# Direct Evidence for a Three-Dimensional Magnetic Flux Rope Flanked by Two Active Magnetic Reconnection X Lines at Earth's Magnetopause

M. Øieroset,[1] T. D. Phan,[1] J. P. Eastwood,[2] M. Fujimoto,[3] W. Daughton,[4] M. A. Shay,[5] V. Angelopoulos,[6] F. S. Mozer,[1] J. P. McFadden,[1] D. E. Larson,[1] and K.-H. Glassmeier[7]

[1]*Space Sciences Laboratory, University of California, Berkeley, Berkeley, California 94720, USA*
[2]*The Blackett Laboratory, Imperial College, London SW7 2AZ, United Kingdom*
[3]*ISAS/JAXA, 3-1-1 Yoshino-Dai, Sagamihara, Kanagawa, 229-8510, Japan*
[4]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[5]*Department of Physics and Astronomy, University of Delaware Newark, Delaware 19716, USA*
[6]*IGPP, University of California, Los Angeles, California 90095, USA*
[7]*Technical University of Braunschweig, Germany*
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We report the direct detection by three THEMIS spacecraft of a magnetic flux rope flanked by two active X lines producing colliding plasma jets near the center of the flux rope. The observed density depletion and open magnetic field topology inside the flux rope reveal important three-dimensional effects. There was also evidence for nonthermal electron energization within the flux rope core where the fluxes of 1–4 keV superthermal electrons were higher than those in the converging reconnection jets. The observed ion and electron energizations differ from current theoretical predictions.

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Magnetic reconnection in a current sheet is a universal plasma process that converts magnetic energy into particle energy. The process is initiated at an X line. It is thought that thin current sheets are often prone to multiple X line formation, leading to a string of magnetic islands between pairs of X lines. In the two-dimensional (2D) picture, which has been extensively studied via computer simulations, there are highly dynamical effects associated with magnetic islands such as magnetic field and density compression, island contraction, and coalescence which could theoretically lead to significant electron energization [1–6]. In the 3D picture, however, magnetic islands become magnetic flux ropes [7]. The formation and evolution of magnetic flux ropes as well as their role in particle energization is of critical importance for a number of collisionless plasma phenomena.

It is presently unclear whether the properties of 2D islands including particle energization are significantly modified by 3D effects, in part because experimental observations of the onset and growth of such flux ropes in space plasmas are very rare. Interestingly, most reported observations of islands/flux ropes in Earth's magnetosphere are not flanked by active X lines. Magnetopause flux transfer events (FTEs) at the dayside magnetopause and plasmoids in the magnetotail are often embedded in only a single reconnection jet from one X line or no jet at all [8–12], indicating that these islands/flux ropes were mature and not observed during their formation or most active stage. While reconstruction techniques have successfully revealed the presence of a flux rope in a bidirectional jet event [13], the best signature of active flux ropes involving two X lines is the presence of converging bidirectional plasma jets toward the center of the flux rope. However, it is often difficult, especially with single spacecraft observations, to distinguish between diverging bidirectional jets from an X line versus converging jets from two X lines since both scenarios produce similar flow and magnetic field reversals, an example of which has been shown in the Earth's magnetotail [14].

In this Letter we report direct evidence for a flux rope flanked by two active X lines at the subsolar magnetopause observed by three THEMIS spacecraft. These observations represent perhaps the most comprehensive observations to date of an active magnetopause flux rope, caught in the process of forming, and reveal flux rope properties that are fundamentally 3D, even though the current sheet geometry is quasi two-dimensional. The direct deduction of a flux rope (as opposed to an X line) crossing was made possible by the new (Year 2010) THEMIS orbit configuration in which three spacecraft were separated in magnetic latitude (roughly along the flux rope motion direction) by more than 1000 km (or 20 ion skin depths) as they traversed the dayside subsolar magnetopause where flux ropes are likely to form.

On October 6, 2010 at 15:00–16:00 UT the THEMIS A (THA), THEMIS E (THE), and THEMIS D (THD) spacecraft traversed the dayside subsolar magnetopause on an outbound pass. All three spacecraft were located slightly north of the magnetic equator. The spacecraft data will be presented in the magnetopause current sheet coordinate system, with $x'$ along the current sheet normal (toward the Sun), $y'$ along the X line (toward dusk), and $z'$ along the reconnection outflow direction (toward north). This coordinate system is close to the usual GSM coordinate system (see Fig. 1 caption for details). Relative to THA, THE was located 1093 km in the $+z'$ direction and 770 km in the $+y'$ direction, whereas THD was 1447 km in the $+z'$ direction and 3611 km in $+y'$. Initially, all three spacecraft were located inside the magnetosphere, characterized by $B_{Z'} > 0$ [Figs. 2(b), 2(e), and 2(h)]. At ~15:19:50 UT THA crossed the magnetopause followed by further reencounters at ~15:25 UT, ~15:46 UT, and ~15:57 UT with embedded plasma jettings indicative of reconnection observed each time [Figs. 2(b) and 2(c)]. At 16:04:50 UT THA finally entered the magnetosheath proper. The magnetic shear across the magnetopause was ~145° (corresponding to a 32% guide field) and rather constant throughout this interval. THE and THD crossed the magnetopause at 15:21:35 UT and 15:20:15 UT, respectively, followed by multiple encounters with the magnetopause current sheet and associated plasma jets, before exiting into the magnetosheath proper at 16:05:25 UT and 16:03:15 UT, respectively. We now focus on the last magnetopause crossing at around 16:00 UT (marked by the blue horizontal bar in panel 2i). During this crossing $V_{Z'}$, the reconnection outflow, reversed direction.

The reversal in $V_{Z'}$ could be due to either an $X$ line moving southward in the $-z'$ direction or a flux rope, flanked by two active $X$ lines, moving northward in the $+z'$ direction. In the former ($X$ line) scenario, the northernmost spacecraft (THD) would detect the flow reversal first, followed by THE and THA. In the latter (flux rope) scenario, THD would observe the flow reversal last. Figure 3 (which overlays the flow and field of the three spacecraft) shows that the flow reversal (panel d) was first detected by THA, followed by THE and THD, which implies a northward moving flux rope.

A ~21 km s$^{-1}$ propagation speed of the flux rope along the outflow ($z'$) direction (comparable to the external magnetosheath flow speed) was deduced from the 51 s time delay between the flow reversal detected by THA (at 15:59:29 UT) and THE (at 16:00:20 UT), which were located along the same meridian, but separated by 1094 km along $z'$. Using this speed, and the fact that the three spacecraft traversed the flux rope for a total of nearly 12 min (from 15:52:52 UT to 16:04:36 UT), the cross section (along $z'$) of the flux rope was at least 14780 km (or 274 magnetosheath ion skin depths).

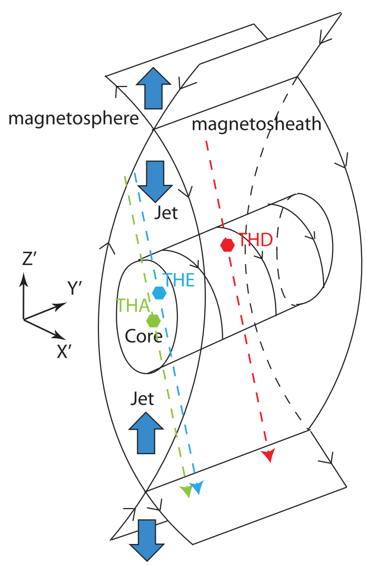


FIG. 1 (color). A simplified sketch illustrating the large-scale features of the observed magnetic flux rope deduced from data at around 16:00 UT shown in Figs. 2–4 and the paths of the three THEMIS spacecraft through it. At 16:00 UT THA was located at GSM [10.51, 1.64, 0.61] $R_E$, THE at GSM [10.41, 1.75, 0.78] $R_E$, and THD at GSM [10.42, 2.19, 0.87] $R_E$. A common current sheet normal coordinate system ($x'$, $y'$, $z'$) is used for data from all three spacecraft and was determined by the minimum variance of the THEMIS A magnetic field across the magnetopause. This current sheet coordinate system differs only slightly from the GSM coordinate system: $x' =$ GSM $[0.998, -0.026, 0.049]$ is the normal vector and is 3.2° from $x_{\mathrm{GSM}}$, $y'$ ($=$ GSM [0.022, 0.997, 0.070]) is 4.2° from $y_{\mathrm{GSM}}$, and $z'$ ($=$ GSM $[-0.051, -0.069, 0.996]$) is 4.9° away from $z_{\mathrm{GSM}}$.

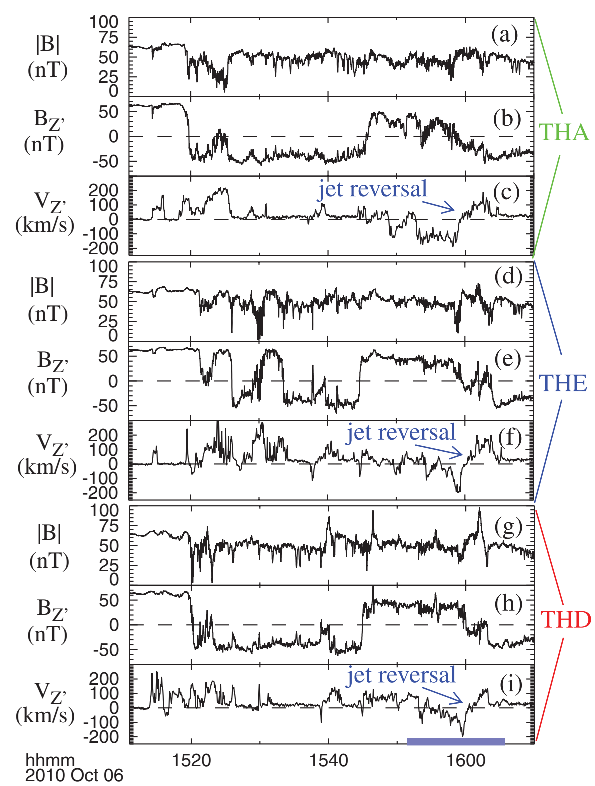


FIG. 2 (color). Overview of the multiple magnetopause crossings by three spacecraft, including the flux rope observations near 16:00 UT. (a)–(c) THA magnetic field magnitude, magnetic field and velocity components along $Z'$, (d)–(f) THE magnetic field magnitude, magnetic field, and velocity components along $Z'$, (g)–(i) THD magnetic field magnitude, magnetic field, and velocity components along $Z'$.

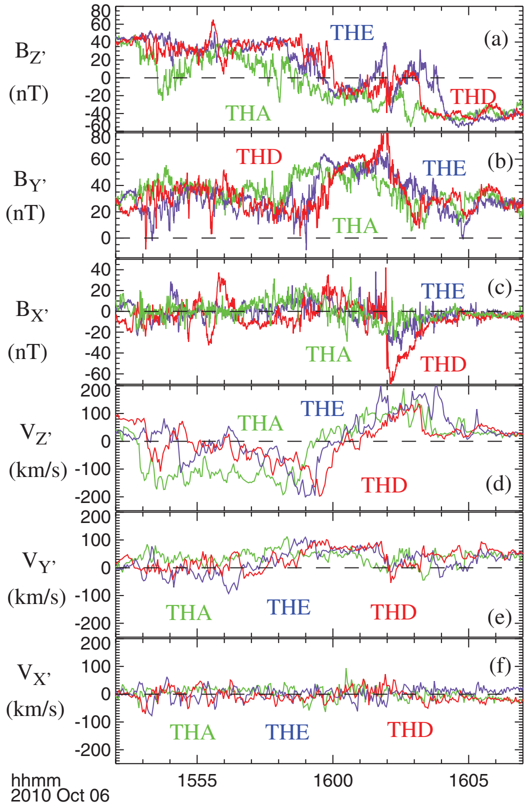


FIG. 3 (color). Zoom-in of the magnetic field and plasma velocity observed by the three spacecraft in the 15:53–16:05 UT interval to illustrate the motion and dimension of the observed flux rope, as well as the substructures within the flux rope.

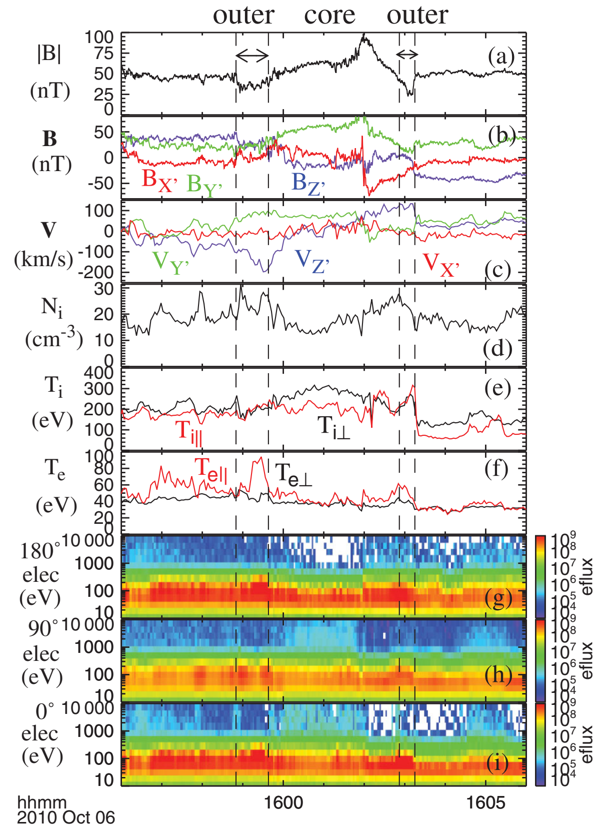


FIG. 4 (color). Detailed THD observations in and around the flux rope (interval marked by the horizontal blue bar in Fig. 2(i)]. (a),(b) magnetic field magnitude and components, (c)–(e) ion velocity, density, and temperature, (f) electron temperature, (g)–(h) 180°, 90°, and 0° electron pitch angle spectrograms. $\mathbf{T}_\perp$ and $\mathbf{T}_\parallel$ refer to the temperature perpendicular and parallel to the local magnetic field, respectively. The left and right pairs of vertical dashed lines denote the outer regions of the flux rope. The flux rope core region is approximately between the two inner dashed lines.

Figure 4 shows the detailed structure of the flux rope detected by THD which reveals that the flux rope consisted of an outer and a core region. The outer region consists of converging plasma jets (encountered at 15:58:50–15:59:38 UT and 16:01:58–16:03:15 UT, marked by two pairs of vertical dashed lines). Sandwiched between the two jets is a slower flow region where the bidirectional jets converge (15:59:38–16:01:58 UT) and where the out-of-plane magnetic field $B_{Y'}$ [Fig. 4(b)] and total field strength was strongly enhanced, reaching a peak value of 80 nT at 16:01:58 UT. At exactly this time the normal magnetic field $B_{X'}$ switched sign from positive to negative, signifying that this location also corresponds to the center of the flux rope. Furthermore, $B_{X'}$ on both sides was enhanced (in magnitude) just before the sign reversal, suggesting that the normal field was compressed by the colliding jets.

The plasma properties in the outer and core regions were very different. The plasma density in the outer region was enhanced by as much as a factor of 2 compared to the magnetosheath value, but the density in the core was depressed compared to the jet region [Fig. 4(d)].

In terms of plasma heating, ions, and electrons were heated differently in the flux rope. $\mathbf{T}_{\mathbf{i},\perp}$ was enhanced especially in the core region and less enhanced in the outer jet region, indicating true ion heating within the flux rope core [Fig. 4(e)].

For the electrons, there was a rather peculiar difference between thermal and nonthermal heating. Figure 4(f) shows that $\mathbf{T}_{\mathbf{e},\parallel}$ was enhanced in the outer region but did not show any enhancement in the core region. In contrast, the superthermal (1–4 keV) electron fluxes [Fig. 4(h) and 4(i)] were significantly enhanced in the core region but not in the outer region. The comparison of electron spectra in the core region versus the outer region, the magnetosheath, and the magnetosphere (Fig. 5) shows that the 1–4 keV electrons observed in the core are not simply present because of leakage of energetic magnetospheric electrons since the fluxes of 1–4 keV electrons were much lower in the magnetosphere. The pitch angle spectrograms [Figs. 4(g)–4(i)] show that the 1–4 keV electron fluxes inside the core region were highly unbalanced, with enhancements in the 0° and 90° electrons, but a void of these electrons at 180°, which

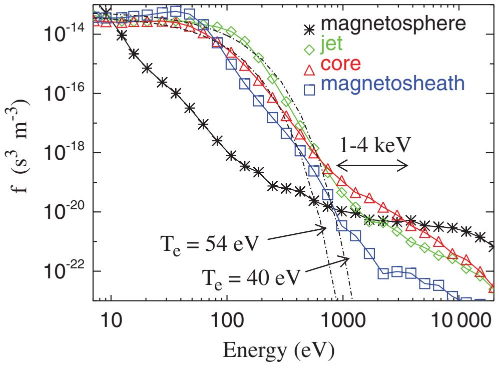


FIG. 5 (color). Comparison of electron distribution functions observed by THD inside the magnetosphere (at 15:12:55 UT), in the southward jet (at 15:59:21 UT), in the flux rope core (at 16:00:25 UT), and in the magnetosheath proper (at 16:07:30 UT). The highest fluxes of 1–4 keV electrons are observed inside the flux rope core. Maxwellian distributions with the observed $T_e = 54$ eV in the jet region and 40 eV in the core region are also plotted for comparison. The observed electron distributions in the jet and core regions deviate from Maxwellian distributions above 500 eV.

implies that this high-energy electron population was untrapped. The fact that the 1–4 keV electrons were observed in the core and not in the outer region indicates that the superthermal electrons were generated somewhere along the flux rope core, although the exact energization mechanism is unknown. The absence of 180° pitch angle electrons implies that the flux rope must have been open ended. Finally, 1–4 keV is ~3–10 times higher than the kinetic energy (~ 320 eV) of electrons moving at the magnetosheath electron Alfvén speed.

Qualitatively, THA and THE observed similar magnetic field and plasma properties inside the flux rope as those shown above for THD in Fig. 4. The density depression and perpendicular ion temperature in the core region as well as the enhancement of 1–4 keV superthermal electrons and their open field signatures were also seen at THA and THE. A slight difference is that at THA and THE the 1–4 keV electron flux enhancements were not confined to the core region, but were also seen in one of the jets. However, some differences in the large-scale structure were observed, particularly in the main normal field reversal at the center of the flux rope at [ ~ 16:01–16:02 UT, Fig. 3(c)]. The $B_{X'}$ reversal, first observed by THA, was gradual, but the $B_{X'}$ reversals detected by THE and THD were abrupt, especially at THD. These differences could be due to flux rope structure, with THD crossing perhaps closest to the center, or could indicate dynamical evolution, with steepening of the $B_{X'}$ reversal due to the colliding flows toward the center of the flux rope.

In summary, the three-spacecraft observations allowed the unambiguous identification of the passage of a flux rope flanked by two active $X$ lines. This type of active flux rope has rarely been reported; most reported magnetospheric flux ropes are associated either with a single active $X$ line on one side or with no active $X$ lines at all [8–12], which indicates that they were detected at later stages of their evolution. The fact that active flux ropes are rarely seen suggests that $X$ lines flanking flux ropes are short-lived once the flux ropes convect away from the generation region. The observed plasma density depletion and the open-ended flux rope signature reveal important three-dimensional effects that are significantly different from the 2D magnetic island picture. In 2D islands, particles are trapped and the plasma density is strongly compressed (and enhanced) by the strong core field whereas the present observations indicate that the plasma was squeezed out of the flux rope core region resulting in density depletion instead. The density depletion feature (and 3D effect) may be a common property of flux ropes at the magnetopause since it was also seen in another flux rope detected 20 min earlier (at 15:38:44–15:41:50 UT) by THD, as well as in two previously reported magnetopause flux ropes [15]. On the other hand, a recent 3D hybrid simulation of a flux rope without a background guide field [16] still did not reproduce this feature which may suggest that this 3D effect becomes important in the presence of a guide field.

Interestingly, although the observations indicate that the electrons are no longer trapped inside the open-ended flux rope, the superthermal (1–4 keV) electron flux was still enhanced inside the core region where the bidirectional jets converge. This observation differs from recent 2D PIC simulations where energetic electrons were confined to the edges of the magnetic island [3]. The thermal properties of the ions and electrons were equally intriguing, with the enhancement of the ion perpendicular temperature primarily in the core region while the electron parallel temperature was enhanced only in the outer region of the flux rope associated with the converging jets. As far as we know, these behaviors of the ion and electron temperatures have not been reproduced in any reported simulations. It therefore remains to be seen how the flux rope properties, especially particle heating and energization, depend on the specific properties of active $X$ lines flanking the flux rope. The degree of particle energization in 2D island dynamics (which are due in part to particle trapping in closed field) may also be altered in the real open-ended 3D configuration.

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