The diffusion region in collisionless magnetic reconnection:
New results from in-situ observations in the Earth's magnetotail

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30 July 2010
Gyrokinetics in laboratory and astrophysical plasmas
Isaac Newton Institute for Mathematical Sciences, Cambridge, 19 July – 13 August 2010
Introduction

• How to measure reconnection in space

• Average properties – anti-parallel reconnection

• Guide field reconnection

• Secondary islands in the diffusion region

• Waves in the diffusion region
Different laboratories for reconnection research

Near Earth space provides several natural laboratories for reconnection research.

In-situ observation enables highly quantitative comparison with theory.

- Solar wind reconnection: large-scale; quasi-steady
- Magnetopause reconnection: asymmetric; driven
- Near tail reconnection: explosive; particle acceleration
- Distant tail reconnection: properties largely unknown
Example of a modern space plasma physics mission

Cluster

European Space Agency / NASA
Four spacecraft
2.9m diameter, 1.3m height
1200kg (650kg fuel, 71kg instruments)
Spin rate: 15rpm
Telemetry: up to 262 kbit/s
Cost: $10^8 \text{\euro}$
Launched in 2000
10th Anniversary workshop this year.
## The Cluster mission

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<td>WHISPER</td>
<td>Resonance sounder</td>
<td>Total electron density 0.2 – 80 cm⁻³</td>
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<td>Search coil magnetometer &amp;</td>
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<td>WBD</td>
<td>Wide band receiver</td>
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<td>DWP</td>
<td>Digital wave processor</td>
<td>Coordinates WEC, performs particle</td>
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The Cluster orbit

Diagram showing the interaction between the solar wind, magnetosheath, magnetosphere, bow shock, and the positions of May, Feb, Aug, and Nov.
The Cluster separation strategy
The diffusion region in the Earth’s magnetotail

- Geotail
  - Hall currents and Hall fields along the separatrices [Fujimoto et al., 1997; Nagai et al., 2001; 2003; Asano et al., 2004]
  - Typical location of X-line [Nagai et al., 1998; 2005]

- Wind
  - Observation of diffusion region structure [Oieroset et al., 2001]

- Cluster
  - Considerably enhanced our understanding of the diffusion region – see review by Paschmann, Geophys. Res. Lett., 2008
  - Progress almost entirely via case studies

- THEMIS
Questions

• Does the existing set of published (Cluster) observations constitute the entire set of encounters?
  • Observing the diffusion region is a matter of chance

• If one observes macroscopic reconnection signatures, does that also correspond to the diffusion region?

• Do the reported diffusion regions constitute the average (selection effect)?

• What is the average experimental picture?
Cluster orbit: August – September tail season
Cluster magnetotail survey 2001 - 2005

• After 2005, the Cluster apogee was allowed to precess towards the south pole
  • crossed plasma sheet closer to Earth.
  • dwell time in the plasma sheet is reduced.

• Survey for the macroscopic signatures of reconnection
  • Identify plasma sheet intervals ($\beta > 1$)
  • Search for flows that reverse direction
  • Accompanied by reversals in Bz (avoid BBFs/flow vortices)

• 33 events
Summary

• General remarks
  • Observed numerous Earthward BBFs
  • Many more intervals of Earthward flow compared to tailward flow

• Of 33 events, 21 events amenable to multi-spacecraft analysis
  • Observe diverging jets \( v_x \)
  • Or reversal of \( B_z \) (qualitative timing)
  • Spacecraft can’t be too close or too far apart
  • Of these 21 events, 20 are X-lines; 1 is an O-line [Eastwood et al., 2005]
  • In the remainder of the events, we assume a single X-line

• Most X-lines are observed to move tailward

• Pairs of X-lines sometimes observed – Multiple X-line Reconnection
Cluster magnetotail survey 2001 - 2005

Then examine the electric and magnetic field for qualitative and quantitative consistency with Hall physics

Use 4 second resolution data

Electric field reconstructed assuming $\mathbf{E} \cdot \mathbf{B} = 0$

Examine correlation of different field components
Hall fields example

1 October 2001
- 0946 UT– 0951 UT
- Famous event

Qualitative behavior:

\( V_x - B_z \)
- correlated

\( E_z - B_x \)
- anti-correlated

\( B_y - B_x \) earthward flow
- correlated

\( B_y - B_x \) tailward flow
- anti-correlated

\( E_y \) positive
Summary of observations

33 field and flow reversals

18 qualitatively consistent with diffusion region

5 not enough data

5 normal electric field $\sim 0$, inconsistent hall magnetic field,

5 apparently consistent with guide field comparable to hall perturbation
All data

Anti parallel reconnection

In the GSM coordinate system the Hall field pattern emerges
Hall magnetic fields (anti-parallel)

Red = $B_x$ positive (above current sheet)

Black = $B_x$ negative (below current sheet)

Solid = average value

Open = peak value

Average and peak out of plane magnetic field for earthward flow (Red: $B_x > 0$, Black: $B_x < 0$)

Average and peak out of plane magnetic field for tailward flow (Red: $B_x > 0$, Black: $B_x < 0$)

Event Number
Hall electric fields (anti-parallel)

Red = Bx positive
(above current sheet)

Black = Bx negative
(below current sheet)

Solid = average value

Open = peak value

Average and peak normal electric field (Red: B_X > 0, Black: B_X < 0)

Average and peak Hall electric field (Red: B_X > 0, Black: B_X < 0)

Average and peak out of plane Electric Field
Normalized observations (anti-parallel)

Normalized observations (anti-parallel)

\( B \) normalized to inflow magnetic field strength

\[
b = \frac{B}{B_{\text{inflow}}}
\]

\( E \) normalized to inflow field and alfven speed based on current sheet density and inflow field

\[
e = \frac{E}{(B_{\text{inflow}} \times V_A(n_{cs}, B_{\text{inflow}}))}
\]

Peak Hall fields:

- \( b = 0.39 \pm 0.16 \)
- \( e = 0.33 \pm 0.18 \)

Avg reconnection \( E \) field

- \( e_{\text{recon}} = 0.04 \)

Normalized peak Hall electric and magnetic field amplitudes and average \( E_y \)

(A) \( B_{\text{Hall}} = 0.391 \pm 0.158 \)

(B) \( E_{\text{Hall}} = 0.333 \pm 0.184 \)

(C) \( E_y = 0.040 \)
A comparison with simulation

PIC code P3D (Shay et al., PRL 2007)

A small part of the simulation, centered on one of the X-lines at a time when reconnection has established is shown

Normalized in the same way as the data

(Location of cut is not of specific importance)
Guide field?

- (Most) reconnection is not anti-parallel
- Simulations suggest guide field distorts structure of diffusion region
- 1 October 2001 9:35 – 9:43
  - Not the Runov et al. event
- Cluster at [-16.1 7.9 1.1] Re
- Data rotated into current sheet coordinate system (close to GSM)
- Guide field is ~ 20% of reconnecting field
  - Shear = 159°
- Examine interval of tailward flow
  - Cluster 1 above current sheet
  - Cluster 3 below current sheet
Hall fields

- Hall fields – difference is real spatial structure
- Normalized $b_M = B_M/B_{L,max}$, $e_N = E_N/(B_{L,max} V_{out})$
- Anticorrelation of $b_M$ and $e_N$ with $b_L$ is expected
- Magnetic perturbation is not symmetric about $b_M = -0.2$
Particle in cell simulation

- PIC simulation with code P3D (Mike Shay)
- Guide field = 0.2
- Cuts taken through outflow in same geometry as Cluster measurements
- Reversal in $B_M$ relative to the guide field does not occur at the center of the current sheet (reversal in $B_L$)
Comparison with simulations

- Good agreement between simulations and data
- Fairly insensitive to the location of the cut downstream

Tailward Flow, $|B_L| < 50$ nT, $v_L < -50$ km s$^{-1}$
The diffusion region during guide field reconnection

- Guide field alters the pattern of the Hall currents by enabling the reconnection electric field to induce electron motion and currents along the magnetic field.
- Displaces electron outflow in N direction due to $j_{\text{Hall}} \times B_g$ forces.
- Asymmetry in N direction, not in L direction.
- Even a small guide field can significantly alter the structure of the diffusion region.
Example of a secondary island in the ion diffusion region

Cluster 2001-08-22

“Secondary island
Plasmoid
Flux rope
O-line
Nightside FTE”
**Secondary island**

**Secondary Island**
- Only seen by Cluster 3 (green)
- Bipolar $B_z$
- Core $B_y$

**Traveling Compression Region**
- seen by e.g. Cluster 4 (magenta)

**Vertical radius = 1300 km**
- A few $c/\omega_{pi}$

**Ion flow speed is 500 kms$^{-1}$**
- But we are in ion diffusion region
**Secondary Island – Internal Electric Field**

**Magnetic Field:**
- Core $B_y \sim 32$ nT
- External $B_y \sim 10$ nT
- Lobe guide field $\sim 0$

**There is no guide field**
Large core B field, but negligible lobe guide field, unexplained by conventional theory

**Electric Field**
- Core $E_z \sim 150$ mVm$^{-1}$
- Peak to Peak $E_x \sim 100$ mVm$^{-1}$

$V_x \sim 3000$ kms$^{-1}$

**Island length**
- $10 - 20$ c$/\omega_{pi}$
Cluster - magnetotail

9 October 2003

300 km scale tetrahedron

Data shown in current sheet co-ordinate system

\[
\begin{align*}
L & = ( 0.895, -0.441, 0.068) \\
M & = ( 0.445, 0.892, -0.072) \\
N & = (-0.029, 0.094, 0.994)
\end{align*}
\]
Data indicate Cluster crossed a tailward jet from north to south.

\( B_L (B_x) \) reverses
\( B_N (B_z) \) negative
\( V_L (V_x) \) negative

Therefore, if this is an encounter with the diffusion region we can test for the predicted Hall fields.
Hall field signatures

Hall magnetic field
- Red = $B_M$ negative
- Black = $B_M$ positive

Hall electric field
- Points into current sheet on both sides
- Larger than reconnection electric field ($E_M$)

Hall fields fill jet
- Outer Electron Diffusion Region

Minimal guide field
Power spectra calculated using the Thomson multi-taper method.
Wave propagation direction

In what direction are the waves propagating?

- k-filtering [e.g. Pincon & Motschmann 1998]
- phase information from four spacecraft gives directional information at different frequencies
- Has been applied to observations of solar wind turbulence (Narita, Sarahoui …)

Regular tetrahedron required
**K-filtering**

A(r, t) is what a spacecraft measures

\[ A(r, t) = \text{Re}\left[ \sum_\omega \sum_k A(\omega, k) e^{i(k \cdot r - \omega t)} \right]. \]

P(w,t) is what we want to know

\[ P(\omega, k) = \langle A(\omega, k)A^\dagger(\omega, k) \rangle, \]

Fourier transform data from N spacecraft

\[ A(\omega) = \begin{pmatrix} A(\omega, r_1) \\ A(\omega, r_2) \\ \vdots \\ A(\omega, r_N) \end{pmatrix}. \]

Define M

\[ M(\omega) = \langle A(\omega)A^\dagger(\omega) \rangle. \]

Define the locations of the N spacecraft

\[ H(k) = \begin{pmatrix} I_L e^{i k \cdot r_1} \\ I_L e^{i k \cdot r_2} \\ \vdots \\ I_L e^{i k \cdot r_N} \end{pmatrix}, \]

‘It can be shown that’ an estimate of P is:

\[ P(\omega, k) = \text{Tr}\left\{ (H^\dagger(k)M^{-1}(\omega)H(k))^{-1} \right\}. \]
K-filtering

- Decomposes the total measured spatial correlation matrix $M(w)$ into a sum of correlation matrices corresponding to plane wave modes
- $M(w)$ is a $NL \times NL$ matrix, and can be decomposed into $NL$ linearly independent correlation matrices, one is incoherent noise, so theoretically the technique can identify $NL - 1$ modes
- Aliasing – a spacecraft pair with separation $r$ cannot distinguish between $k$ and $k + \Delta k$ where $\Delta k \cdot r = 2\pi n$
  - Can’t look at waves smaller than the spacecraft tetrahedron size
- We used k-filtering to look at the waves; only works where the power in the E and B fields diverge. Propagation is along the outflow direction, which is approximately parallel to B.
k-filtering results (f = 0.281 Hz; cuts in k_z)
Assume \( k \) vector along outflow, parallel to \( B \). Then:

\[
k_x = \frac{\omega_{sc}}{v_{ph}} = 2\pi f_{sc} \times \frac{\delta B_z(f)}{\delta E_y(f)}
\]

Transform to plasma frame

Compare to hot two fluid dispersion relations [Formisano and Kennel, J. Plasma Phys. 3, 55 (1969)]

Appears to be consistent with whistler/ fast mode waves
Applying an analysis similar to that of Ji et al. [PRL, 2004], to the magnetic fluctuations, we find that the associated electric field is $\sim 0.3\ \text{mVm}^{-1}$.

Lower hybrid waves in the $3 – 8\ \text{Hz}$ frequency range

- $f_{LH} = 4\ \text{Hz}$ for $B = 6\ \text{nT}$
- $f_{LH} = 6.5\ \text{Hz}$ for $B = 10\ \text{nT}$

Whistler waves can scatter off plasma density variations and convert into LH waves [e.g. Bell & Ngo, JGR, 1990]

LH wave fluctuations correspond to a reconnection electric field of $\sim 0.01\ \text{mVm}^{-1}$

Modification of the overall reconnection rate is negligible.
- Identified 18 anti-parallel diffusion regions in 5 years of Cluster observations
  - GSM works remarkably well for the average picture
- Average quantities: Hall magnetic field 0.39 +/- 0.16 Hall electric field 0.33 +/- 0.18

- Even a small guide field can significantly change the structure of the diffusion region
- The magnetopause will allow studies examining role of density asymmetry etc to be performed, but such studies are complex.

- Secondary islands are observed – formed on/near the separatrix?
- Have strong internal electric field

- Turbulent cascades in electric and magnetic fields inferred from power law scaling
- Wave dispersion seems to be consistent with fast mode/whistler waves; LH also observed
- Associated anomalous resistivity was not found to significantly modify the reconnection rate