Themis-Double Star-Cluster observations of reconnection and dynamics across the dayside magnetopause.

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Study of the operation and extent across the Earth's magnetopause of fast magnetic reconnection (MR), the dominant process responsible for energy and plasma transport into the magnetosphere, has recently benefitted from an unprecedented growth in complexity of multi-point, *in situ* measurements, on the small and meso-scale, from Earth-bound space missions. Recent findings in active sites of MR have increased the theoretical understanding of the detailed structure within the ion diffusion region surrounding the magnetic X-line or null field. Nevertheless, direct measurements of this small region in space are still relatively rare, since clear spatial signatures are difficult, owing to the time variable nature of the near-Earth space environment.

The key result here reports for the first time direct evidence of the X-line structure resulting from the operation of MR at two widely separated locations along the expected sub-solar merging line (line of maximum current) on the Earth's magnetopause; confirming the extended operation of MR across this region. This evidence results from observations of the associated ion and electron plasma distributions, present within the magnetic X-line structure, which are taken from a conjunction of the THEMIS-A [*Angelopoulos et al*., 2008] spacecraft and the Double Star, TC-1 [*Liu et al*., 2005] spacecraft, separated by ~9 RE near the low latitude, sub-solar region of the Earth's magnetopause, either side of noon.

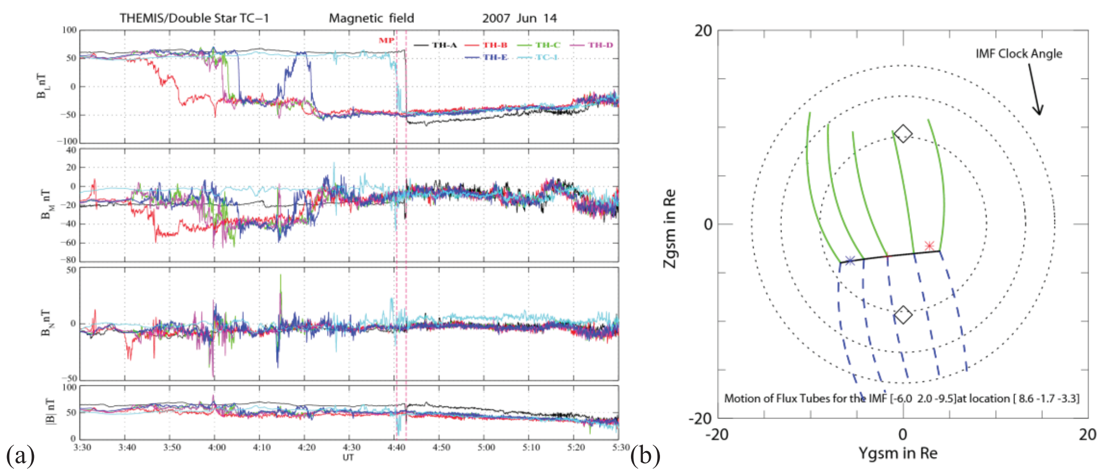

Figure 1 (after *Dunlop et al*. [2011]): (a) Magnetic field data, taken during the time interval around the MP crossing of the spacecraft in magnetopause aligned "LMN" coordinates, where N is the magnetopause normal, L is in the (Z_{GSM},N) plane and M completes a left-handed set (GSM is the geocentric solar magnetospheric coordinate system). (b) Conditions at the magnetopause during the simultaneous MP encounter. The TC-1 spacecraft is marked by the blue star; the Th-A spacecraft by the red star, and the view is of the Earth's magnetopause from the Sun. The diamonds mark the position of the magnetic polar cusps and the curved tracks are the predicted motions of any reconnected flux tubes arising from positions along the merging line (blue), which is fitted to the ambient, draped magnetosheath field [*Cooling et al*., 2001] and threads through the spacecraft positions.

The magnetic field data for all 5 Themis spacecraft, and the TC-1 spacecraft are shown in Figure 1(a), in boundary aligned coordinates (LMN) and show sharp reversals in the B_L components (aligned to the MP surface) at each spacecraft location. These mark the exits from the magnetosphere to the magnetosheath. At about 4:00 UT, the TC-1 and TH-A spacecraft cross the magnetopause within 2 minutes of each other. The TH-A and TC-1 locations on the magnetopause surface are shown in Figure 1(b). The interplanetary magnetic field (IMF), which ultimately controls the magnetosheath field

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orientation, has a southward orientation, suggesting that the low latitude, dayside merging line (drawn as a blue line on Figure 1(b)) takes an orientation close to East-West and is fitted for the particular conditions at the time of the crossings. The expected directions of motion of any reconnected flux tubes moving away from this line are also computed and are indicated. Actual flux tube motions inferred from observed bipolar signatures in B_N are consistent with the model directions shown. The merging line therefore threads through each spacecraft position, as shown in Figure 1(b), and the X-line geometry is ordered to this orientation.

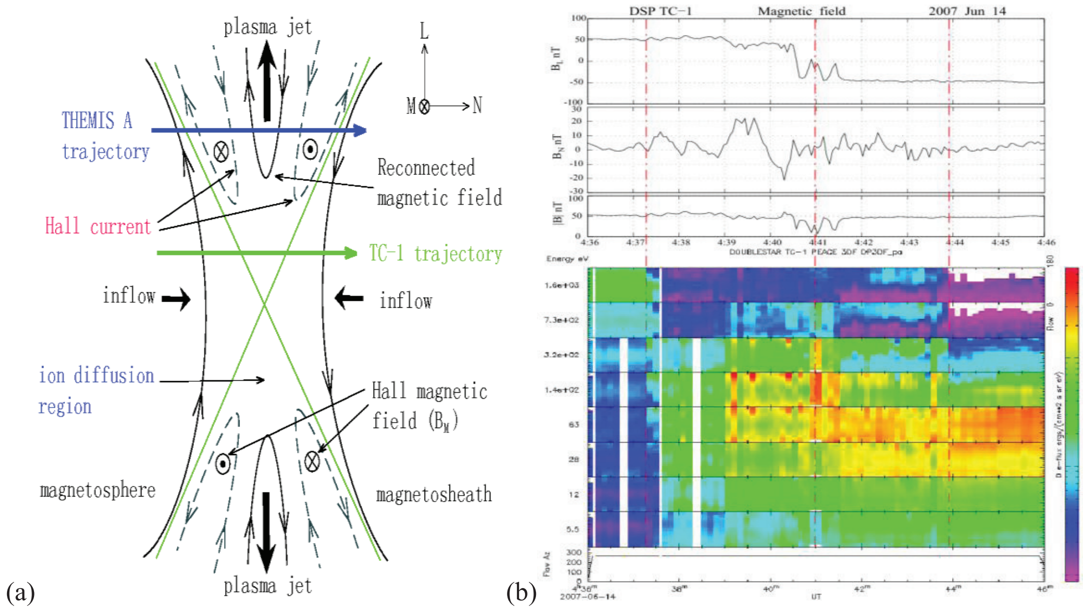

Figure 2 (after *Dunlop et al*. [2011]): (a) Schematic of the inferred positions of each spacecraft relative to the reconnection X-line. The inferred (simplified) tracks of the spacecraft are shown. (b) The differential energy flux of the TC-1 electron distribution is shown on the bottom panels. Each sub-panel shows the pitch angle spectrogram for an energy range indicated on the left. The pitch angle is the angle between the vector of the particle velocity and the magnetic field vector. Each sub-panel, therefore shows the populations of electrons flowing at each angle to the field (0-180)deg, from bottom to top of each sub-panel). The top panels show the field magnitude, B_N and B_L components.

The evidence from the plasma data strongly suggests that the spacecraft pass very close to possible X-line structure, as indicated by the schematic in Figure 2(a). In this scheme, both spacecraft pass from an initially closed field region inside the magnetosphere, sampling in turn the most recently reconnected field on the magnetospheric side of the current sheet, the ion outflow region and then the most recently reconnected field again (this time on the magnetosheath side). The evidence suggests that THEMIS A passes further from the null field than TC-1, as indicated schematically in Figure 2(a), with the implication that TC-1 passes very close to, or within the diffusion region, rather than across the ion outflow region. We show here only the electron data from TC-1 in Figure 2(b), which indicates the presence of a reconnection layer and that the spacecraft passed through the X-line very near the null field point (as indicated by the drop-out of the field magnitude at the current sheet, where B_L reverses, and the peak in electron energisation) and possibly inside the diffusion region. The electron distribution shows a clear boundary at 4:37:20 UT, where the spacecraft move from high energy, magnetospheric electrons, into a region of anisotropic distributions, which show both bi-streaming and beamed populations, particularly after 4:39 UT. After this time there is also a consistent out-flowing population of out-flowing magnetospheric electrons. We place the outer edge of the electron boundary layer at 4:44 UT, where the magnetosheath population is recovered. The Themis A spacecraft shows plasma signatures with also confirm the presence of a nearby reconnection layer.

Both the in-situ magnetic field and plasma data therefore confirm the simultaneous operation of MR at two widely separated sites along the expected low latitude merging line stretching across the dayside, sub-solar region of the magnetopause. Both electron and ion energisation and reflection are observed, together with characteristic ion-D distributions (not shown here), which confirm X-line formation with significant extent. These data are consistent with either an extended X-line over a distance of more than $9R_E$, or the presence of multiple patches of MR along the merging line over the same distance.

Secondly, we report one of the first, clear transitions through a reconnection layer which shows a complete traversal across all reconnected field lines and the associated plasma populations, confirming details of the ion and electron mixing, time history and acceleration through the current layer. Figure 3(a), shows the positions of the five THEMIS spacecraft during this event, which occurred on the 26 August 2007, from 5:30-9:00 UT. The four leading spacecraft (THEMIS B-E) exited into the magnetosheath in a bunched configuration, as indicated, while the trailing spacecraft, THEMIS-A, followed sometime later. Figure 3(b) shows the data from Themis C for the short time interval around the crossing.

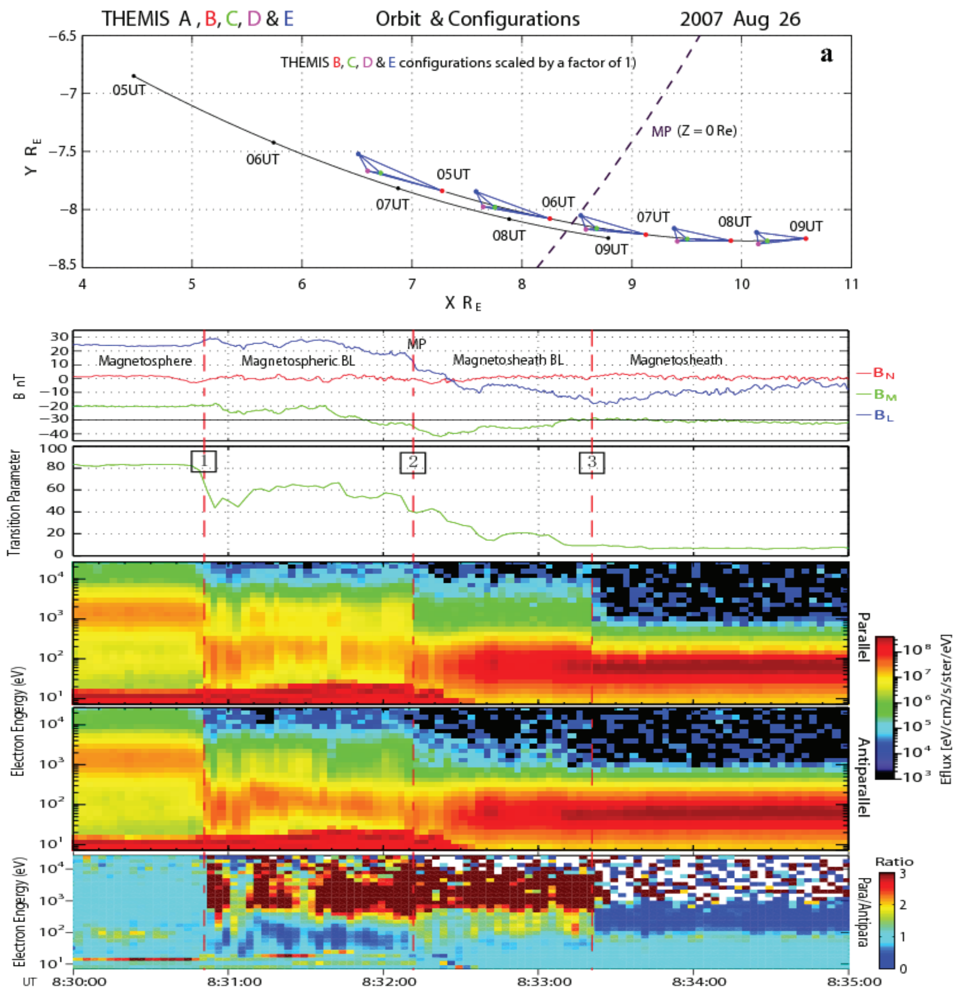

Figure 3 (after *Zhang et al*., [2011]): (a) The Themis orbital configuration at the magnetopause. (b) Thermal electron anisotropy data from Themis C.

The vertical lines marked 1, 2 and 3 define the open-closed field line boundary at the MR separatrix, central current sheet and the outermost (most recently) reconnected field line, respectively. Between these lines, we mark the region as magnetospheric boundary layer (BL) and magnetosheath BL, respectively. The top two plasma panels of energy spectra verses time show the progressive transition from the magnetospheric to magnetosheath distributions with a clear boundary layer, surrounding the current sheet. Mixed high and low energy populations are present within the layer. A significant degree of structure is seen in addition to an underlying diffusive transition and part of this is revealed in the bottom panel which shows the electron energy anisotropy. After line '3', the magnetosheath distribution is seen, which shows a nearly isotropic band (balanced electron anisotropies) of inflowing plasma. Before line '1', the plasma shows characteristics of boundary layer magnetospheric field (i.e. plasma at magnetospheric energies, together with an anisotropic, field aligned, bi-streaming distribution at low magnetosheath energies. Between the lines '1' and '3', the distributions show both bi-streaming and field aligned populations of electrons, where it should be noted that parallel fluxes correspond to out-flowing particles for the southward and dawn-ward location of the spacecraft with respect to the X-line. At line '1' the electrons show a sharp change as they move onto open field lines.

The parallel/anti-parallel anisotropy shows the onset of an out-flowing (field parallel: dark red), magnetospheric population. Either side of the current sheet at line '2', accelerated magnetosheath electrons are seen flowing into the magnetosphere (anti-parallel: dark blue), and reflected and accelerated electrons flowing away from the X-line (yellow). The final exit into magnetosheath is marked by absence of magnetospheric electrons.

Other observations taken from conjunctions of 4-Cluster, 5-THEMIS and the Double Star, TC-1 spacecraft will be mentioned.

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