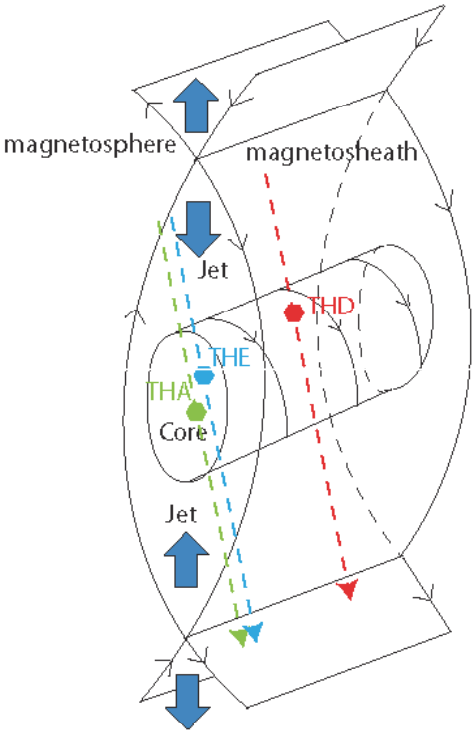
THEMIS multi-spacecraft observations of a 3D magnetic flux rope flanked by two active reconnection X-lines at the Earth's magnetopause

Marit Øieroset (*UC Berkeley)*



Collaborators: Tai Phan, Jonathan Eastwood, Masaki Fujimoto, Bill Daughton, Mike Shay, Vassilis Angelopoulos, Forrest Mozer, Jim McFadden, Davin Larson, Karl-Heinz Glassmeier

This event reveals:

- A rare spacecraft encounter with an "active" flux rope flanked by two active X-lines
- 3D effects
- Super-thermal electron heating in the flux rope core

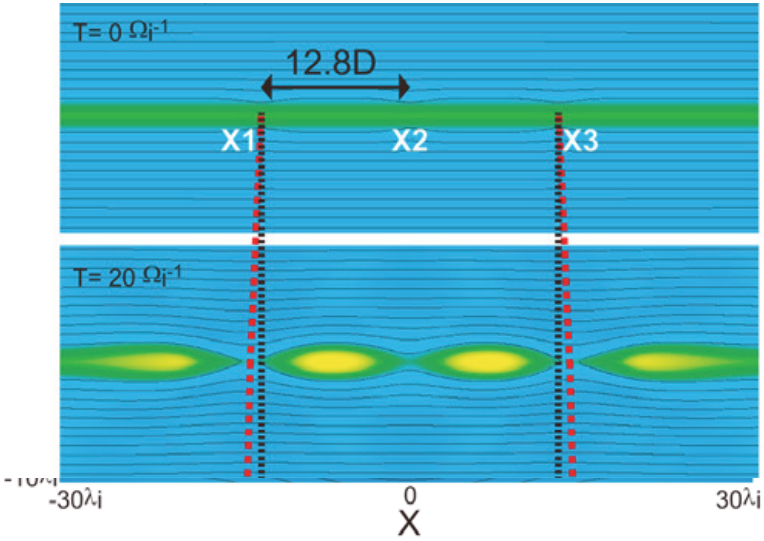
Øieroset et al. [*Phys. Rev. Lett*., 2011]

Outline

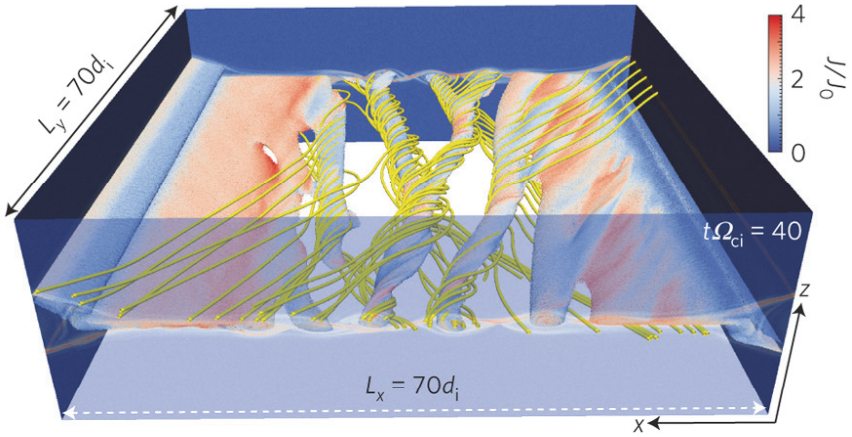
1. Theoretical predictions of reconnection-generated flux ropes: 2D versus 3D

2. THEMIS multi-spacecraft observations of an active 3D flux rope

Thin current sheets are prone to multiple X-lines



Nakamura et al. (2010)



Daugton et al. (2011)

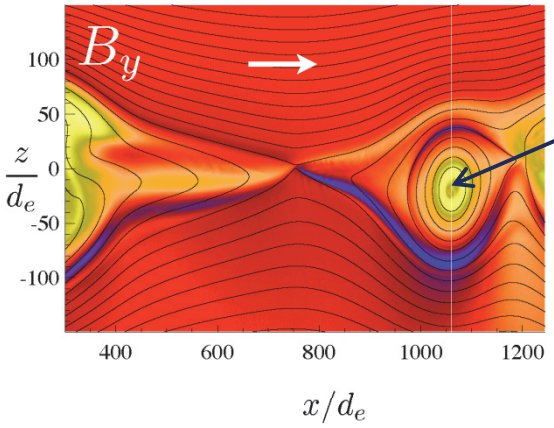
2D: magnetic islands are formed between X-lines

3D: magnetic islands become magnetic flux ropes

Basic properties of 2D magnetic islands (with a finite guide field)

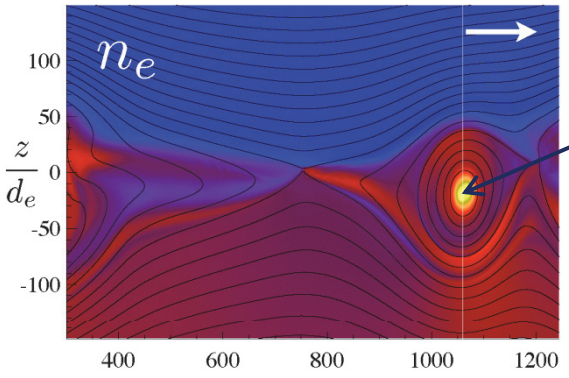
- Strong core field
- Enhanced density in the core region of the island: 2D effect?

Out-of-plane By



Enhanced core field

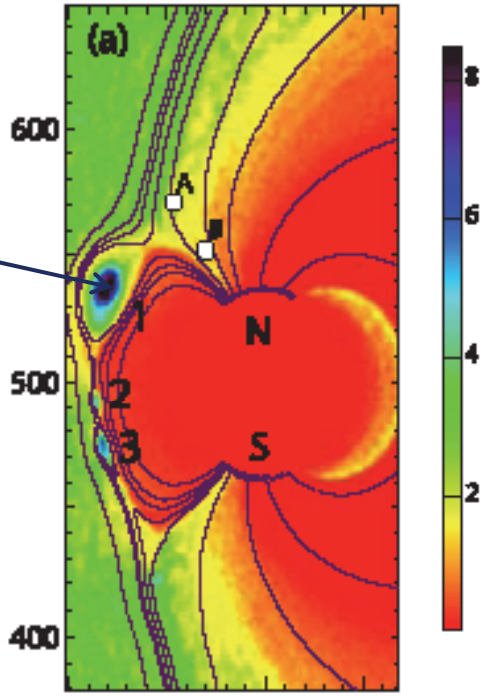
Density



Enhanced density

(Bill Daughton)

Island at magnetopause



Enhanced density

Density

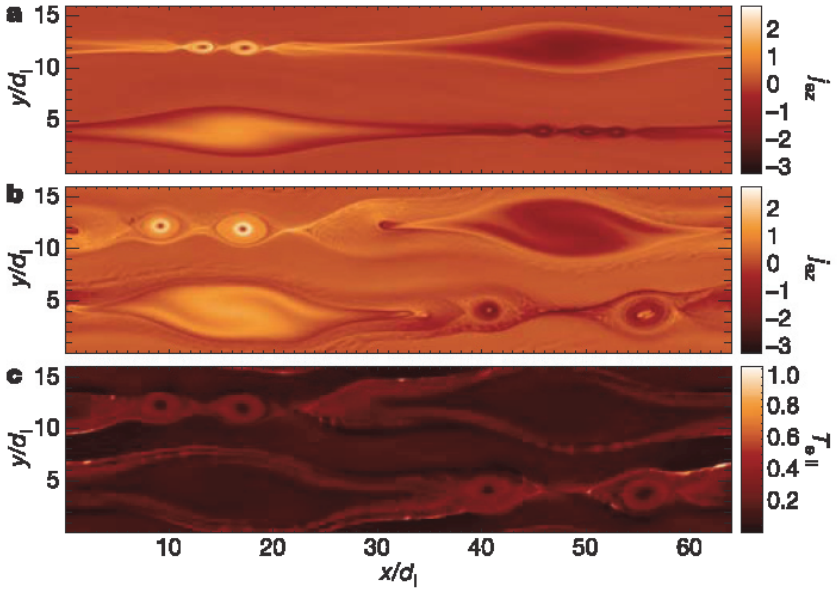
Omidi and Sibeck (2007)

Electron energization in 2D islands

- 2D islands: electrons are trapped

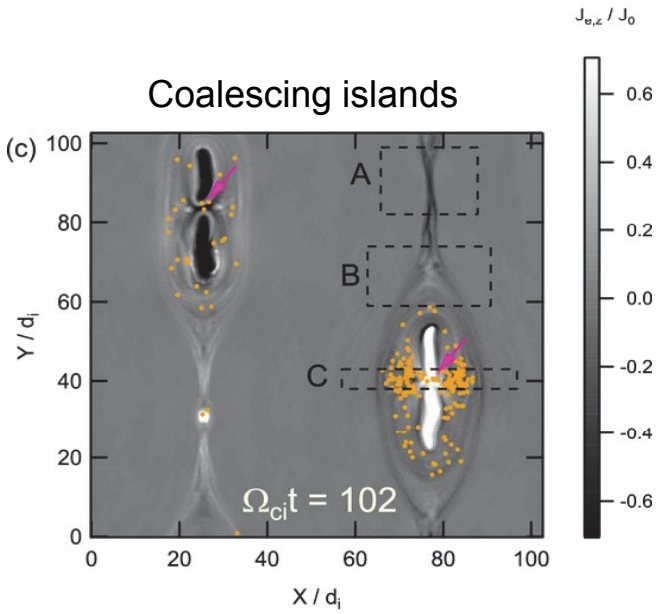
- Electrons can be energized via:
  - Acceleration at X-line (e.g., Pritchett, 2006)
  - Island contraction (Drake et al., 2006)
  - Island coalescence (e.g., Pritchett, 2008; Oka et al., 2010, Tanaka et al., 2010)

Island contraction



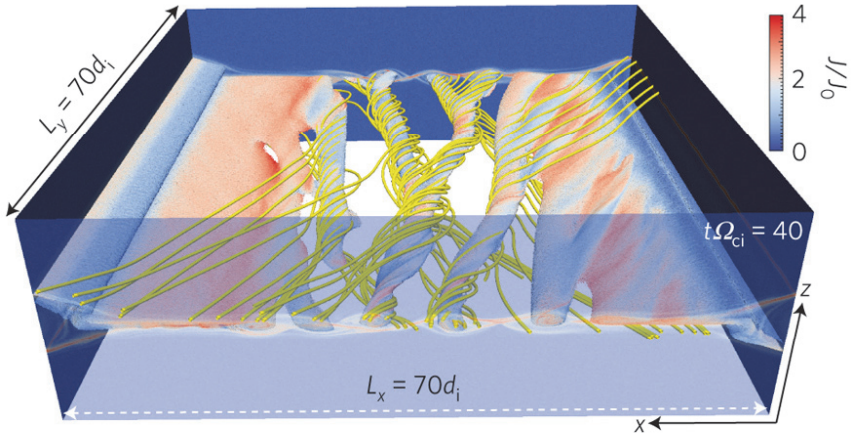
Drake et al. (2006)

Coalescing islands



Oka et al. (2010)

In 3D the islands become flux ropes and particles are no longer trapped



Daugton et al. (2011)

Flux ropes are not uniform in the 3rd dimension

Formation, properties, and evolution much more complex

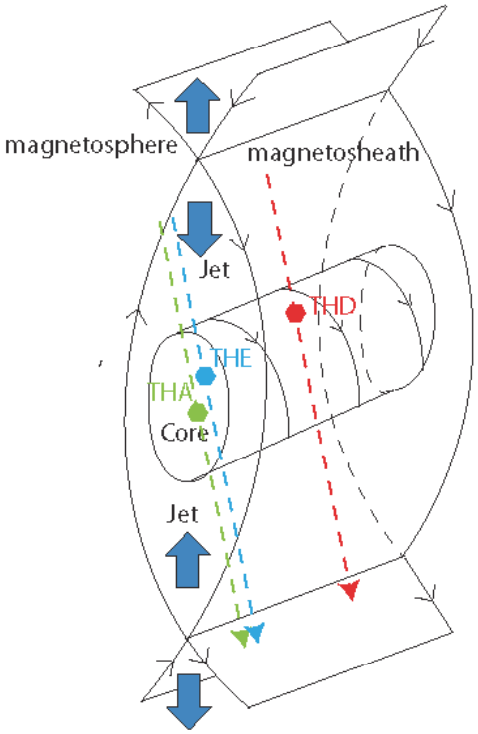
It is not clear how processes seen in 2D simulations are modified by 3D effects

Outline

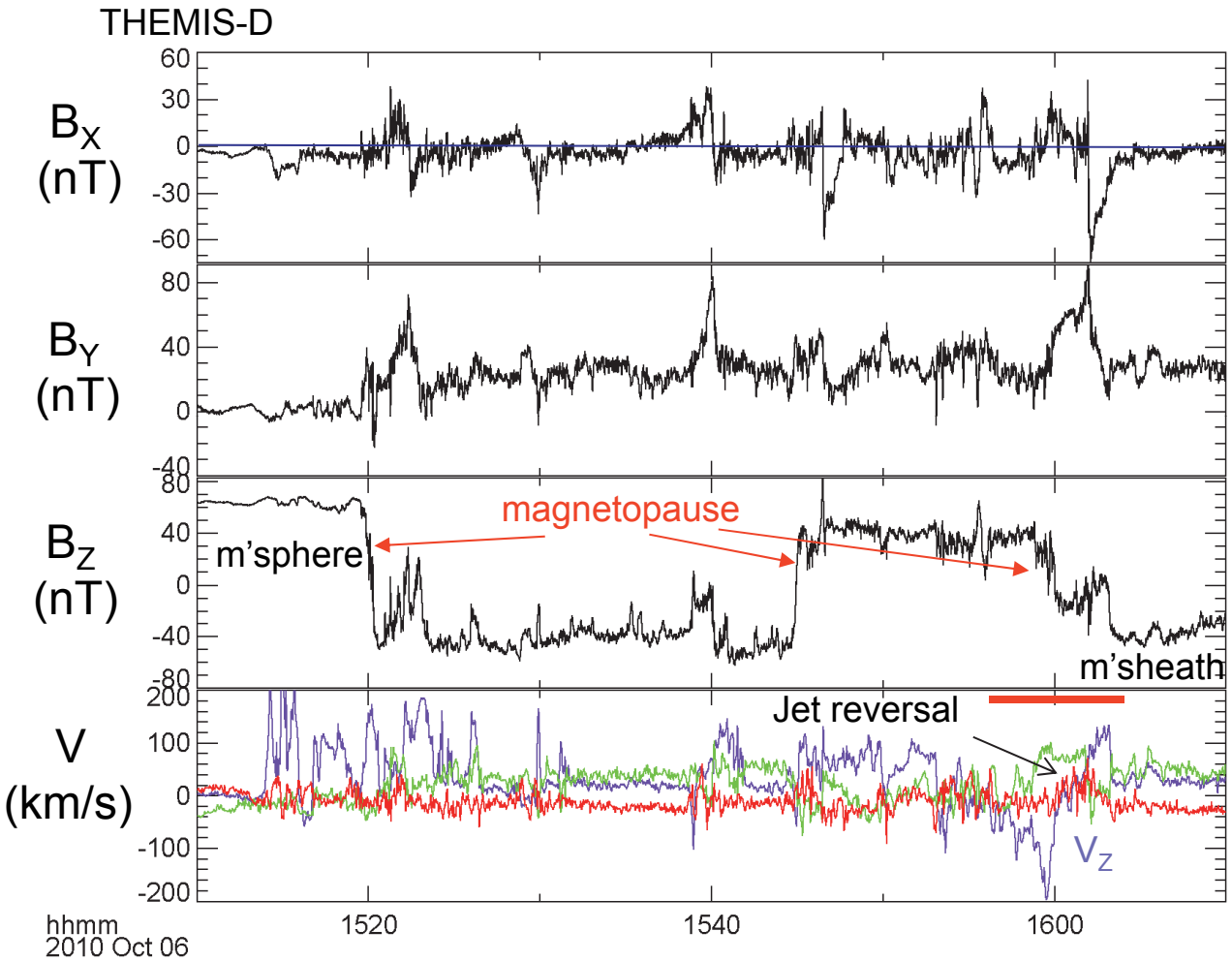
1. Theoretical predictions of reconnection-generated flux ropes: 2D versus 3D

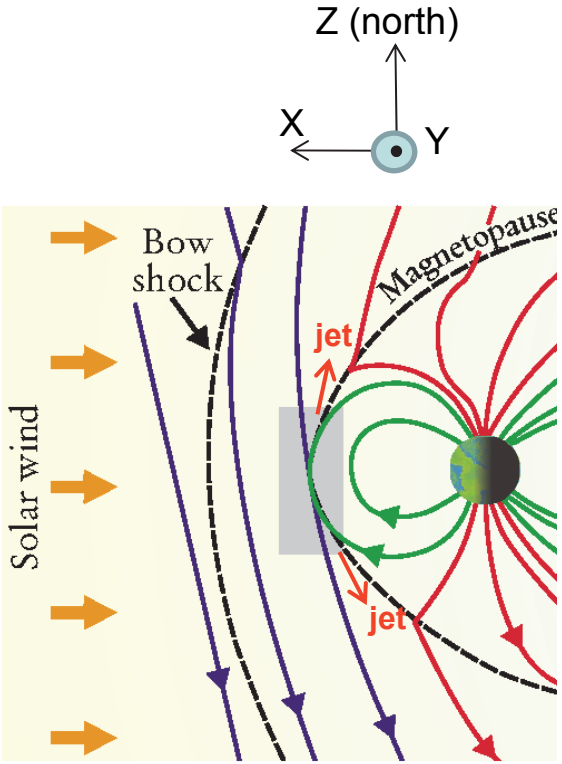
2. THEMIS multi-spacecraft observations of an active flux rope

   - Establish the flux rope encounter using multi-spacecraft (non-trivial)
   - 3D effects:
     - Density depletion in flux rope core
     - Electrons are not trapped
   - Super-thermal electron energization



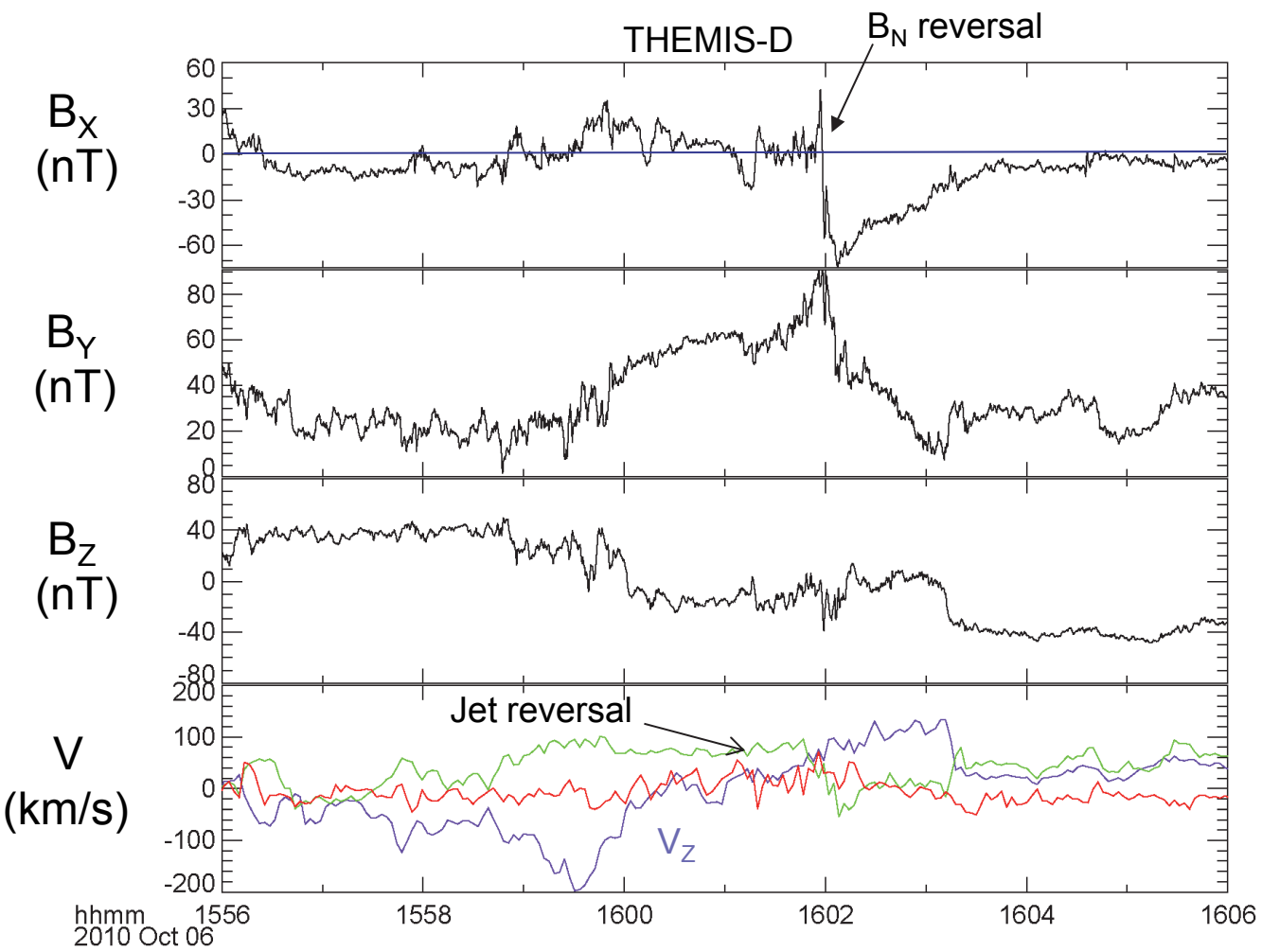
THEMIS multiple magnetopause crossings: Reconnection jets

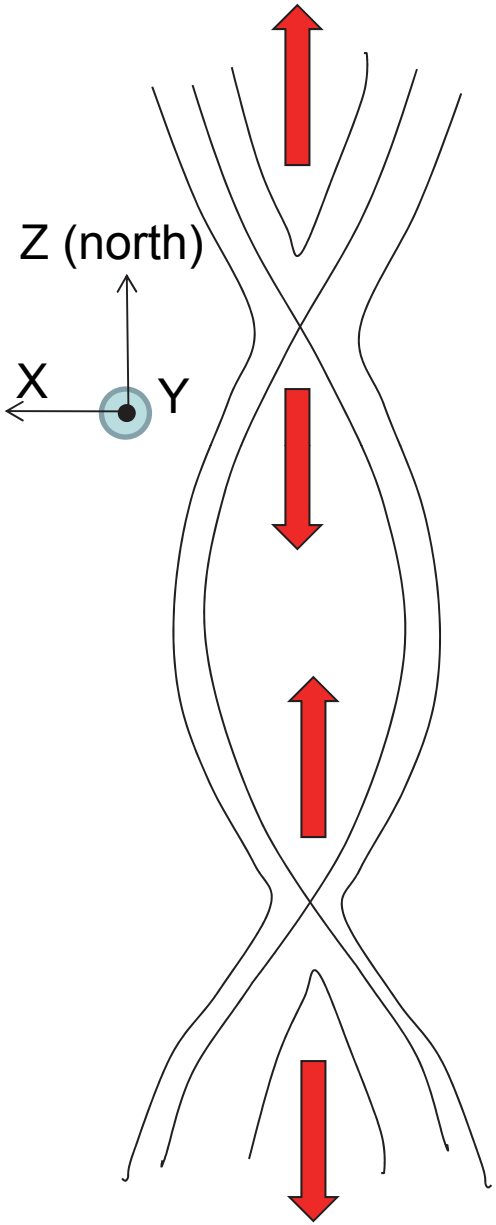




Guide field across the magnetopause = 0.3 of reconnecting field

Reconnection Jet Reversal: X-line or O-line Crossing?

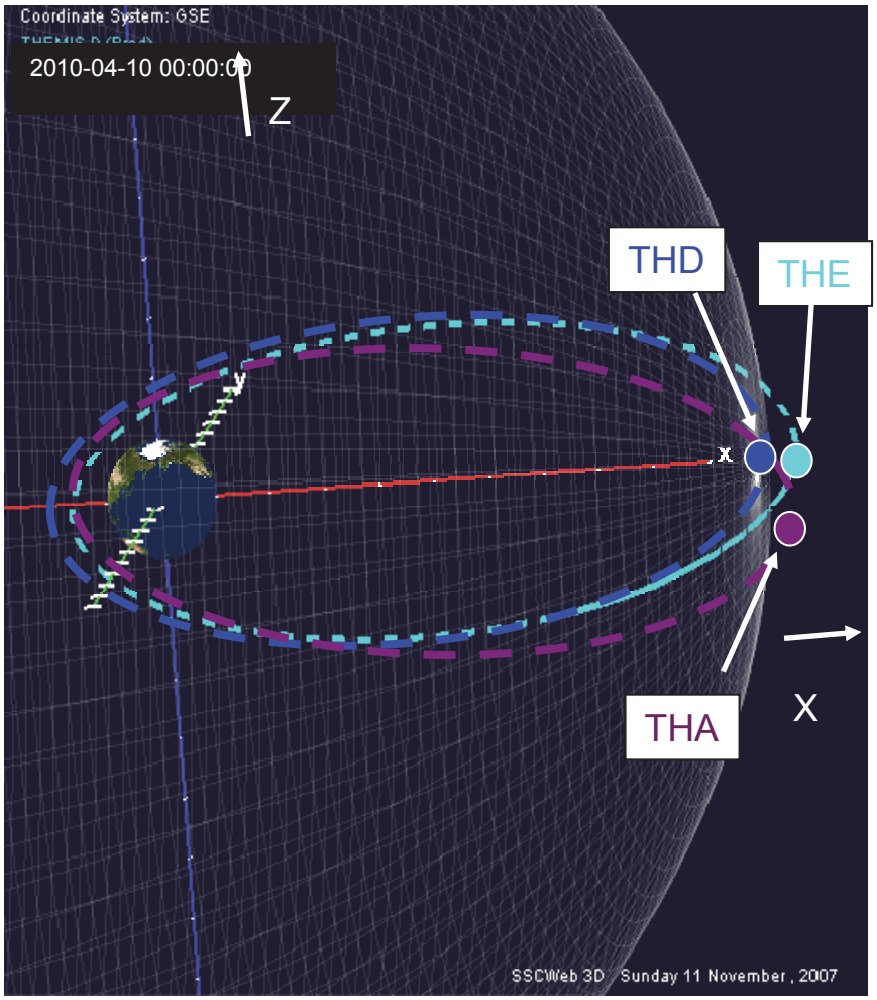




With single spacecraft observations it is often difficult to distinguish between an X-line and an O-line

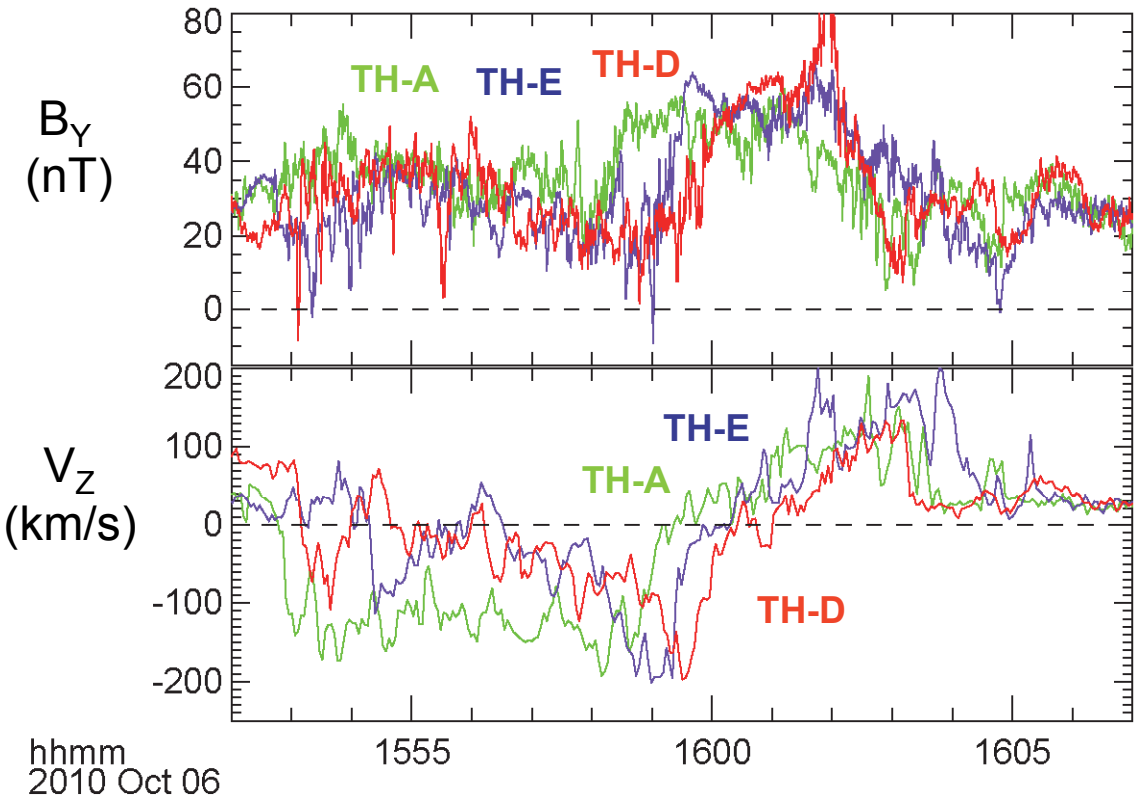
THEMIS in 2010-2011: Z_{GSM} separation

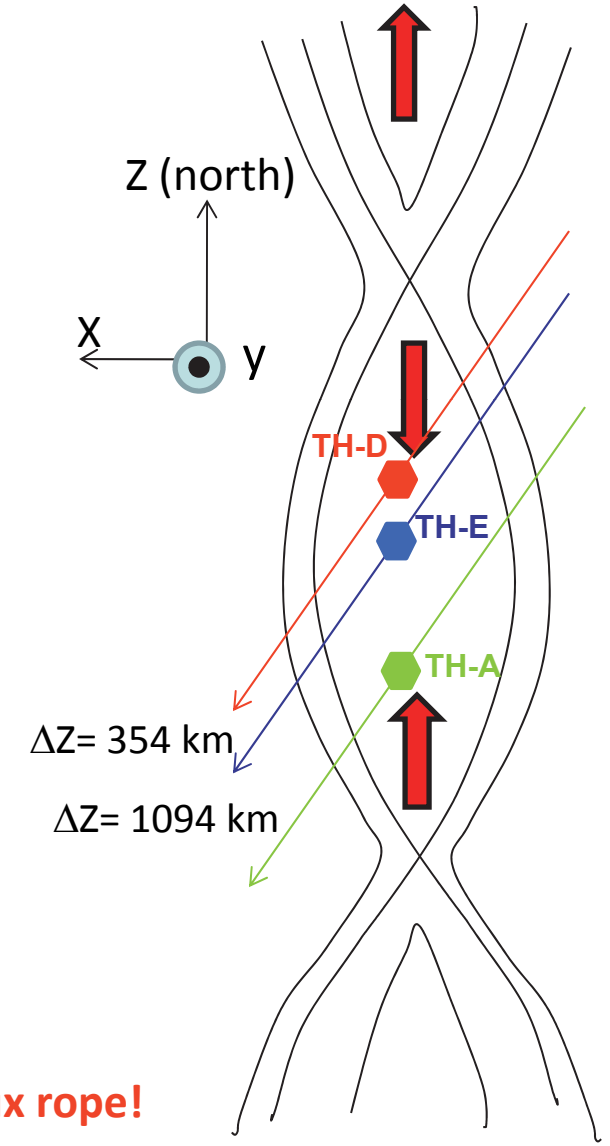
Z separation = 1000-3000 km
= 10-30 ion skin depths



All three spacecraft observed the flow reversal

→ Can determine conclusively whether this is an X-line or an O-line crossing





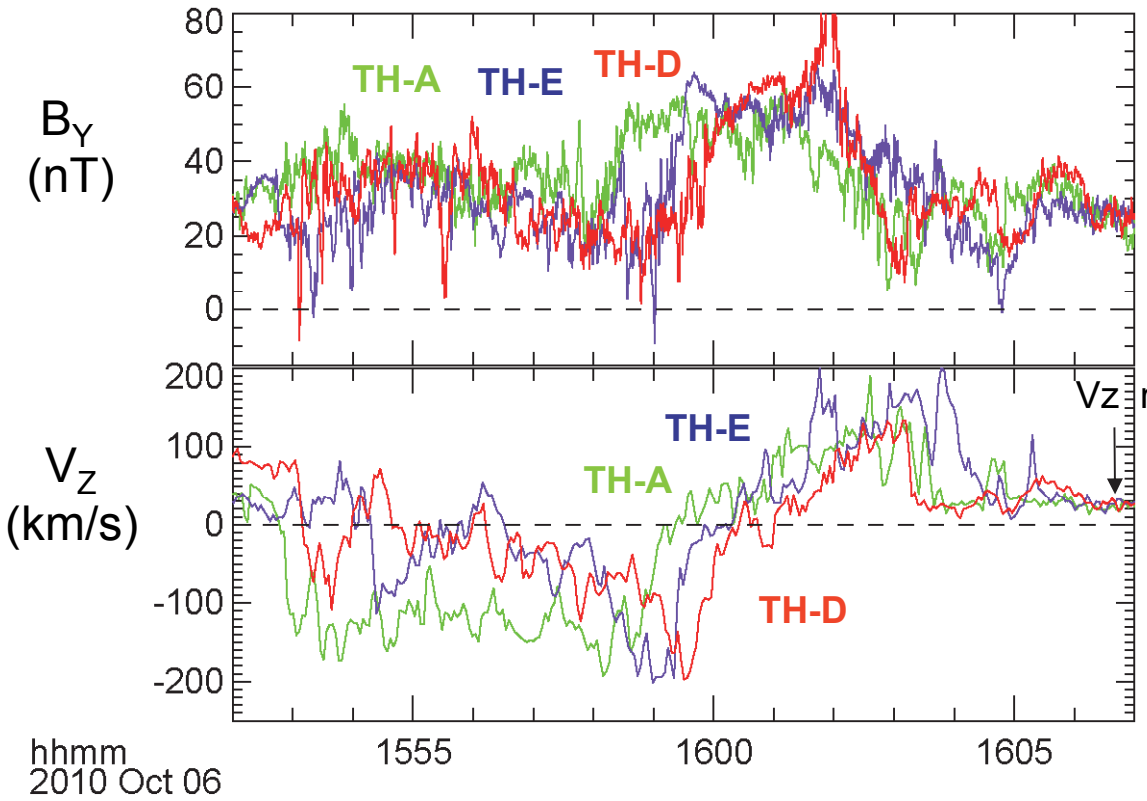
Flow reversal sequence:

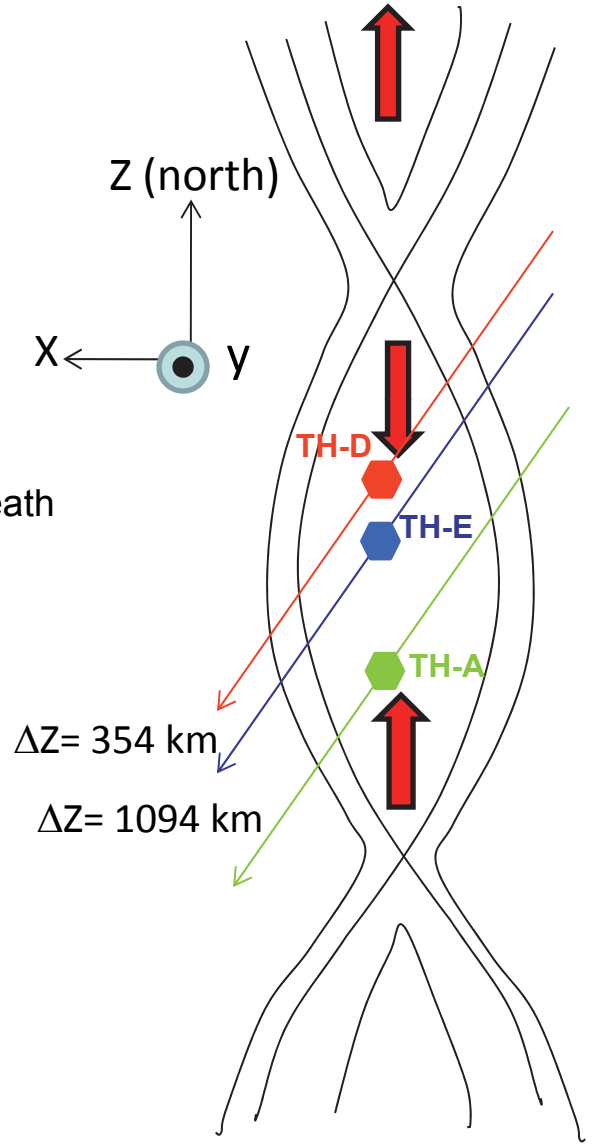
If southward moving X-line: **TH-D**, **TH-E**, **TH-A**

If northward moving O-line: **TH-A**, **TH-E**, **TH-D** → **this is a flux rope!**

Spatial dimension of flux rope along Z (outflow direction):

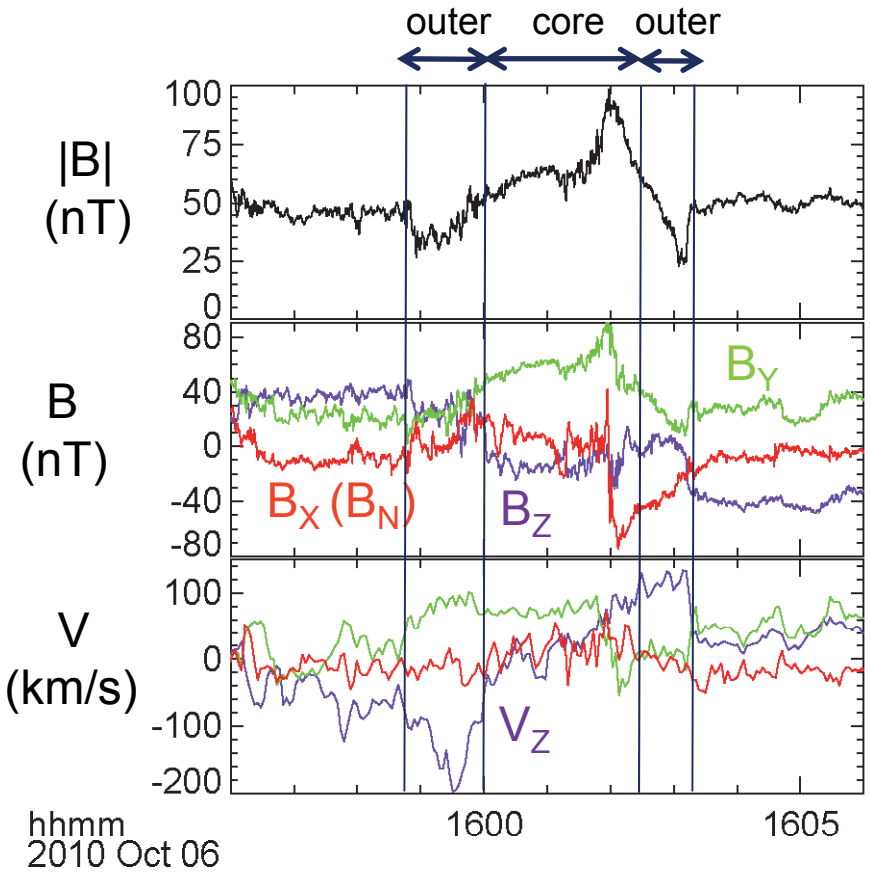
15,000 km = 274 ion skin depths

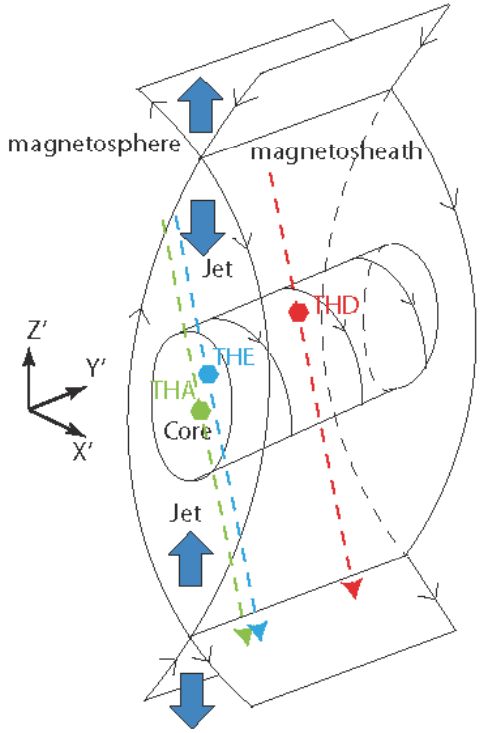




Propagation speed of flow reversal: 21 km/s
(comparable to the external magnetosheath flow)

Flux rope consists roughly of an outer and an inner (core) region





Outer region: converging bi-directional jets

Core region: nearly stagnant and enhanced core field (B_Y)

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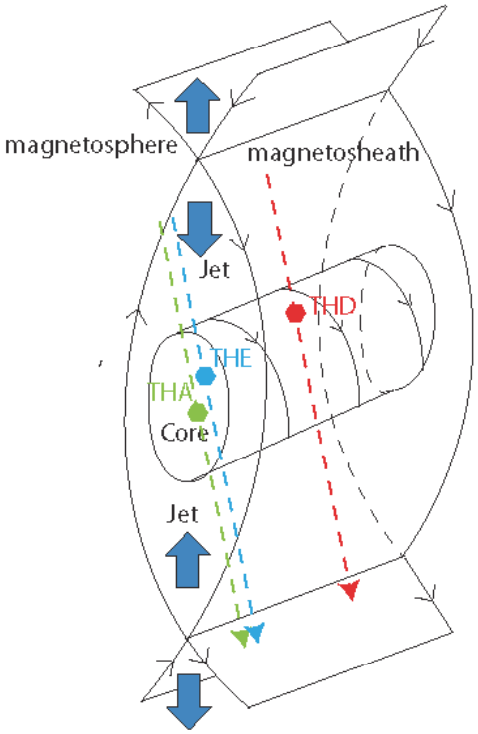
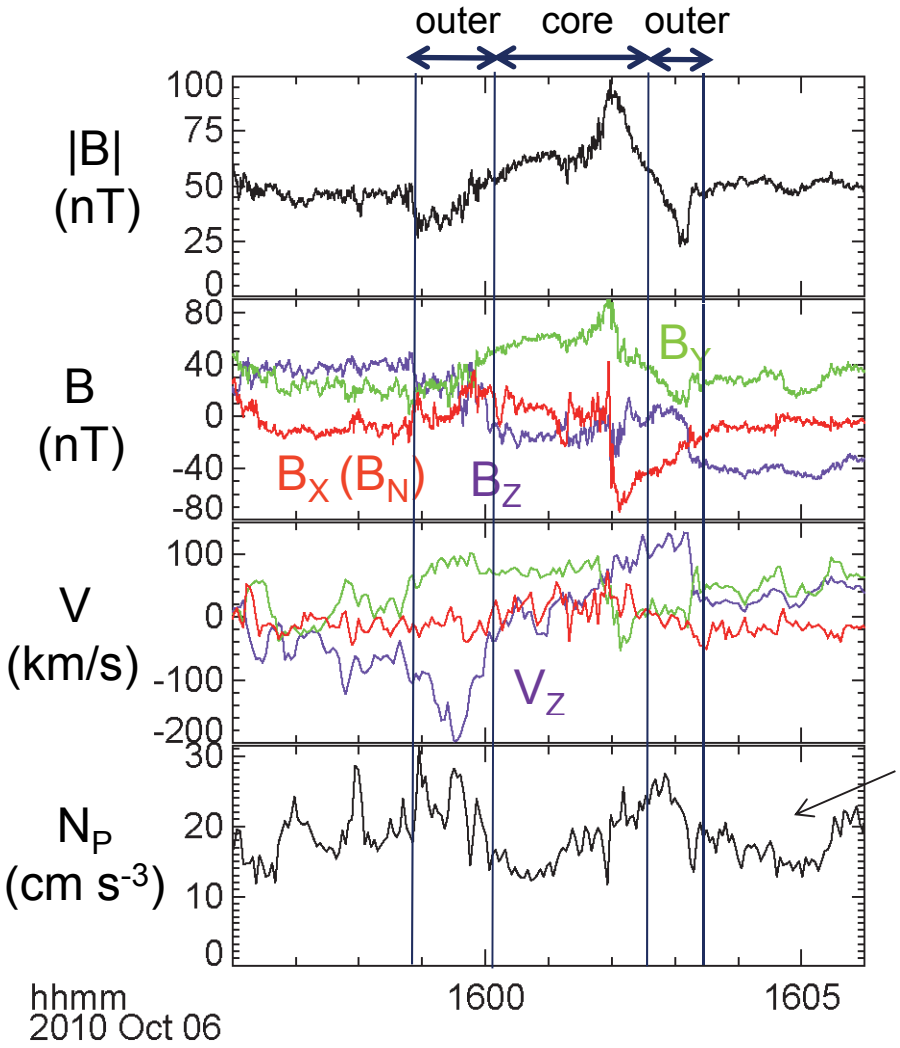
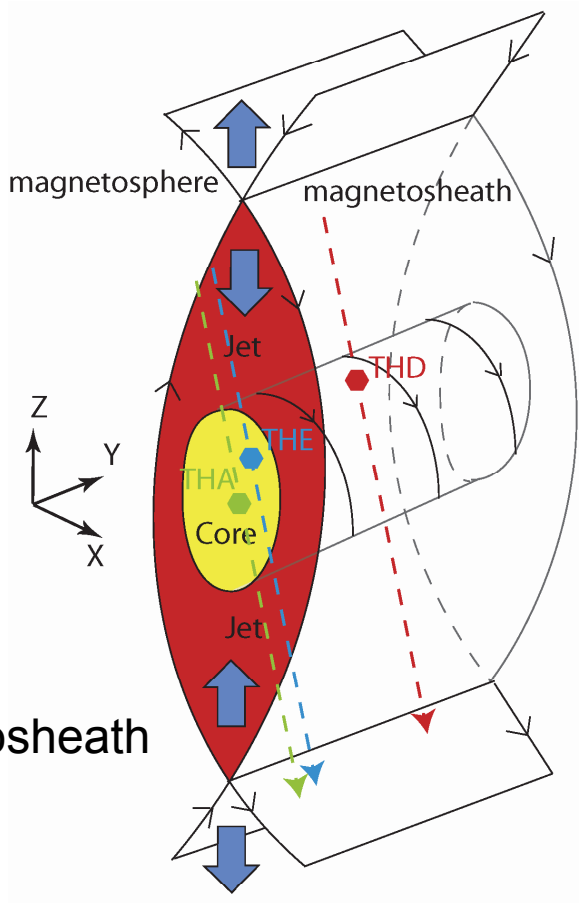


Density variations in the flux rope

Outer region: The density is enhanced

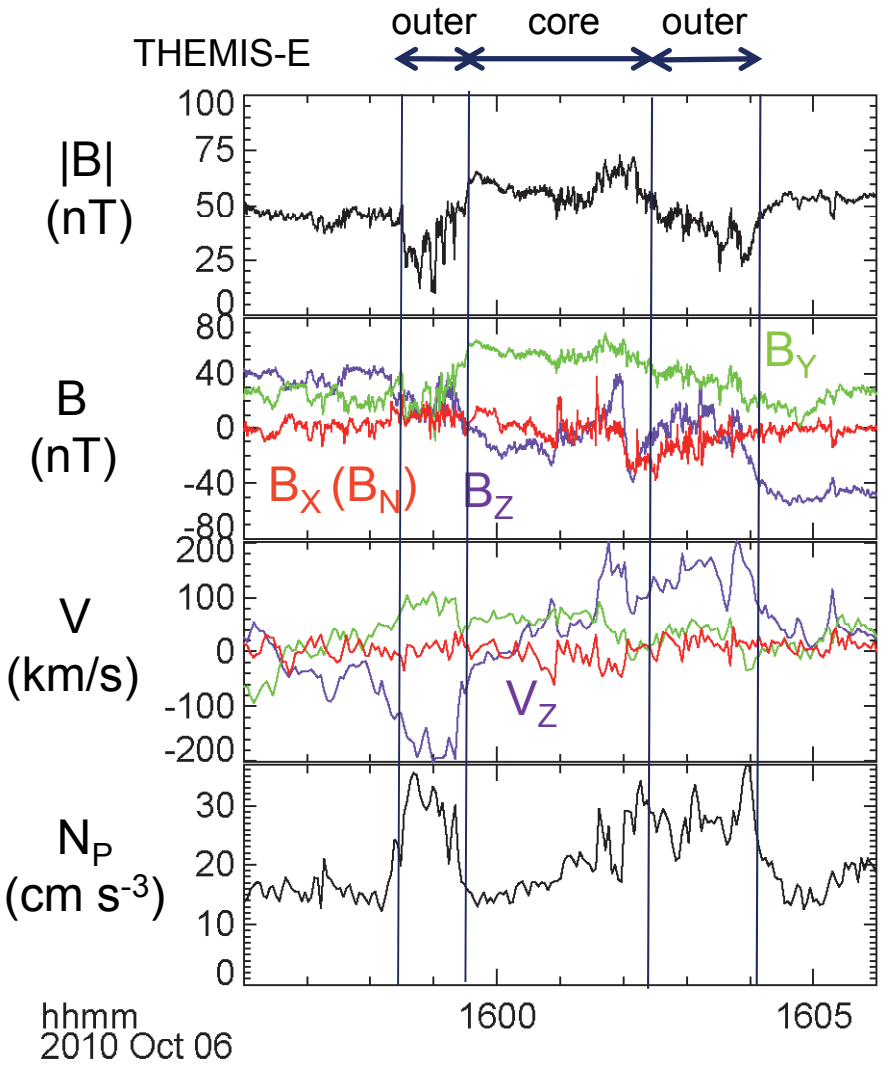
Core: The density is reduced compared to outer region → 3D effect

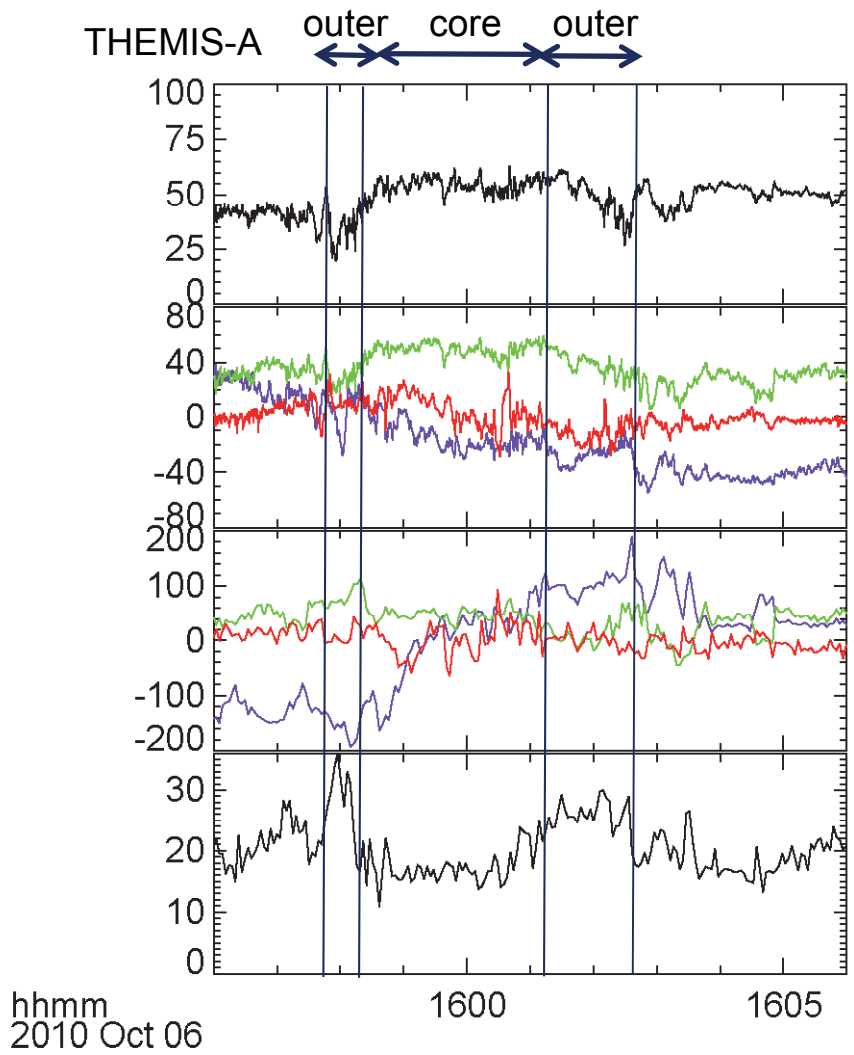




Density depletion seen by all three spacecraft

→ a robust feature





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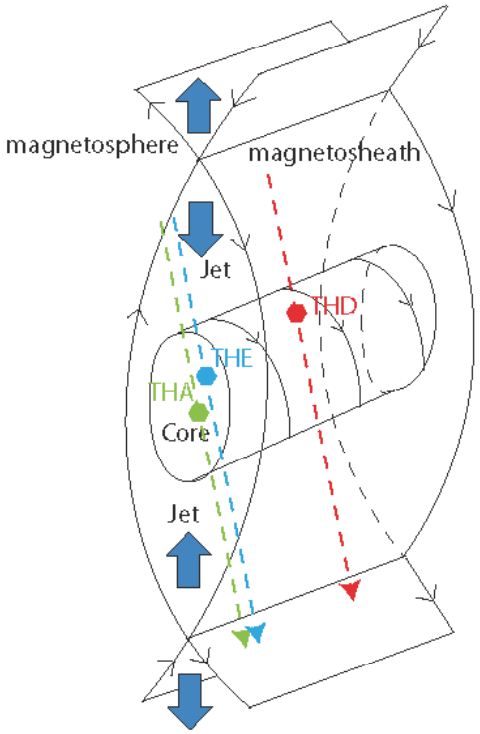
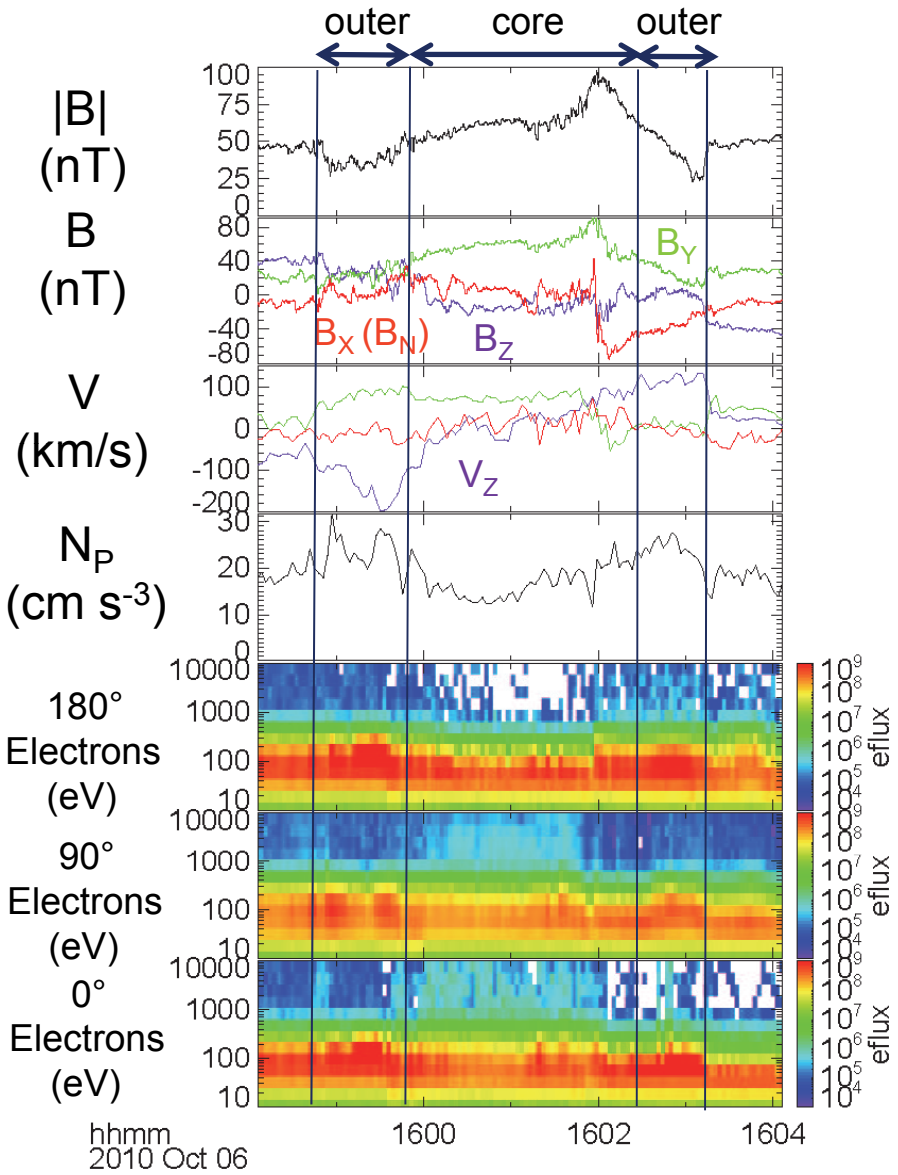
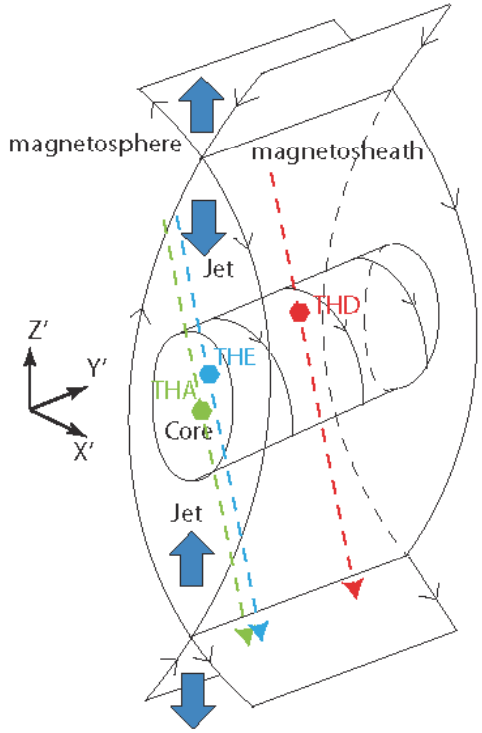


Electrons are not trapped in the flux rope → 3D effect





Electrons are unbalanced
→ flux rope is open-ended

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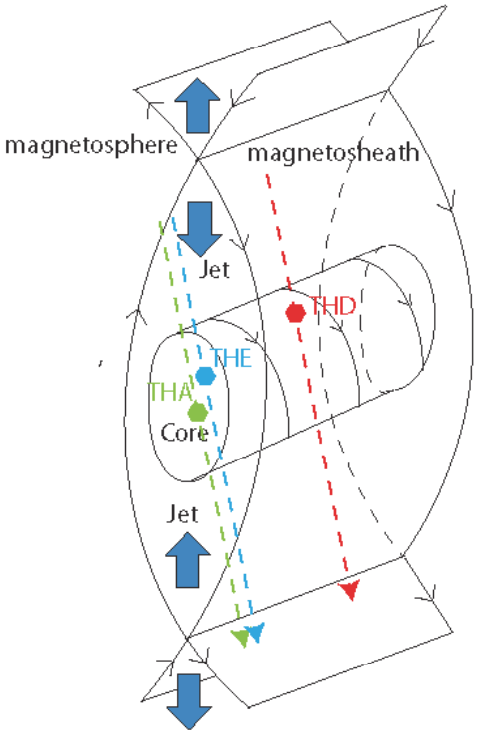
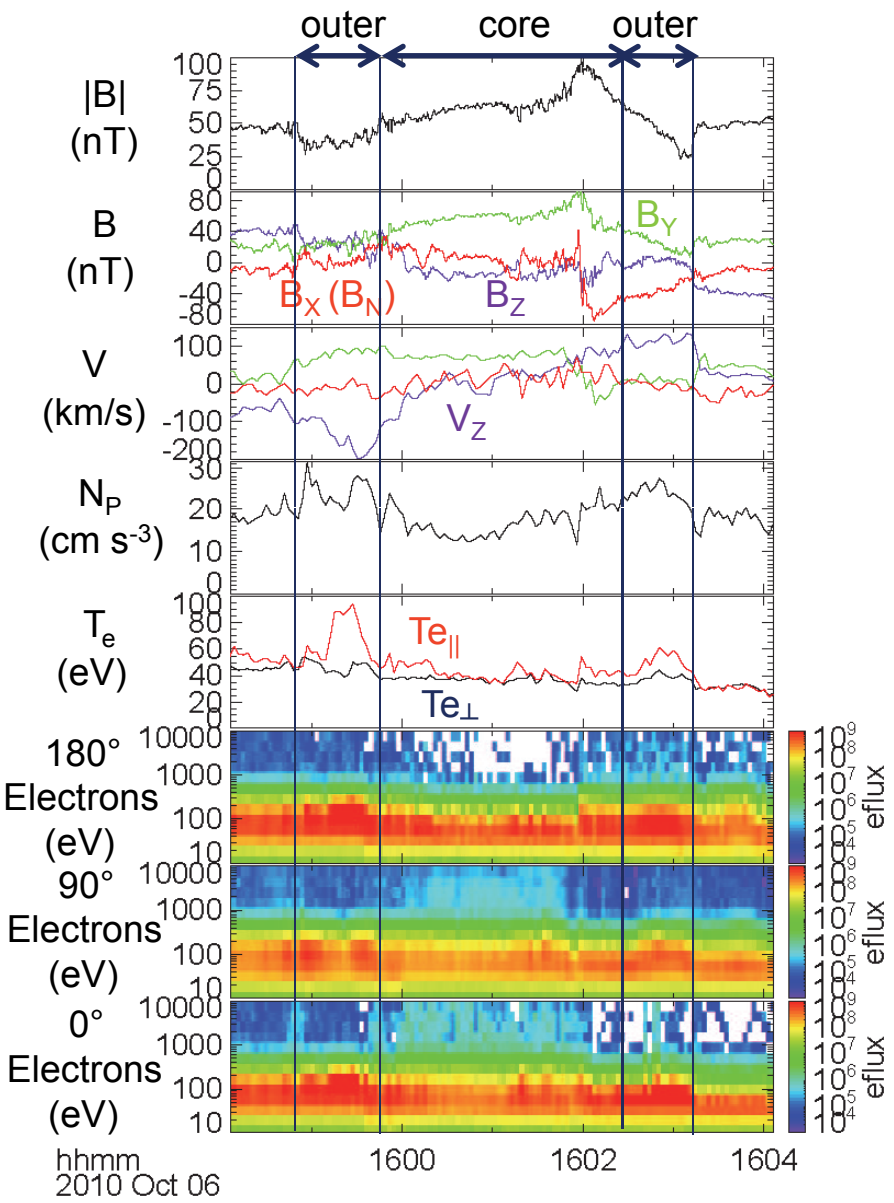
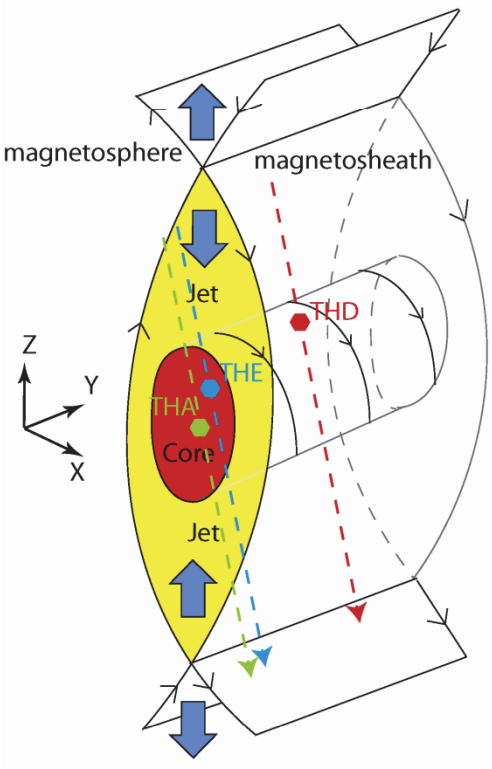


Super-thermal electron energization



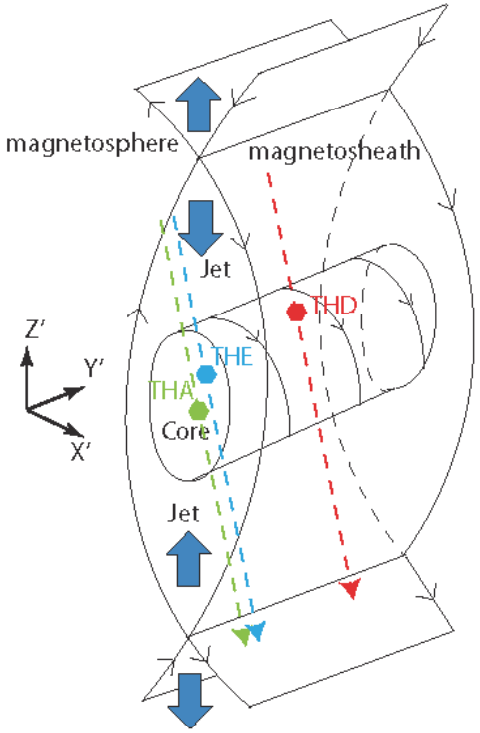


The super-thermal (1-4 keV) electron fluxes significantly enhanced in the core

$Te_{||}$ is enhanced in the outer region, but not in the core

Summary

Three THEMIS spacecraft observed the passage of a 3D flux rope flanked by two *active* X-lines



<u>3D effects:</u>

- Density depletion
- Electrons not trapped

<u>Particle heating and energization</u>

- $T_{i\perp}$ is enhanced inside the flux rope core
- $Te_{||}$ is enhanced in the outer region
- Super-thermal (1-4 keV) electrons likely energized somewhere along flux rope core

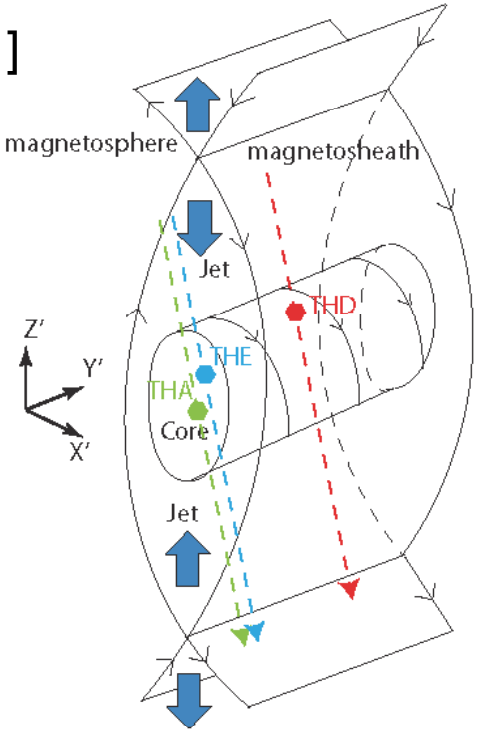
Open questions

Active versus non-active flux ropes:

Fact: The majority of flux ropes detected in space are not flanked by active X-lines [Zhang et al. 2011]

→ X-lines associated with flux ropes die quickly as they convect away

How does particle energization depend on the activeness of flux ropes?



2D versus 3D:

How does the fact that particles are not trapped affect the level of particle energization?

Øieroset et al. [*Phys. Rev. Lett.*, 2011]