Geotail data analysis
and related simulation results
on magnetic reconnection
in the magnetotail

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With contributions from
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This talk

- Where is the reconnection region located?
- What is going on at the reconnection region?
- What triggers the reconnection process?
- Future perspectives: The X-Scale mission
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Magnetotail Reconnection Event

Bz < 0

Geotail

1996 1 27

Bz (nT)

Vx (km/s)

V=3000 km/s

Outflow Ions

EQ off EQ boundary

X_GSM=-28.9  Y_GSM=5.8  Z_GSM=-2.6 RE

Discussion at the particle distribution function level

Nagai et al. (JGR 1998)
Nagai et al. (JGR 2001)

Electrons for Hall currents in the December 10, 1996, event

Hall Current density \( \cdots \cdots \cdot 6 \sim 13 \, \text{mA/m} \)

Electrons for Hall currents in the December 10, 1996, event

Discussion on the ion-scale dynamics

Nagai et al. (JGR 2001)
How to spot the X-line location:

When the spacecraft is close to the reconnection region...
1996/02/18 Reconnection Event

- Highly accelerated electrons
- Thermal electron energy spectra
- Fast tailward flows with $B_z < 0$
- Criterion: $f(5\text{keV})/f(1\text{keV}) > 1.5$
- Highly accelerated electrons
In 1995-1997

Solar Minimum
Low B and Low V

Solar Wind

IMF Bt

Velocity

Solar Maximum
High B and High V

In 1995-1997
Solar Minimum
in 1996-1998
19 events

Solar Maximum
in 1999-2003
15 events

\[ X_{\text{GSM}} = -25 \text{ to } -31 \text{ RE} \]

\[ X_{\text{GSM}} = -17 \text{ to } -31 \text{ RE} \]
Solar Wind Energy Input

(c) $-V_x \times B_s$

Near-Tail circles 1996-1998 events
black dots 1999-2003 events

Midtail

$X = -25 \text{ RE}$
Solar Wind Energy Input

(b) $-V_x \times B_s$

Near-tail Reconnection

$X_{GSM} = -15$ to $-25$ R_E Geotail

Midtail Reconnection

$X_{GSM} = -25$ to $-31$ R_E Geotail

hours

km/s nT

3000
2000
1000
1000
2000
3000
Solar Wind Energy Input

High Efficiency of Solar Wind Energy Input

Near-Tail

Low Efficiency of Solar Wind Energy Input

Midtail
Cluster sees tailward flows at $X=-19$ Re while AMPTE did not.
Solar Wind Energy Input

VELA
15R

IMP-6

ISEE-2
> 22R

ISEE-1
> 21 Re

IRM
> 18 Re

Geotail 1996-1998
> 25 Re

Geotail 1999-Cluster
15-30Re
Cluster tailward flow events give us the chance to study physics in the near-X-line region.
Another way of asking “where is the X-line?”

- In which part of the thinned current sheet?
Evolution of thin current sheets in the mid-tail region during the course of substorms

Implication:
X-line located at the tailward-edge of thinned section?

Thin CS prior to detection of earthward flow
Not necessary thin CS prior to detection of tailward flow
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Geotail@tail-reconnection
Flow reversal $-600\text{km/s} \rightarrow +300\text{km/s}$
In 12 sec. = 1 sampling time
Dynamic ion behavior visible in the distribution function data

Beam comp. Changing its direction

Two-component feature
Electron dynamics?

Electron heating, Intense wave power, Dynamic wave spectrum feature  
→ suggests  
dynamic electron behavior

Flow reversal

200 msec
Electron dynamics?

• But there is no way beyond because of the low-time resolution (12 s) of the electron detector.
Have to rely on the wave data for the moment:

Cluster has a better chance because of more chance of getting the wave form data at the right time.
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The classic candidate: Lower-Hybrid Wave (LHW)

• Anomalous resistivity at the neutral sheet? NO.
• Anything else? YES.
GEOTAIL Observation

Did we find LH wave?

YES – GEOTAIL frequently observes LH waves in the plasma sheet (even in high $\beta$ region)

NO – The observed wave power is insufficient for fast magnetic reconnection. (At least one order smaller)
Dec. 10, 1996  GEOTAIL/MGF-SC

LH wave
Identification of Instability Mode

• Comparison between Theory & Observation
  – Positive growth rate
  – Close to the local LH freq.
  – Calculated $c/B/|E|$ is consistent
  – Almost perpendicular propagation
Statistical Study on Wave (2-32 Hz) Energy Density in Plasma Sheet (1)

Plasma $\beta$ dependence

- Scatter plot of $E_f/(nT_i)$ vs. $\beta$
- Histogram of $\log_{10}\beta$
- Histogram of $E_f/(nT_i)$
An Example of Electron Distribution Function Associated with LH Wave

(a) Electron distribution function
Jan 15, 1994 1256:42-57:42 UT

(b) Electric field wave spectrum
Jan 15, 1994 1256:43-57:42 UT
Statistical Study on Wave (2-32 Hz) Energy Density in Plasma Sheet (2)

Electron heating – Temperature Ratio

![Graph showing electron heating and temperature ratio]

- $E_f / (nT_i)$ vs $T_i / T_e$
- Occurrence
  - $< 2$
  - $2 \sim 4$
  - $4 \sim 6$
  - $6 \sim 8$
  - $8 \sim 10$
  - $> 10$
Relation between intense LHW and the highly accelerated electrons most likely close to the X-line

Yet to be inspected.
Should be a good topic for Cluster as well.

Thanks to the Uppsala team for bringing this issue to my attention.
Intense LHW at the edge: A simulation study

• It may lead to quick triggering of reconnection even if the current sheet thickness is large (~ ion scale)
3D Simulation Setup

1D Harris current sheet

$\frac{m_i}{m_e} = 400, \frac{T_i}{T_e} = 8$

Thick current sheet at ion-scale

$\sim 10^9$ particles
QMRT

XSC=Cross-Scale Coupling

LHDI at the edges of thick current sheet
= reduction of current density locally at the edges
Meso-scale redistribution of current density
= bifurcated current layer
Anisotropic heating of electrons at the neutral sheet
= Quick growth of tearing mode

Explosive growth,
by copuling to the bi-furcated layer,
of large scale reconnection
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So, how do we want to understand the reconnection process?
Cross-Scale Coupling (XSC)

Slow in time

Large in space

The coupling is dynamic!
Unlikely to be described properly in terms of transport coefficient
XSC in reconnection

- Physics of the reconnection region (X-line):
  - Electron inertial effects
  - MHD-scale jets emanated from the X-line
  - MHD-scale jets sense the global boundary condition
  - X-line movement induced as jets sense the asymmetric global boundary condition

- Magnetic field lines
- X-line supported by electron dynamics
- Open boundary
- Closed boundary
- MHD scale jet
The magnetosphere is the field but our ultimate goal is understanding the Plasma Universe

- We are fascinated by *dynamic large scale* phenomena in the plasma Universe.
- The large scale dynamic phenomena have *key regions* that control the global dynamics.
- The key regions is quite often *small and embedded* in the global structure.
- The *key physics* in the key region is quite often at *micro-scale.*
The true understanding of the plasma Universe requires **multi-scale** to be observed simultaneously.
The shape of the mission resolving the Cross-Scale Coupling

• **In-situ observations** in the magnetosphere
• **High time resolution** to resolve the key micro-physics in the key regions
• **Formation flying observations** at more than one scales and that simultaneously

More sophisticated instruments, more and more spacecraft …. **Highly demanding!**
Mission looking into the cross-scale coupling processes as the natural next step: European and Japanese magnetospheric communities coming to similar mission ideas

- Europe M$^3$ based on Cluster-II experience
- Japan SCOPE
In planning phase at ISAS/JAXA
Launch ~2015

SCOPE

High-time resolution Electron measurements

The daughter s/c dedicated to wave-particle interaction issue

Electron scale

Ion scale dynamics monitors

Ion scale
Formation Flight Mission to Reveal Essential Structures of Space Plasma

**SCOPE**
Electron dynamics at the shock

5 s/c is a minimum set

Key regions not only in the magnetosospheric physics but also in the plasma Universe context
post-MMS
XSC explorer

More s/c surrounding the electron dynamics resolving core formation (like SCOPE) via ESA-ISAS collaboration should be the natural choice
One of the starting points of the discussion on ESA-ISAS collaboration

ESA-ISAS “CrossScale”

Ion-scale shell
\(\sim 1000 \text{ km}\)

MHD-scale monitors

SCOPE ele.-scale kernel
\(\sim 100 \text{ km}\)

More is different.
X-Scale: *LESS BULL, MORE MEAT.*

ESA-ISAS collaboration framework enables us to form a network and to work even harder to design the mission.

*The demanding mission in a smart way.*

The “CrossScale” mission is guaranteed to become an epoch making mission in the context of “the plasma Universe”. 