selected stations from the CANOPUS chain. A small localized substorm started south of PDB at 0402 UT and expanded poleward of PDB at 0422 UT. The substorm onset can be seen also in the CANOPUS Pi2 pulsations. A field line resonance seen at GILL between 0310 and 0340 UT allows mapping of that station to $|X| < 15\ R_E$ in the magnetotail.

The sign of the *Z*-component perturbation at PDB is significant: when positive (negative) activity was equatorward (poleward) of PDB. The observed positive-then-negative perturbation of that component implies that the electrojet intensified first equatorward of PDB at 0402 UT and then poleward of PDB at ~0422 UT (second vertical line on top panel). The *X*-component at station KAQ, located 2° poleward and only 1 hour of local time eastward of PDB, shows the beginning of a negative bay at 0422 UT and confirms that the activity expanded poleward of PDB at that time.

Periodic oscillations were seen at Gillam (GILL) between 0310 and 0340 UT, i.e., prior to substorm onset. A spectral analysis reveals a narrow peak at 3.2 mHz. Such oscillations have been attributed to field line resonances [*Walker et al.*, 1992; *Samson et al.*, 1992]. *Walker et al.* [1992] (see their Figure 18 and Table 2) provided theoretical values for the equatorial crossing of dipolar field lines resonant at 3.3 mHz (near the 3.2 mHz oscillation seen at GILL). Their calculations are valid for a slightly distorted dipole field; at moderately disturbed times such as the one studied here these calculations are pertinent. For an equatorial density of 1 cm^{-3}, the equatorial crossing is at 15 R_E and is weakly dependent on the density. Stretching of the field lines at the nightside can only reduce the distance of the equatorial projection of the resonant field lines for the same frequency. Thus 15 R_E is an upper estimate of the radial distance of the equatorial projection of station GILL. As PDB is at a slightly lower magnetic latitude from GILL, we conclude that the field lines on which the 0402 UT substorm started (i.e., south of PDB) had an equatorial projection earthward of 15 R_E. The activity did not map tailward of that distance until after 0422 UT.

3. Discussion

At 0402 UT the onset of a small, localized substorm took place slightly east of midnight and south of station PDB (magnetic latitude ~66.6°). A plasmoid seen at GEOTAIL at 0413 UT was associated with that substorm. The active electrojet expanded poleward of PDB at 0422 UT, as inferred from the Z-component perturbation at that station. Based on field line resonance observations at station GILL, close to the latitude of PDB, the equatorial projection of the active electrojet was earthward of $X = -15$ R_E at 0402 UT and expanded tailward of that distance at 0422 UT.

The magnetic field observations at IMP 8 and GEOTAIL are consistent with a duskward tail twist of 7° (due to a Y-component of the solar wind velocity) in addition to aberration. This fortuitous magnetotail twist brought GEOTAIL 4 R_E duskward of the expected center of the geomagnetic tail, in a good location to observe the tailward-moving plasmoid resulting from the near-midnight tail activation at 0402 UT.

At 0408 UT and while GEOTAIL was in the plasma sheet moving towards its center plane, the EPIC instrument observed an electron beam followed by ion beams. Gradient anisotropy effects at the beam onset suggest a motion of the spacecraft relative to an energetic particle layer that had already formed. Thus the separatrix layer associated with the ensuing plasmoid had already formed by 0408 UT and resided for some finite time period within closed plasma sheet field lines. At 0411 UT, 3 min after the observation of the tailward beams at GEOTAIL, a brief, earthward-directed energetic ion beam was detected at IMP 8, near the plasma sheet/lobe interface. Thus by 0411 UT, the separatrix layer was at the outermost layers of the plasma sheet. Outbound from the plasma sheet at 0431 UT, GEOTAIL also measured energetic particle beams, confirming that the separatrix was at (or near) the boundary of the plasma sheet. The above observations imply that, contrary to the typical observation of plasmoid-associated energetic particles at the plasma sheet boundary, the plasmoid presented is associated with a separatrix layer that grew from inside the plasma sheet and eventually encompassed the entire thickness of the plasma sheet.

The earthward-directed energetic ions were seen at IMP 8 at 0411 UT, i.e., 11 min prior to the expansion of the active electrojet poleward of PDB. Thus the magnetotail acceleration region related to the substorm was located between $X = -37$ and -73 R_E downtail 11 min prior to the inferred tailward expansion of the equatorial projection of the active electrojet past $X = -15$ R_E. At 0413 UT the plasma sheet magnetic field at GEOTAIL started exhibiting the bipolar B_z characteristic signature of a plasmoid with a strong core field in the B_y direction. The core of the plasmoid moved tailward of $X = -73$ R_E at 0419 UT, i.e., at least 3 min prior to the poleward expansion of the substorm. Our observations imply that during this isolated substorm lobe reconnection (tantamount to full plasmoid growth out of the thermal plasma sheet) and plasmoid retreat down the tail are processes that take place at locations very different from the expected equatorial projection of the auroral electrojet intensifications they are related to.

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