Structure of magnetic reconnection jets at Earth’s dayside magnetopause: Geotail and MMS simultaneous observations

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MR2016 (The US-Japan workshop on magnetic reconnection) @Andaz Napa (Mar. 7-11, 2016)
Outline

We show coordinated Geotail and MMS observations of the Earth’s dayside magnetopause (MP) for southward IMF, when reconnection signatures were seen by both spacecraft.

- Both temporal & spatial properties of MP reconnection
- Geomagnetic dipole tilt (seasonal) effect on the location of MP reconnection
Southward IMF (Wind) & MP crossings (Geotail)

- Southward IMF
- $V_{sw} \sim 380$ km/s
- $M_A = 4-6$
- Multiple MP crossings@GTL
- Southward jets ($V_L \sim -300$ km/s)
- Shear $\beta \sim 1$
Both spacecraft cross MP nearly simultaneously (N, T, B_L jumps)

Both detect southward jets earthward of almost all MP crossings.

X-line was northward of GTL & MMS.

Jet duration is longer at MMS.
MP reconnection persisted for 5 hours

• $|V_L|$ increases with increasing $B_L$ for almost all MP crossings, consistent with observations reported by Phan+ (AG04).

• $V_A \sim 250$ km/s in the sheath.

$\uparrow$ Cluster observations of continuous MP reconnection (Phan+, AG04)
X-line extended over a distance of ~10 \( R_E \)

- Geotail moved from subsolar regions to \( y=+11 \) \( R_E \).
- The X-line extended over that distance (MLT \( \geq 4 \) hours).
Reconnection jet@MMS is broader along MP normal

- A larger number of high-density jet points for MMS than Geotail in MP & on the magnetospheric side.
- Jet expanded to M’sphere.

Paschmann+ (Nature79)
Flux transfer events@GTL, no or weaker FTEs@MMS

- FTE signatures: bipolar $B_N$, and increases in $|B|$ & total (magnetic+ion) pressure.
- FTE duration is short ($\leq 1$ min), so we call mesoscale FTEs.

\[
\nabla \cdot \left( \frac{\rho B j}{\mu_0} \right) = - \nabla P_T
\]

Magnetic tension = $P_T$ gradient force

$P_T$ maximum at the center
Models of FTE generation

(a) Transient & localized (3-D) reconnection (Russell-Elphic78)
(b) Transient (bursty) but 2-D reconnection (Extended X-line)
(b’) Time variation of continuous reconnection rate (Phan+, AG04)
(c) Multiple X-line reconnection: “flux rope” generation
At least one FTE is from multiple X-line reconnection

- Northward flow & $+B_M$ (Hall field expected northward of X), before the southward-moving FTE1.
- Another X-line existed southward of FTE1.
- Consistent with FTE formation by multiple X-line reconnection.

Bipolar, rather than quadrupolar, $B_M$ for reconnection with density jump (Nakamura & Scholer, JGR00; Pritchett, JGR08).
Decay of mesoscale FTEs, rather than 3D effects

• FTE axes are directed roughly in GSM-y, parallel to the X-line.
• If FTEs were 3D, MMS & Geotail would have detected an equal number of FTEs. But 9 large FTEs@GTL, only 1@MMS.
Possible decay processes of mesoscale FTEs

- Disentanglement of tangled FTE field lines via reconnection within FTE flux tube/rope.
- Merging with preexisting outflow jet.
- Cascading (breakup) into even smaller FTEs or flux ropes.

2D PIC simulation (Hesse+, PoP99)

3D global hybrid simulation (Tan+, JGR11)
Mesoscale FTEs may decay, but large-scale FTEs (with diameter ~1 $R_E$) are often seen at high latitudes

- The FTE amplitude is generally larger at higher latitudes (Wang+, JGR05).
- Does decay occur only during continuous reconnection, or on meso-scales?

2.5D global hybrid simulation
(Omidi & Sibeck, GRL07)

3D global MHD simulation (Dorelli & Bhattacharjee, JGR09)
Geotail-MMS conjunction on 2015-11-18

- Shift of the magnetopause reconnection line to the winter hemisphere for southward IMF [Kitamura et al. (2016) to be submitted to the GRL special issue on MMS].

![Spacecraft orbits 2015-11-18 0145-0315 UT](image1)

Dipole tilt: $-27^\circ$

MMS separation: $\sim$10 km

Solar wind

- WIND (Dawnside)
  - GSM Position (215, $-97$, 20) [$R_E$]
- ARTEMIS-B (Duskside)
  - GSM Position (17, 55, $-4$) [$R_E$]
**Data (MMS-3, ARTEMIS-B, Wind, Geotail)**

Magnetopause crossing (MMS)

Southward IMF with dawnward and sunward component (WIND, ARTEMIS)

Weak By just after the crossing? (MMS after ~0216 UT)

Bz became ~0 in the magnetosheath: ~0300 UT

GSM x y z Magnetopause crossing (MMS)

Southward IMF with dawnward and sunward component (WIND, ARTEMIS)

Weak By just after the crossing? (MMS after ~0216 UT)
Data (MMS-3, ARTEMIS-B, Wind, Geotail)

Magnetopause crossing (southward jets despite Geotail@GSM Z~1.4 R_E)

Almost purely southward IMF

By ~ 0 (MMS, WIND, ARTEMIS, Geotail after the crossing)
Estimation of the distance to the reconnection line using MMS data

$$R \sim \frac{B_N}{B_L} \sim \frac{D_N}{D_L}$$

R: Reconnection rate
B_L: L component of magnetic fields near the separatrix (ion edge)
B_N: N component of the magnetic fields in the exhaust
D_N \sim V_N * T
V_N: Velocity of the magnetopause along its normal
T: Time interval between the separatrix and current sheet center
D_L: Distance to the reconnection line from MMS

Similar to the method used by Lee+ [JGR14], we use minimum variance of current density (MVAJ) [Haaland+, GRL04], deHoffmann-Teller analysis, & minimum Faraday residue (MFR) [Khrabrov & Sonnerup, 1998] to estimate the velocity $V_N$ & the normal direction $N$ of the MP.
**MMS-1 magnetic field and ion moments in LMN for the MP crossing focused in this study**

\[(L, M, N) = (k_1J, k_2J, k_3J)\]

- **B_{Navg} interval:** 021205–021320 UT
- **B_{avg} interval:** 021205 UT ± 0.5 sec

The time period between the nearest point of the separatrix and the center of the current sheet: 021205–021250 UT (45 s)

**Burst Data**

We also use cutoff energies of energy-dispersed ions (velocity filter effect) to estimate the distance to X-line \(D_L\).
## Estimated location of the reconnection line (2015-11-18 event)

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Method &amp; Basics</th>
<th>$D_L$</th>
<th>GSM Z location of satellite</th>
<th>GSM Z location of X-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMS</td>
<td>MVAJ + HT analysis $D_L \sim</td>
<td>k3_j<em>VHT</em>T/(B_{Navg}/B_{Lavg})</td>
<td>$ &gt; 2.1 $R_E$</td>
<td>−0.33 $R_E$</td>
</tr>
<tr>
<td>MMS</td>
<td>Cutoff energy of energy-dispersed ions (velocity filter effect) $D_L \sim (tV_N/V_C) (V_1V_2/(V_2-V_1))$ 1.8–5.5 $R_E$</td>
<td>−0.33 $R_E$</td>
<td>1.5–5.2 $R_E$</td>
<td></td>
</tr>
<tr>
<td>MMS</td>
<td>MFR method $D_L \sim</td>
<td>V_N*T/(B_{Navg}/B_{Lavg})</td>
<td>$ &gt; 2.7–4.4 $R_E$</td>
<td>−0.33 $R_E$</td>
</tr>
<tr>
<td>Geotail</td>
<td>MFR method $D_L \sim</td>
<td>V_N*T/(B_{Navg}/B_{Lavg})</td>
<td>$ &gt; 0.6 $R_E$</td>
<td>+1.4 $R_E$</td>
</tr>
</tbody>
</table>

All results show that the dayside reconnection line was at GSM Z ~2 $R_E$ or further northward (in the winter hemisphere) when the geomagnetic dipole tilt was large (–27deg.)
Global simulations & statistical studies also show the X-line shift toward the winter hemisphere

Remote sensing of dayside X-line location based on cusp observations (Trattner+, JGR07)

Double Star TC1 observations (Trench+, JGR08)

Global MHD simulations (Russell+, GRL03; Park+, JGR06)
Chances of MMS encountering the diffusion regions are limited

MMS orbits and expected locations of MP crossings (Fuselier+, SSR14)

- **Phase 1a (Magnetopause reconnection 1)**
  (September 1, 2015–March 7, 2016)

- **Phase 1b (Magnetopause reconnection 2)**
  (September 26, 2016–January 31, 2017)

MMS may not observe the diffusion regions of most active subsolar reconnection under dominantly southward IMF.
Summary

Geotail-MMS conjunction on 2015-10-02:

• Evidence of continuous AND spatially-extended magnetic reconnection at the magnetopause (MP) under southward IMF conditions (temporal & y-extent).
• The outflow jet expands toward the magnetosphere with distance from the X-line (x-extent).
• Mesoscale flux transfer events (FTEs) decay in the course of poleward transport (evolution in z).

Geotail-MMS conjunction on 2015-11-18:

• The MP reconnection line shifts to the winter hemisphere for southward IMF (dipole tilt or seasonal effect).
• MMS, usually observing the MP in the summer hemisphere, has limited chances of encountering the diffusion regions.