# Extended magnetic reconnection across wide local time

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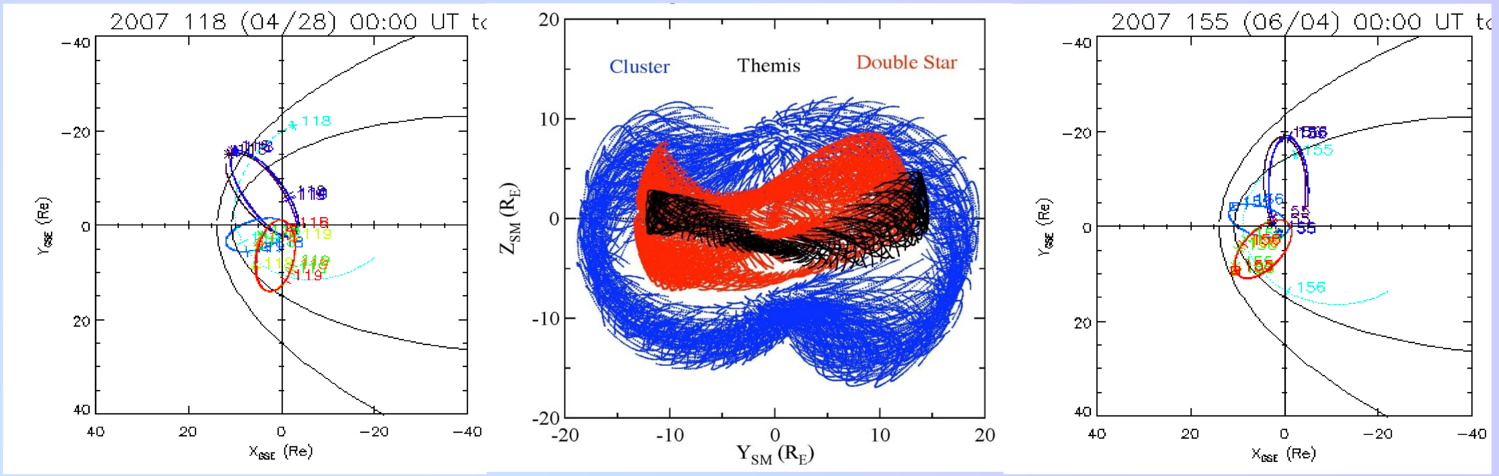
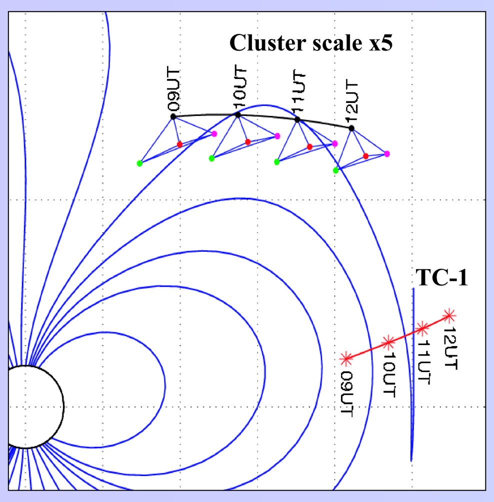
**Abstract:** Recent findings in active sites of magnetic reconnection (MR) have increased theoretical understanding of the detailed structure within the ion diffusion region surrounding the magnetic X-line or null field. Nevertheless, direct measurements of this small region in space are still relatively rare, since clear spatial signatures are difficult, owing to the time variable nature of the near-Earth space environment. We consider a Cluster, Double Star and THEMIS close conjunction at the magnetopause to explore the conjugate response of the dayside magnetopause on the dawn/dusk flanks. This combination of 10 spacecraft provided simultaneous monitoring over a wide range of local times, allowing multi-scale analysis of the occurrence and location of reconnection sites. The key result here reports direct evidence of X-line structure resulting from the operation of MR at two widely (~9 $R_E$) 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 each magnetic X-line structure, which are taken from a conjunction of the THEMIS-A spacecraft and the Double Star, TC-1 spacecraft. All 10 spacecraft encounter reconnected flux tubes, with motions consistent with both a tilted X-line in the LLBL, together with (anti-parallel) reconnection sites extending to flank locations. The observed global pattern of FTE's is consistent with the initially strong, but changing, IMF By conditions, implying that MR activity may occur simultaneously across the sub-solar and flank magnetopause, linked to the (large-scale) extended configuration of the merging line. The occurrence of MR is therefore consistent with a 'component' driven scenario independent of guide field conditions.

**Themis-Cluster-Double Star conjunctions:** During the April to July 2007 epoch, the array of four Cluster spacecraft, in a planar configuration separated at large distances (10,000 km), were traversing the dawn-side magnetopause at high and low latitudes; the five THEMIS spacecraft (typically in a 'string of pearls' configuration) were actually often bunched in a 4+1 configuration when traversing the low latitude, dusk-side magnetosphere, and the Double star, TC-1 spacecraft was in an equatorial orbit between the local times of the THEMIS and Cluster orbits. The figure shows orbital configurations of the five Themis (red), four Cluster (blue), Double Star TC-1 (light blue) and Geotail (cyan) spacecraft in April 2007 (left) and June 2007 (right), provide periodic 10-11 spacecraft coverage of the dayside MP at widely distributed and multi-point locations simultaneously. The middle panel shows orbit track segments within 2 hrs of a nominal magnetopause March to March 2007-8. All spacecraft repeatedly skim the magnetopause at different LT.



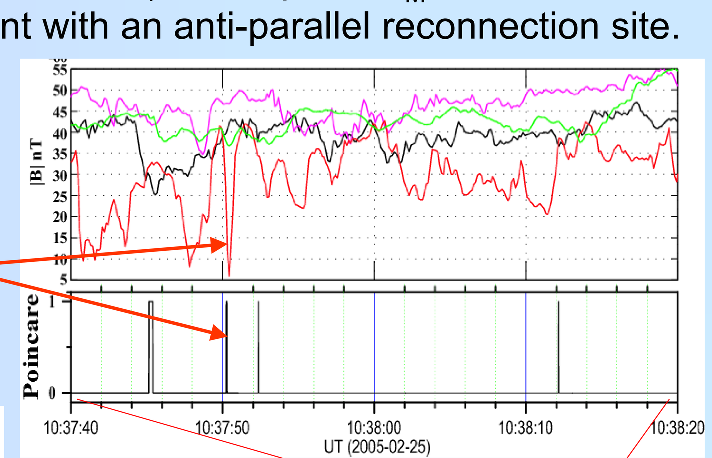

**Multi-point X-line sampling at high latitude:** Cluster exits on the high latitude magnetopause just dayside of the cusp. Data suggest that the 4-spacecraft surround the neighbourhood of the reconnection null field, where small relative motions take the spacecraft in and out of the diffusion region. The distribution of electrons and ions show correlated, energised field aligned signatures, consistent with the relative spacecraft locations. The encounter follows a period of low latitude reconnection at TC-1, which initially sees classic, northward moving FTEs. At the Custer crossings, C1, C2, C4 see multiple reversals of $B_L$ (consistent with motion above and below the X-line magnetic structure) and bipolar $B_M$ consistent with quadrupolar Hall currents. The high latitude location is consistent with an anti-parallel reconnection site.

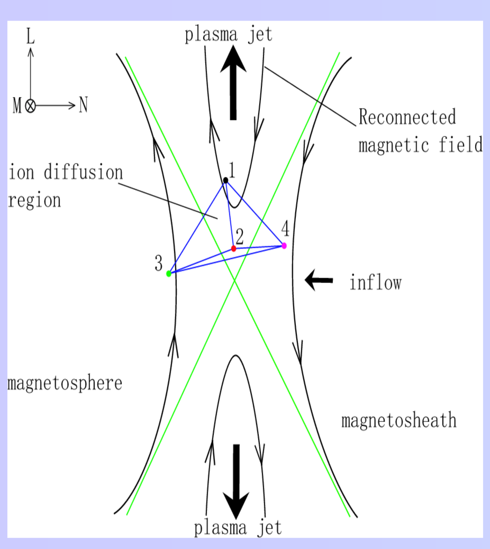


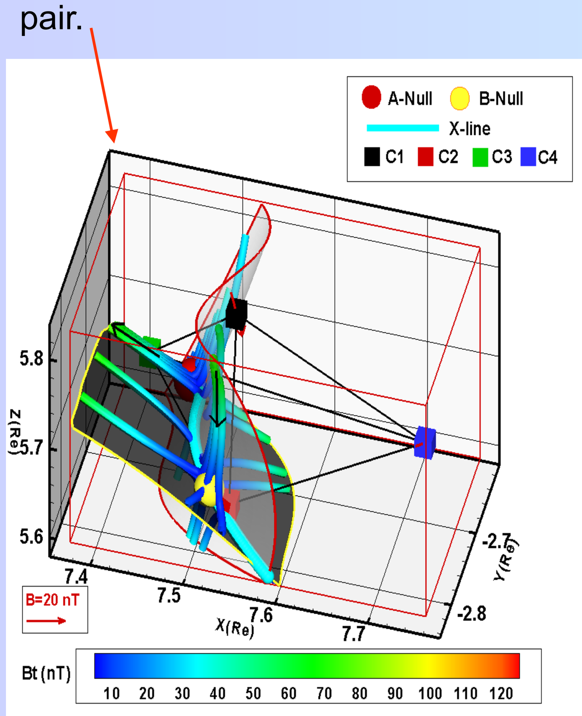

Scales: Cluster size ~1500km, ion inertial ~70km; BL ~2000km.

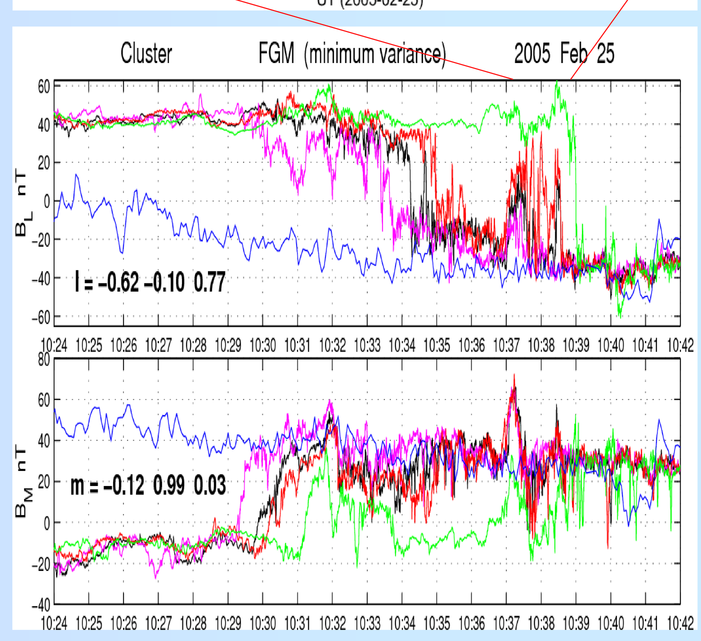
Poincare index shows existence of magnetic type A nulls (some associated with B-field dropouts)

Field reconstruction shows A-B null pair.

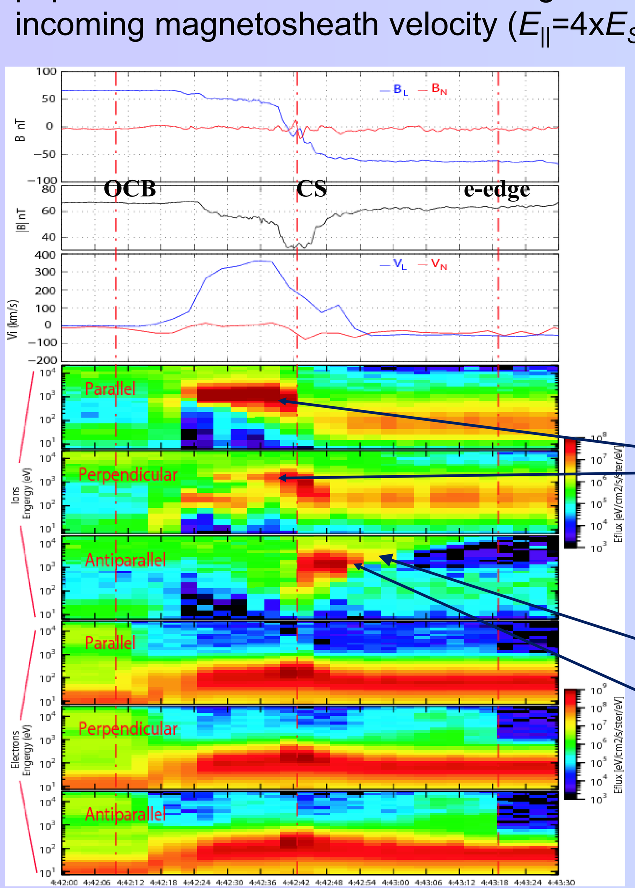


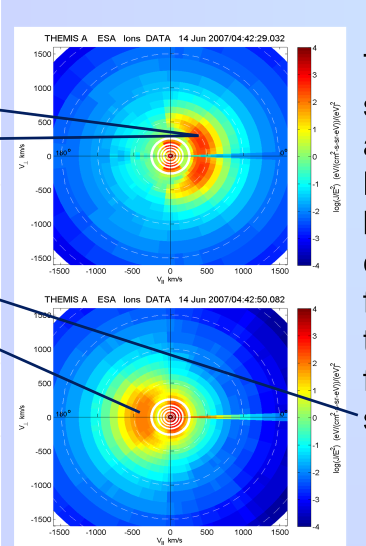



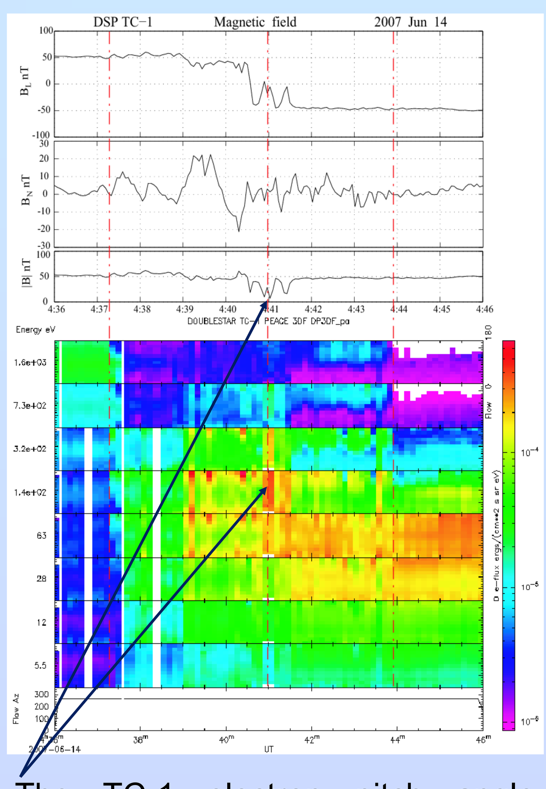

**1 Plasma distributions:** The schematic of the TC-1/Th-A crossing into the magnetosheath (at 4:40 UT) shows the expected trajectories close to the ion diffusion region of the x-line structure at each spacecraft location (separated by 9 $R_E$), as interpreted from the plasma data below. The Th-A energy spectra are shown below (left hand plot) for both ions and electrons, with the magnetic field and the bulk ion flow in the top three panels. The three vertical dashed lines indicate the inner and outer boundaries of the reconnection layer and the location of the current sheet (middle line). There are populations of accelerated ions along B-field (reflected and transmitted by the current layer) to mean energies of twice the incoming magnetosheath velocity ($E_{||}$=4x$E_{SH}$). Th-A crosses the reconnection layer further from the x-line than TC-1.



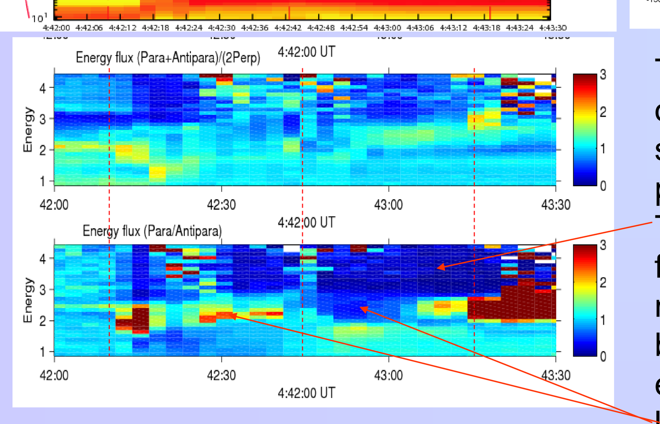

Below, 2-D distributions for ion velocity, perpendicular and parallel to the magnetic field, either side of the current sheet. These distributions are reflected about $V_\perp$=0 and show the4 characteristic 'Cowley' D-shape for reflected and transmitted ions.



The back-streaming and accelerated ions have a lower energy cut-off, arising from time of flight from the current sheet.




The TC-1 electron pitch angle distribution (above), shows the populations of electrons at each angle to the field (each sub-panel) at the energies indicated. The top panels show the magnetic field and the reconnection layer boundaries are indicated. The electron beams, energisation and field dropouts, suggest that TC-1 lies almost in null field region, and passes first south, then north, of the x-line on exit.




Themis-A electron distribution shows only a small anisotropic component, so no strong field aligned flux (top panel left).
The field aligned electrons show out-flowing magnetospheric populations in reconnection layer, and an incoming/back-streaming, magnetosheath electrons either side of the current layer.

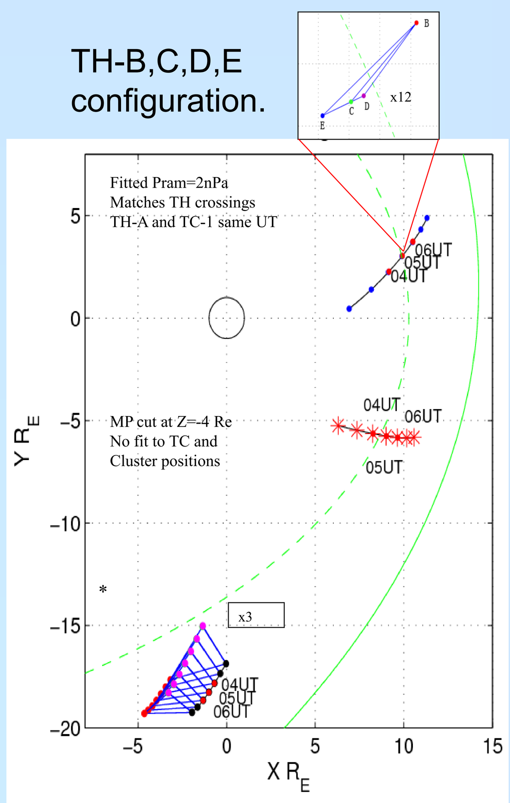
## Conclusions

Reconnection signatures have been tracked across a wide range of local times using 10 spacecraft conjunctions on the Earth's magnetopause, which allow FTE occurrence and motion to be checked:

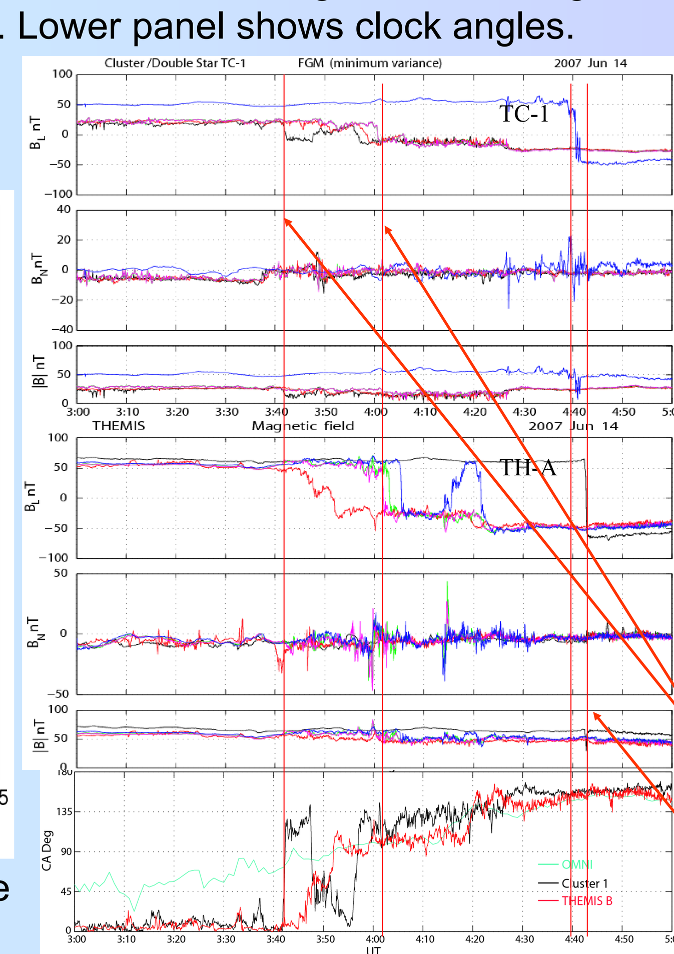
- Confirmation of east-west opposite moving FTEs, consistent with a tilted X-line (Strong IMF By)
- High FTE populations at Cluster, Double Star and Themis suggest generation far from local noon at possible flank anti-|| sites.
- Find simultaneous X-line structure at two locations along expected sub-solar merging line (tilted line of maximum current): at ~9 Re separation.
- Strongly suggests extended (patchy) reconnection occurs, irrespective of clock angle (all along the expected merging line): MR is inherently component driven.
- 3-D geometry of FT and mixing of open/closed electron distributions suggests formation between a double X-line.

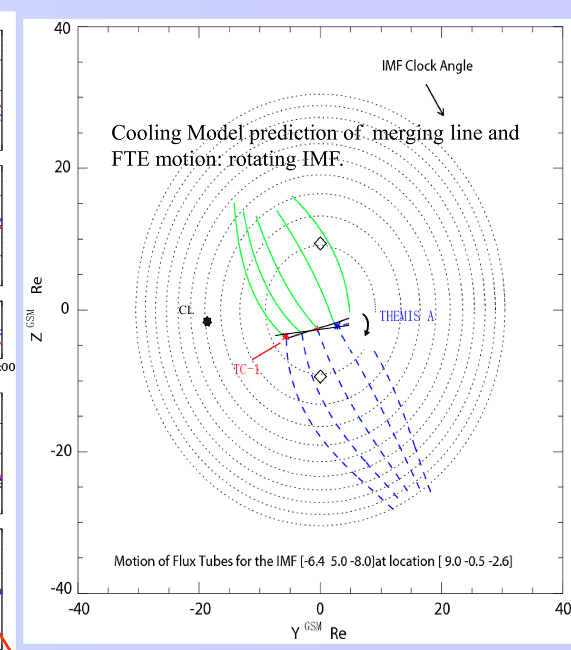
**Multi-scale X-line sampling (14 June 2007):** Close conjunction of 10 spacecraft showing near simultaneous MP crossings and FTEs on all spacecraft. An initially strong IMF +By, turns southward with steady, increasing $P_{RAM}$ during the key interval. Magnetic field data for all 10 spacecraft in boundary normal co-ordinates. Colours are: black, red, green, and magneta, for Cluster 1-4 and Th A-D, and blue for both TC-1 and Th-E. Lower panel shows clock angles.

TH-B,C,D,E configuration.




Cluster remains close to site of anti-|| reconnection.

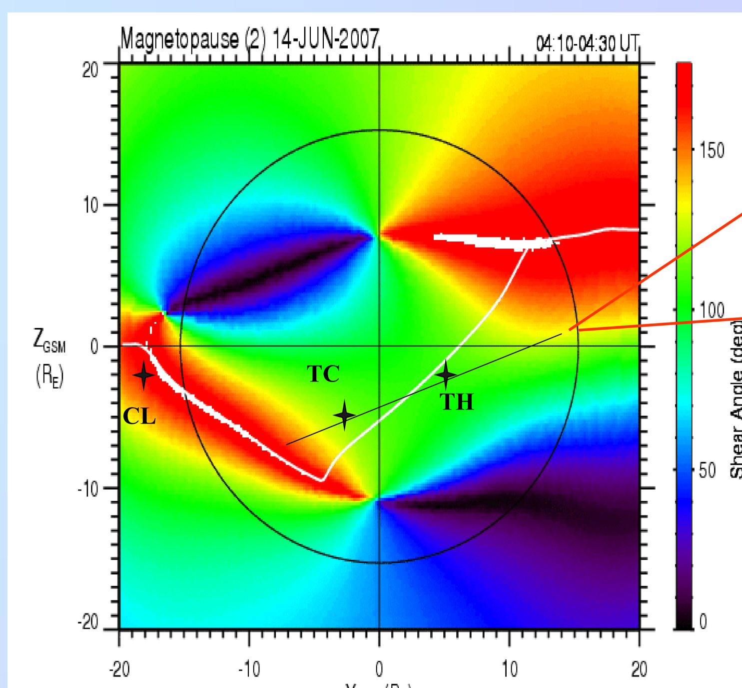


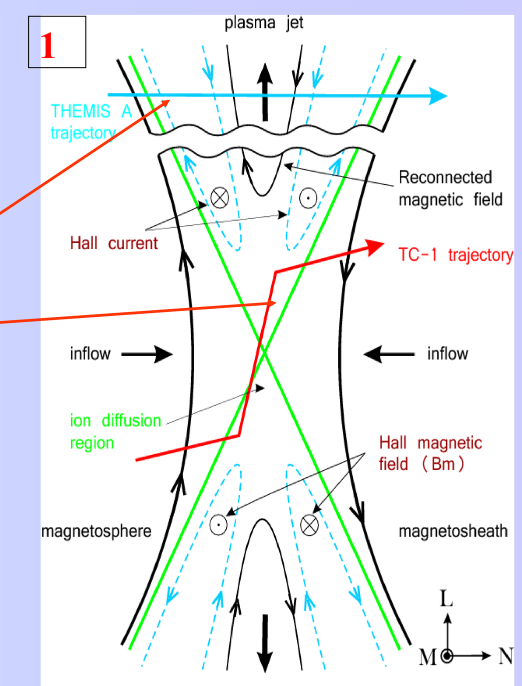




Cluster and Themis arrays exit together (within 20 mins); followed by fast exits of TH-A and TC-1 (1-2 mins apart)

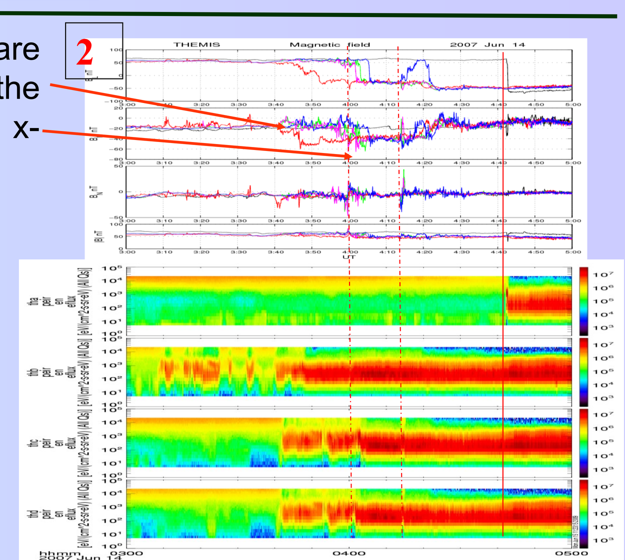
The Cooling plot shows the s/c locations at the MP, as seen from the Sun, with the later (4:40 UT) orientation of the merging current line (most likely location of the reconnection line) indicated as a rotation. The left panel (below) shows modelled, MP shear angles: the white regions are close to anti-parallel and show possible reconnection locations, extending into the flanks; the white line is as predicted by the Maximum Magnetic Shear Model [*Trattner et al.*, 2007], and the black line is the final orientation of the fitted (Cooling) merging current line, which closely threads between the Th-A and TC-1 locations. All locations are shown as black crosses and remain close to both flank and low-latitude, dayside regions. The schematic on the right is suggested by ion and electron plasma distributions.

**MP crossings:** The measured and Cooling model prediction of FT motion supports the interpretation that the Themis s/c initially exit south of a tilted dayside x-line, while Th-A and TC-1 exit north, very close to the expected x-line. The direction of motion of reconnection signatures at Cluster suggest local activity occurs at the same time at the flank, anti-parallel sites.

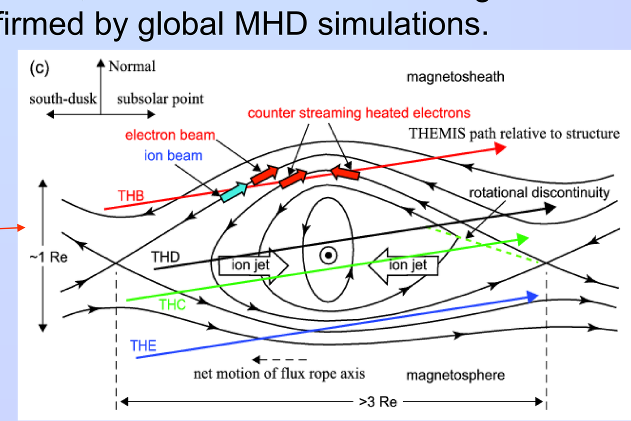


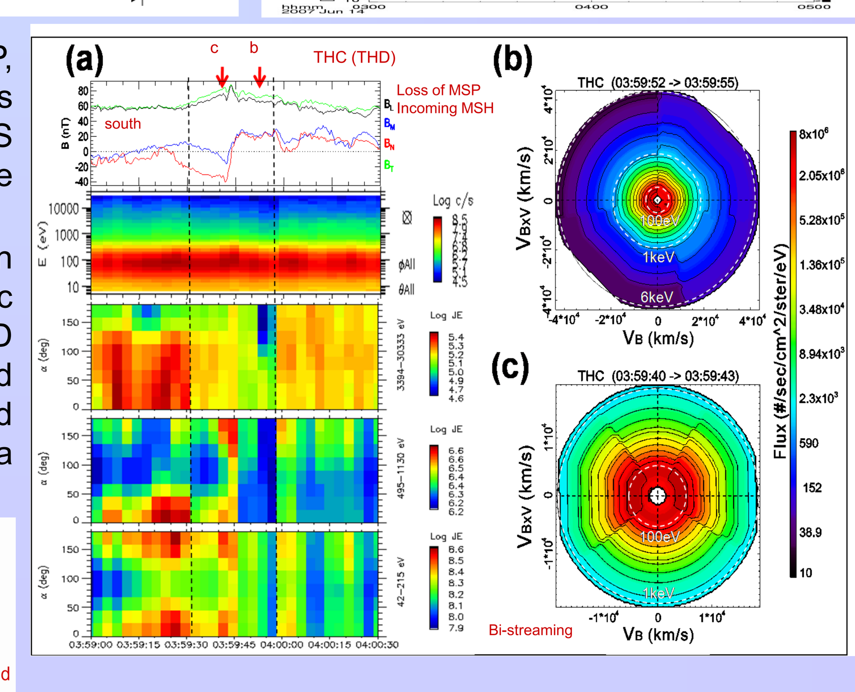

**2 THEMIS:** earlier crossing sequence south of X-line; TH-A and TC-1 are inside magnetosphere. Three key FTEs are observed. The plasma data for the central FTE show complex behaviour, reminiscent of a reforming or double x-line. The scenario is broadly confirmed by global MHD simulations.

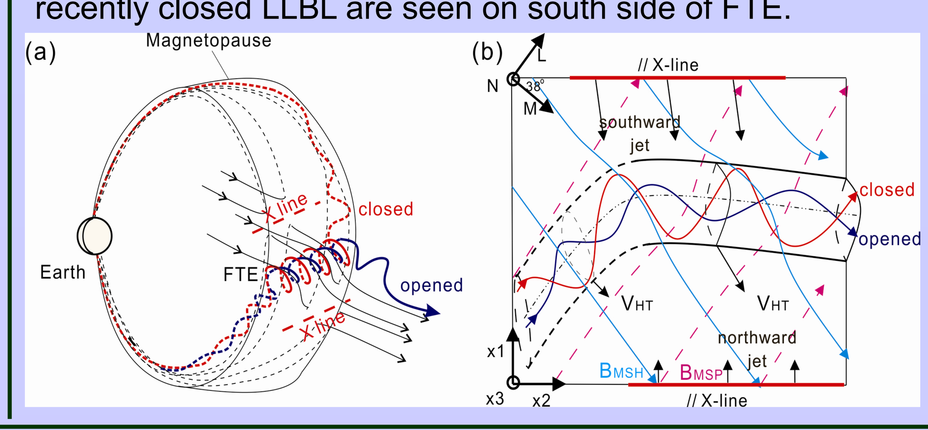


There is multi-spacecraft coverage through the structure and 2-D reconstruction of the flux tube for Th-C and D (Grad-Shavranov) is shown.
Incoming fast flows and well ordered Walen relations either side of signature are suggestive of MXL (sequential formation).




The time shifted s/c tracks show the FT is rolling along MP, dusk-ward, with THB on the m'sheath side. The geometry is actually twisted: flows have a component in Z and the G-S plane is aligned to $XY_{GSM}$, implying THC/THD sample the magnetospheric branch of the FT.
A combination of deH-T, MVAB and merging line prediction appears to confirm SMXL: distinct orientations for m'spheric and azimuthal (m'sheath) branches of the FT are found (3-D picture below). THB shows the azimuthal branch is aligned to the X-line. Plasma signatures (right) show mixed open and closed distributions deep inside the FT. Signatures of a recently closed LLBL are seen on south side of FTE.

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