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

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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

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

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: \textit{2D effect?}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig.png}
\caption{Omidi and Sibeck (2007)}
\end{figure}
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)
In 3D the islands become flux ropes and particles are no longer trapped.

Flux ropes are not uniform in the 3\textsuperscript{rd} 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: $Z_{\text{GSM}}$ separation

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

Coordinate System: GSE

THE

THD

THA

2010-04-10 00:00:00
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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   - Super-thermal electron energization
Electrons are not trapped in the flux rope → 3D effect

| |B| (nT) | B (nT) | V (km/s) | \(N_P\) (cm s\(^{-3}\)) |
|---|---|---|---|---|
| 180° Electrons (eV) | 10000 | 1000 | 100 | 10 |
| 90° Electrons (eV) | 10000 | 1000 | 100 | 10 |
| 0° Electrons (eV) | 10000 | 1000 | 100 | 10 |

Electrons are unbalanced → flux rope is open-ended

[Diagram showing magnetic field lines and electron distribution]
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   • Super-thermal electron energization
Super-thermal electron energization

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

$T_{e\parallel}$ 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

3D effects:
• Density depletion
• Electrons not trapped

Particle heating and energization
• $T_i\perp$ is enhanced inside the flux rope core
• $T_e\parallel$ 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?