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The diffusion region in collisionless magnetic reconnection:

New results from in-situ observations in the Earth's magnetotail

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

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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

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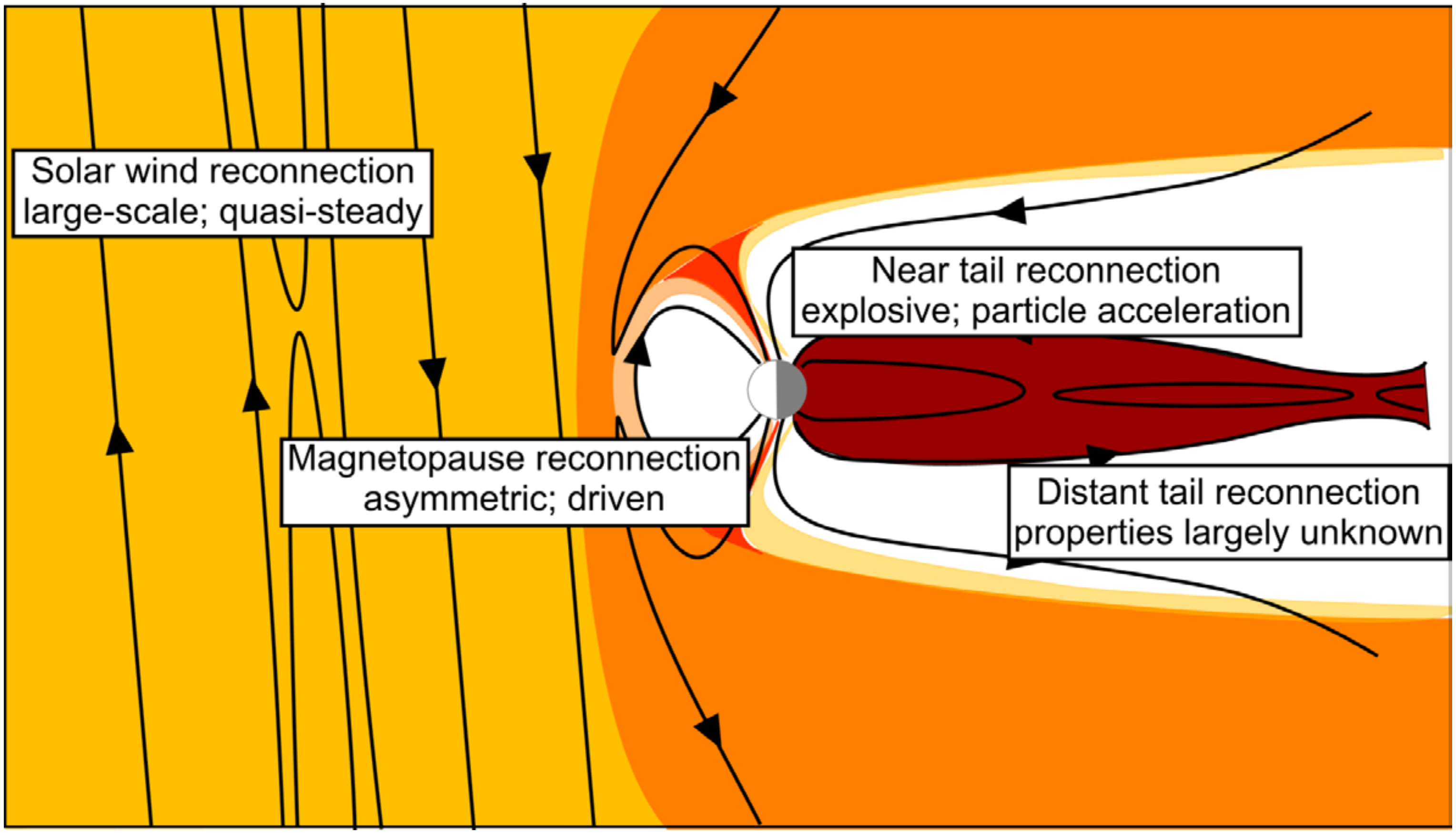
Different laboratories for reconnection research



Near Earth space provides several natural laboratories for reconnection research

In-situ observation enables highly quantitative comparison with theory

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)

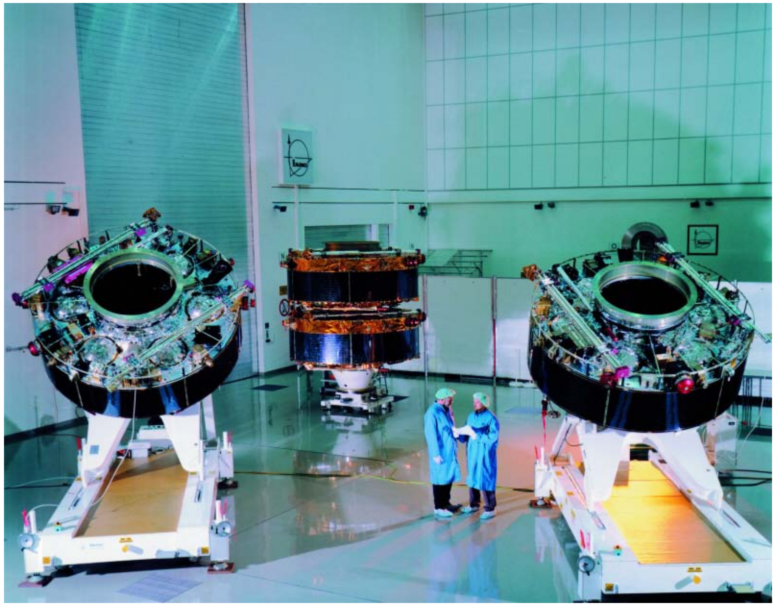
Spin rate: 15rpm

Telemetry: up to 262 kbit/s

Cost: ~ 10^8 €

Launched in 2000

10th Anniversary workshop this year.



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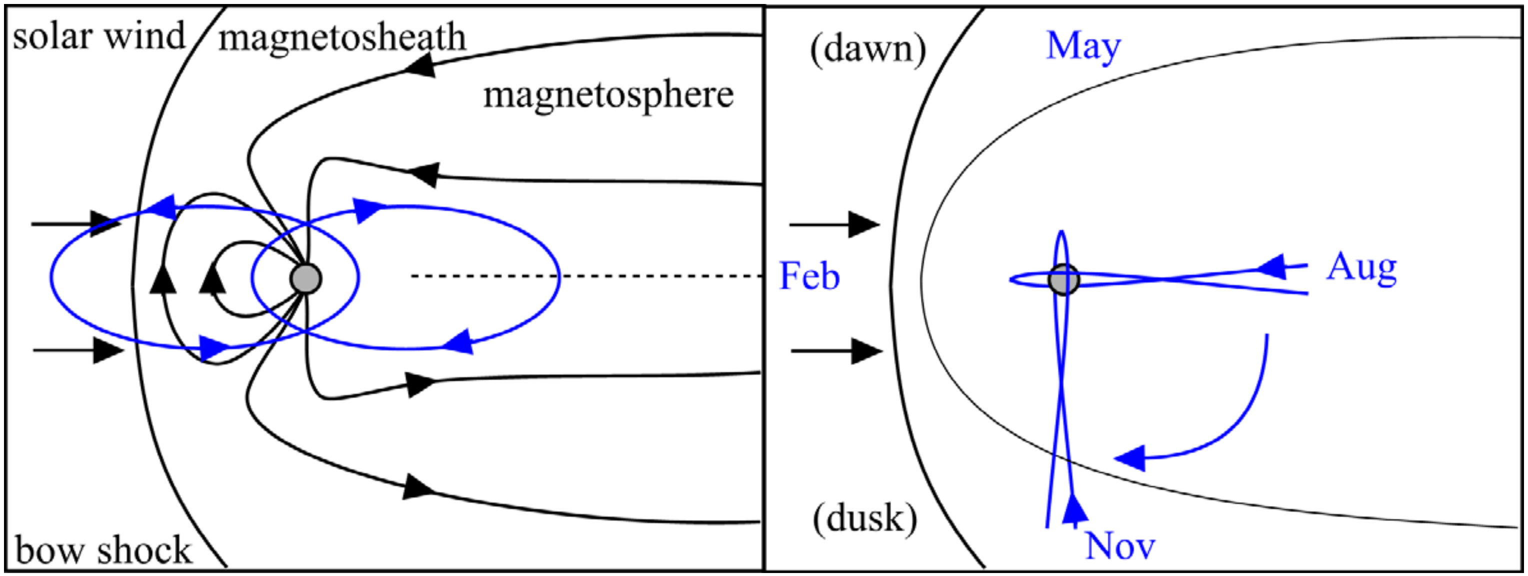
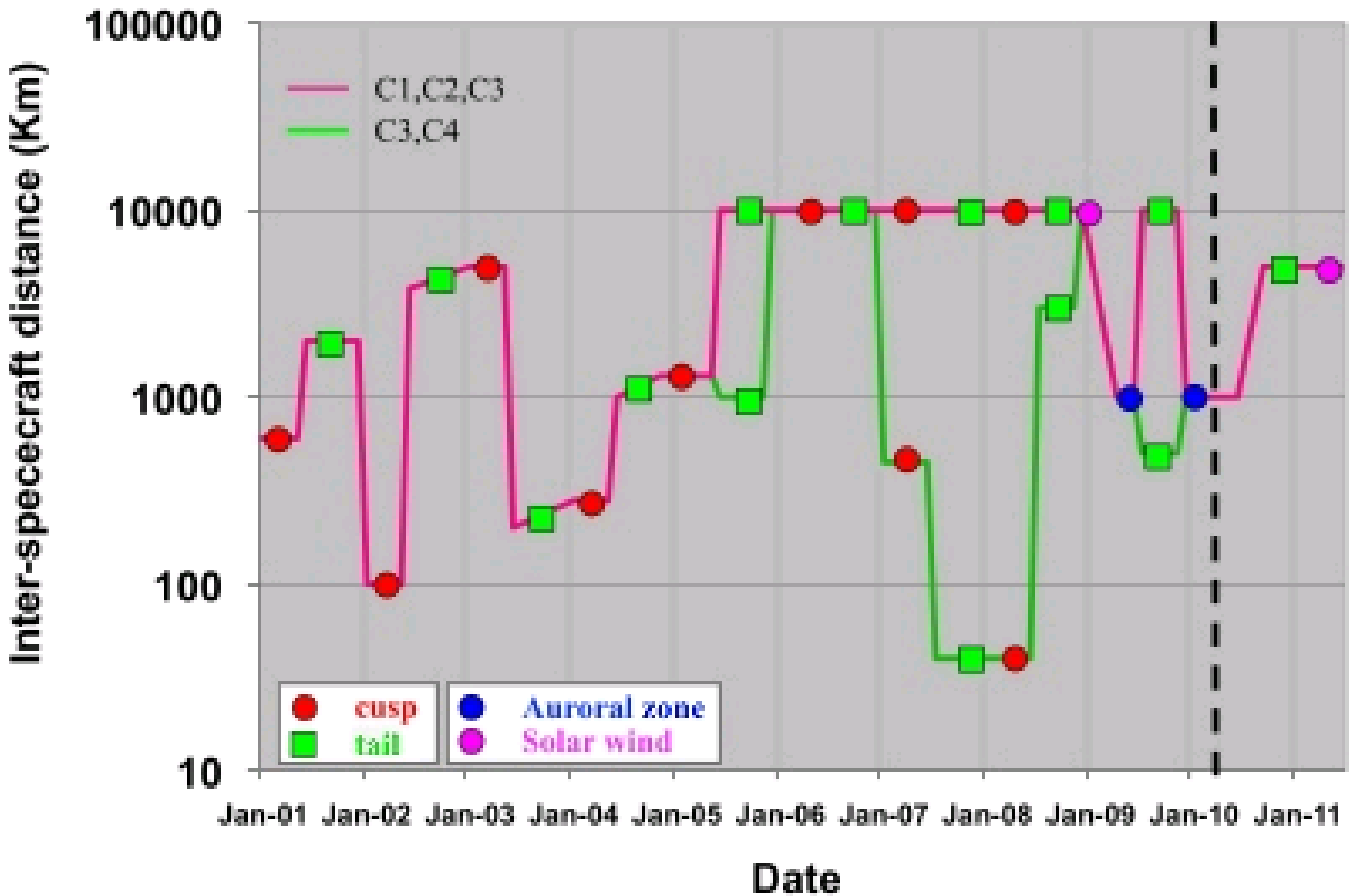
The Cluster mission

Instrument	Description	Notes
FGM	*Fluxgate magnetometer*	DC magnetic field
CIS	*Ion spectrometer*	HIA and CODIF sensors
PEACE	*Electron spectrometer*	3d electron distribution 0.7 - 30 keV
RAPID	*Energetic particle detector*	Solid state detector Ions: 30-1500 keV/q. Electrons: 20-450keV
ASPOC	*Spacecraft potential control*	Indium ion emission; potential control
EDI	*Electric field experiment*	Electron gun design
EFW	*Electric field experiment*	Wire boom spherical sensor (sc potential)
WHISPER	*Resonance sounder*	Total electron density 0.2 – 80 cm^{-3} Passive wave survey 2-80 kHz
STAFF	*Search coil magnetometer & spectrum analyzer*	ac fields 4 kHz electromagnetic field fluctuations
WBD	*Wide band receiver*	High resolution continuous wave forms 25 Hz – 577 kHz
DWP	*Digital wave processor*	Coordinates WEC, performs particle correlations

The Cluster orbit



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

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Questions

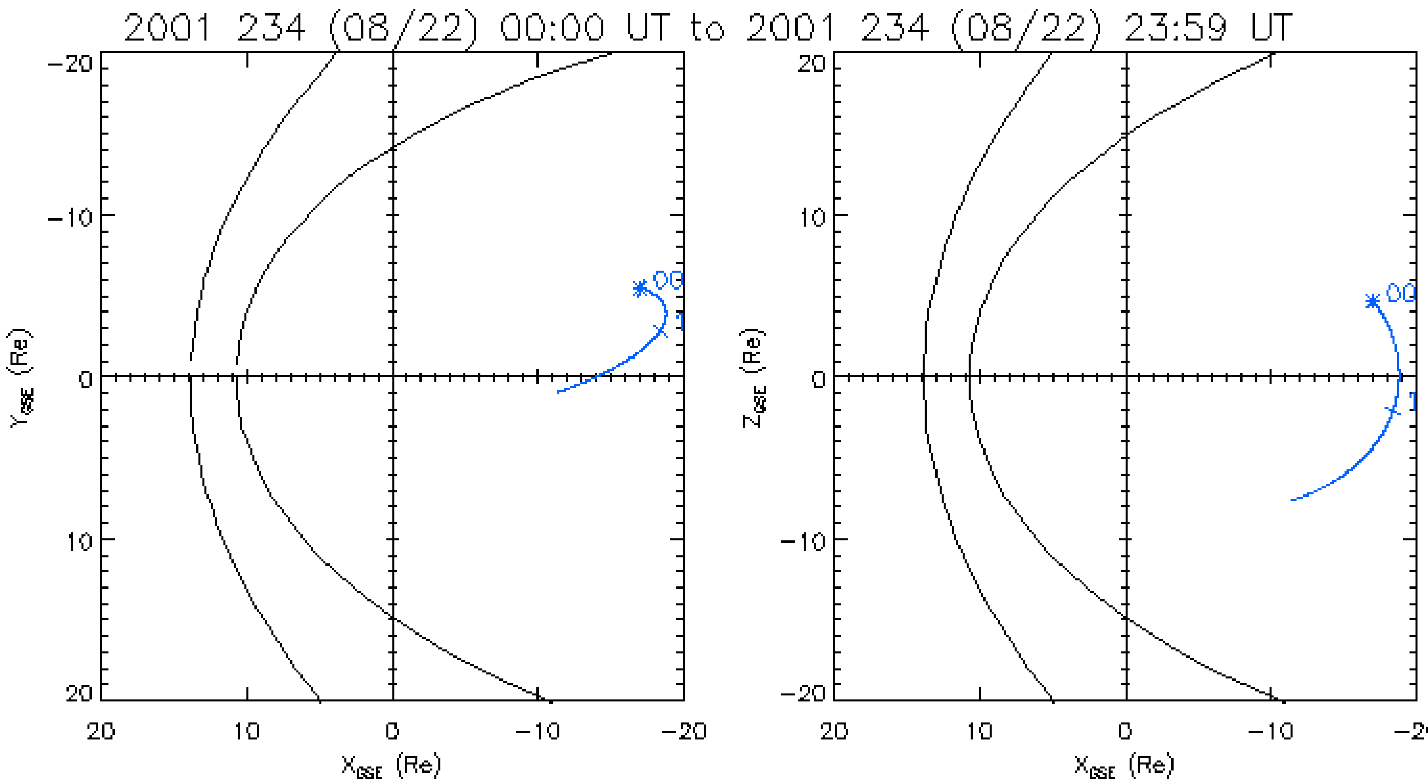
- Does the existing set of published (Cluster) observations constitute the entire set of encounters?
  - Observing the diffusion region is a matter of chance

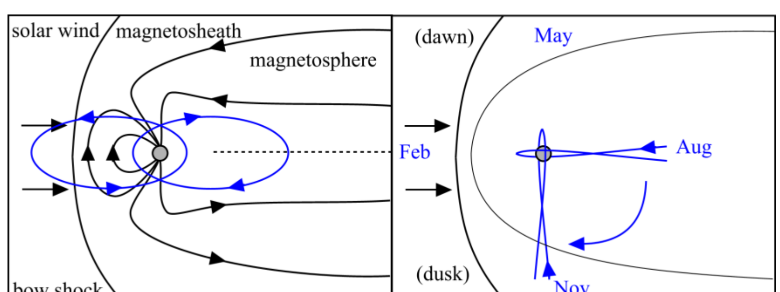
- If one observes macroscopic reconnection signatures, does that also correspond to the diffusion region?

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

- What is the average experimental picture?

Cluster orbit: August – September tail season





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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

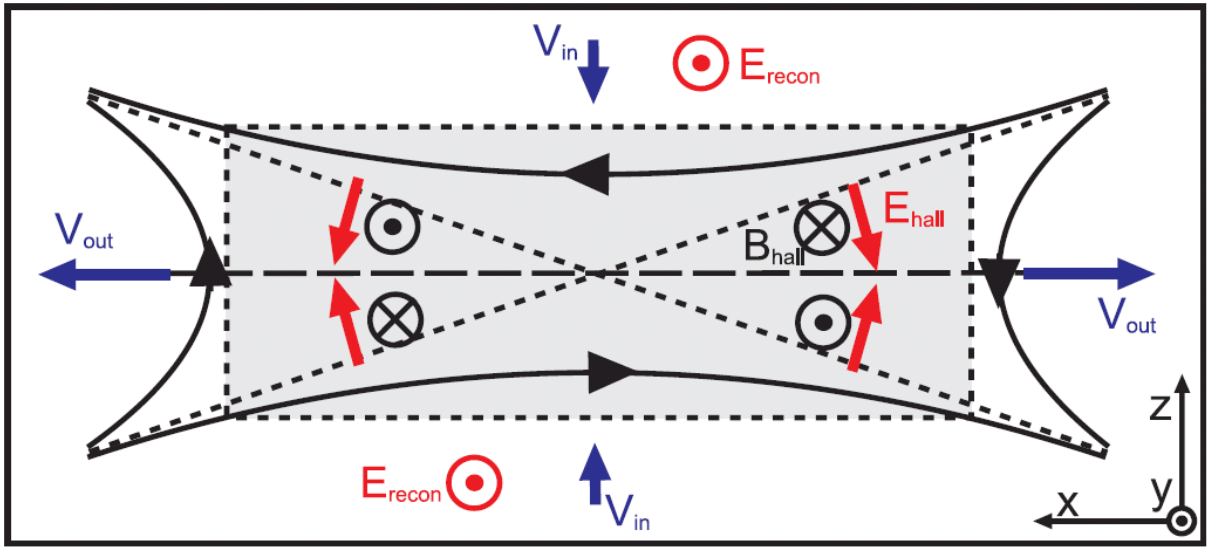
Cluster magnetotail survey 2001 - 2005

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

Use 4 second resolution data

Electric field reconstructed assuming **E·B** = 0

Examine correlation of different field components



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Hall fields example

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

Qualitative behavior:

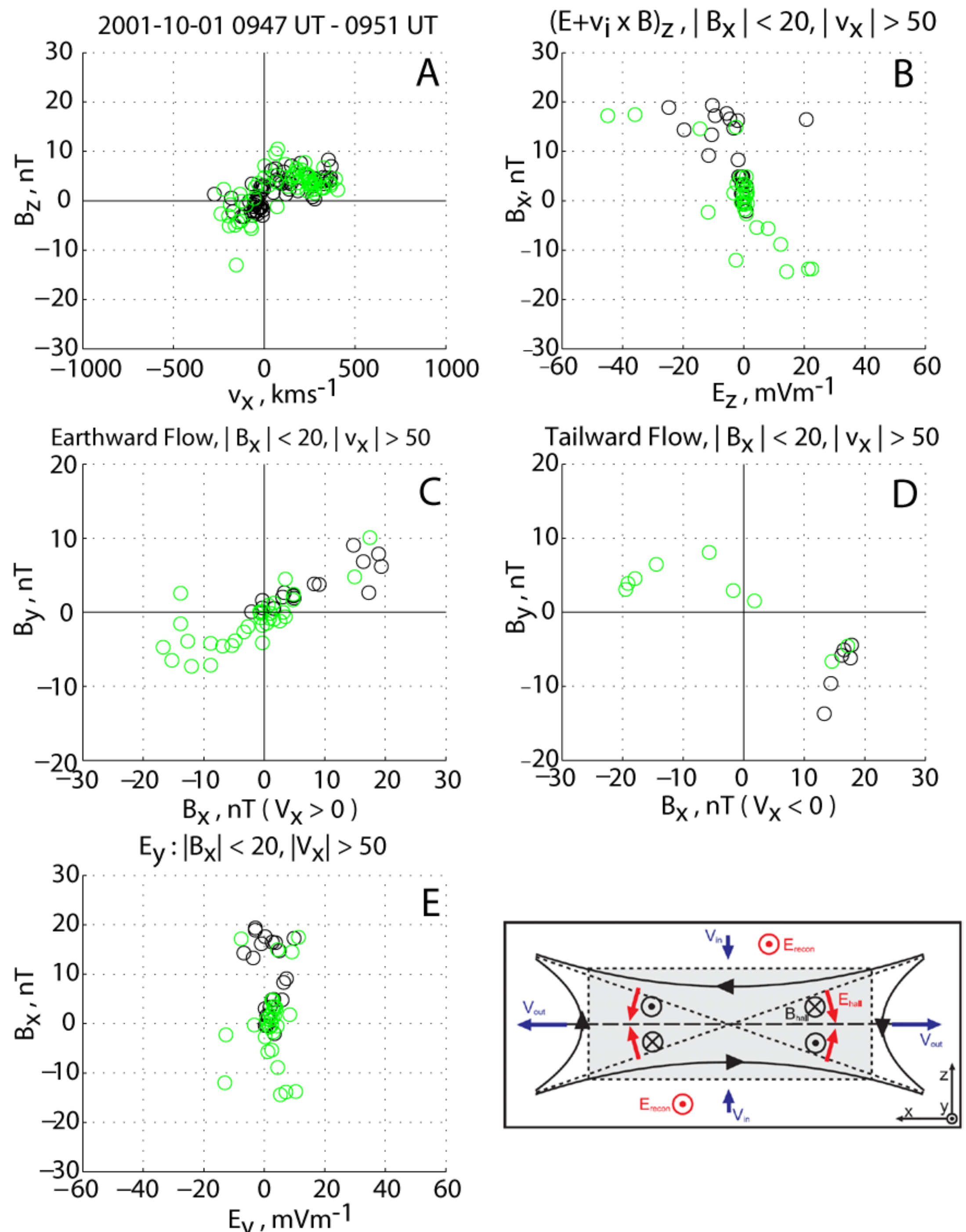
V_x – B_z
- correlated

E_z – B_x
- anti-correlated

B_y – B_x earthward flow
- correlated

B_y – B_x tailward flow
- anti-correlated

E_y positive



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Summary of observations

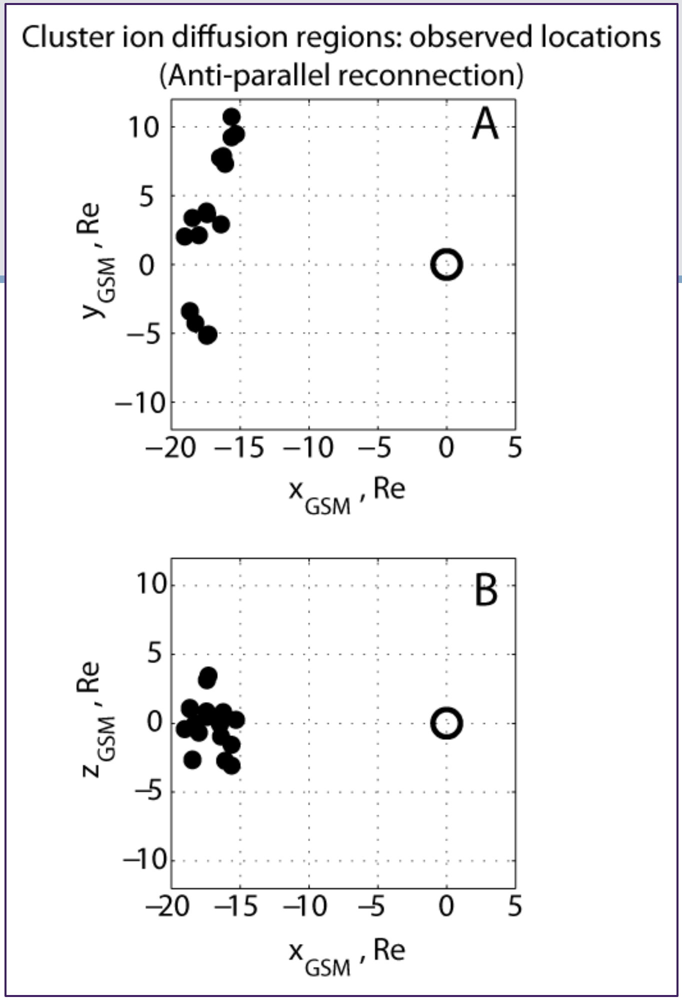
33 field and flow reversals

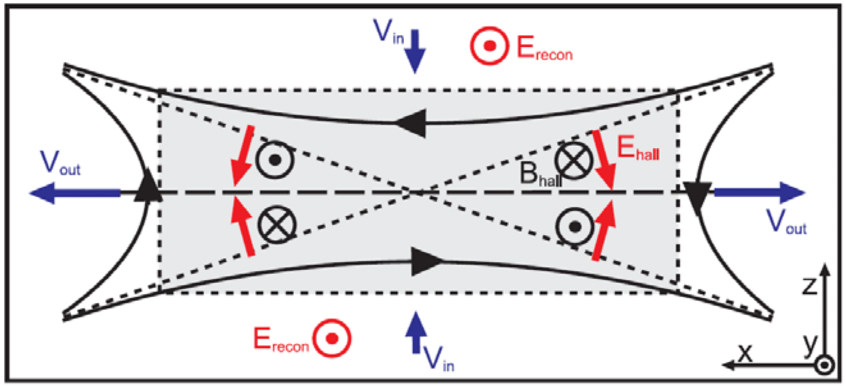
18 qualitatively consistent with diffusion region

5 not enough data

5 normal electric field ~ 0, inconsistent hall magnetic field,

5 apparently consistent with guide field comparable to hall perturbation





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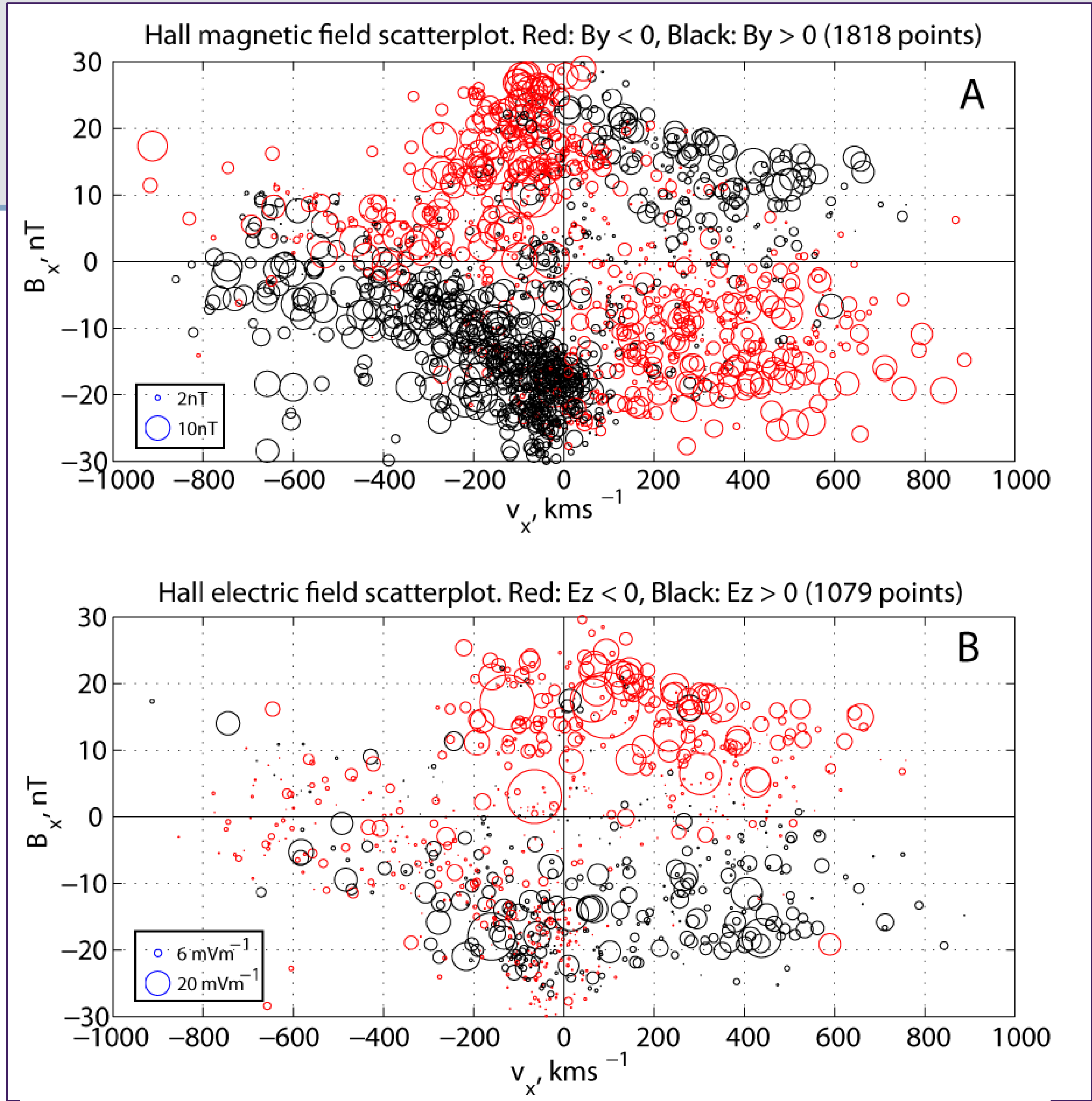
All data

Anti parallel reconnection

In the GSM coordinate system the Hall field pattern emerges



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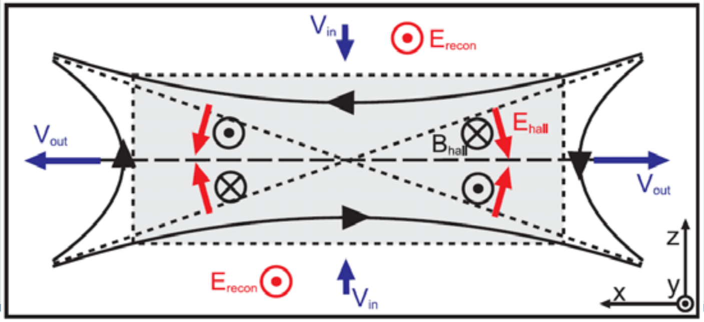
Hall magnetic fields (anti-parallel)

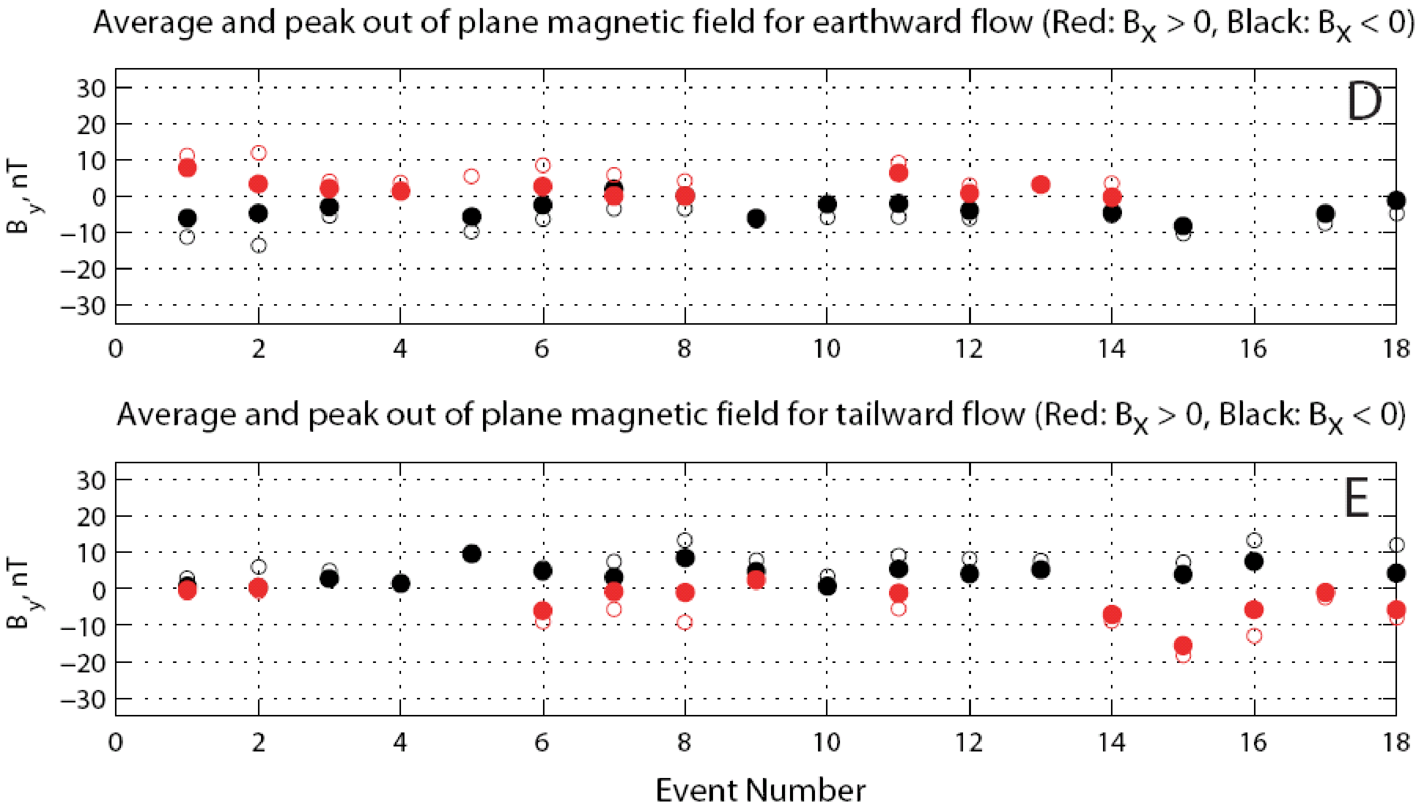


Red = Bx positive (above current sheet)

Black = Bx negative (below current sheet)

Solid = average value

Open = peak value



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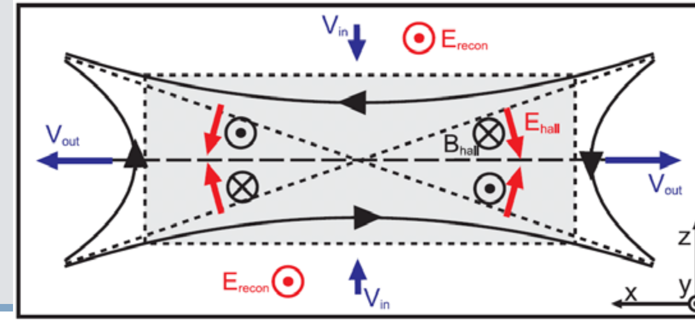
Hall electric fields (anti-parallel)



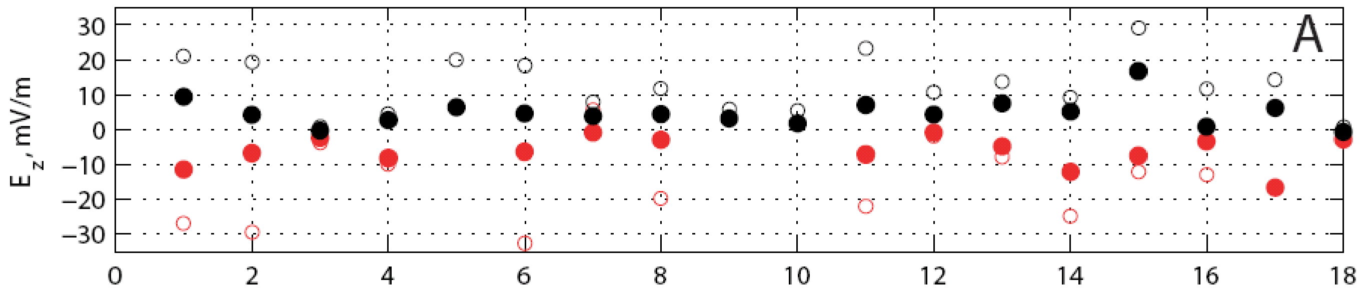
Red = Bx positive (above current sheet)

Black = Bx negative (below current sheet)

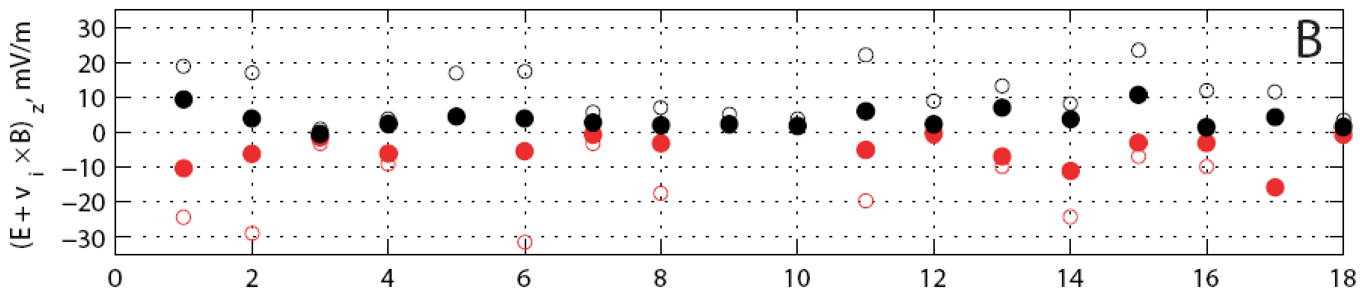
Solid = average value

Open = peak value

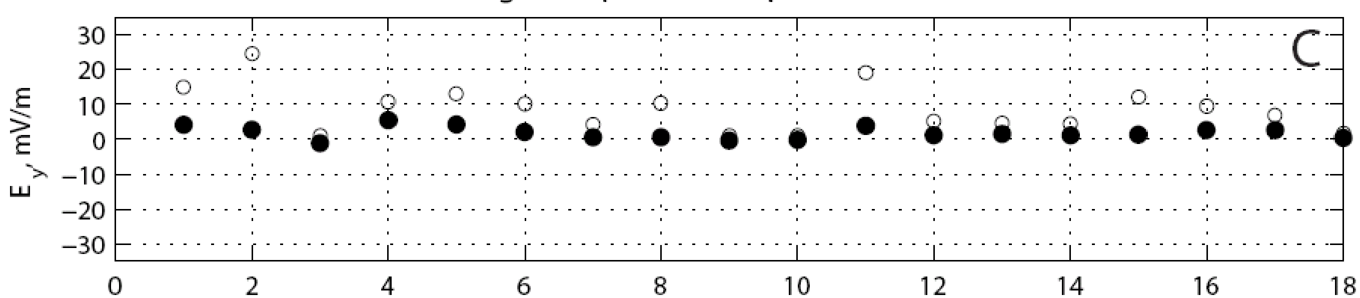
Average and peak normal electric field (Red: $B_X > 0$, Black: $B_X < 0$)



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)

B normalized to inflow magnetic field strength

$b = B/B_{inflow}$

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

$e = E/(B_{inflow} \times V_A(n_{cs}, B_{inflow}))$

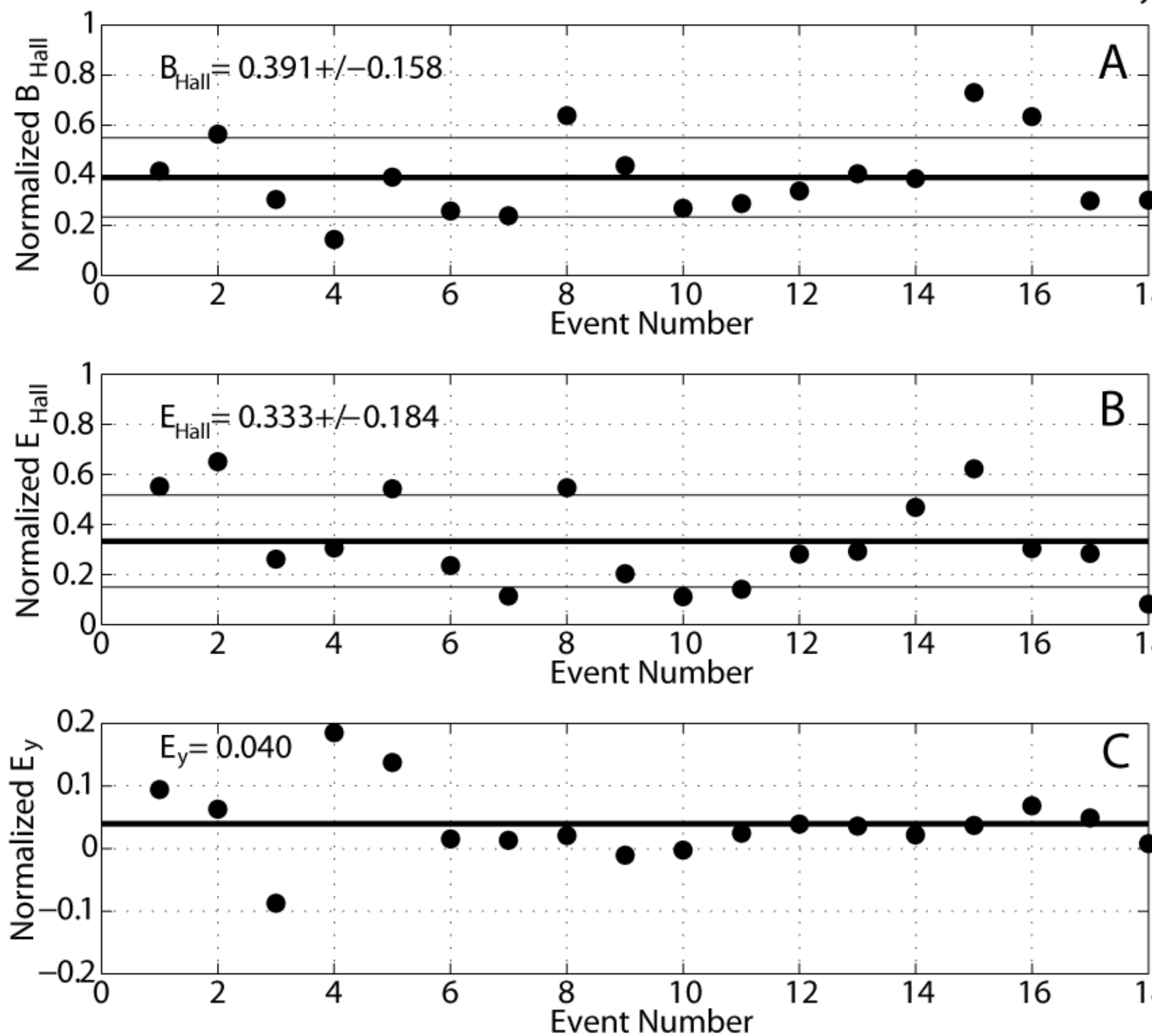
Peak Hall fields:

- $b = 0.39 \pm 0.16$
- $e = 0.33 \pm 0.18$

Avg reconnection E field

- $e_{recon} = 0.04$

Normalized peak Hall electric and magnetic field amplitudes and average E_y



A comparison with simulation

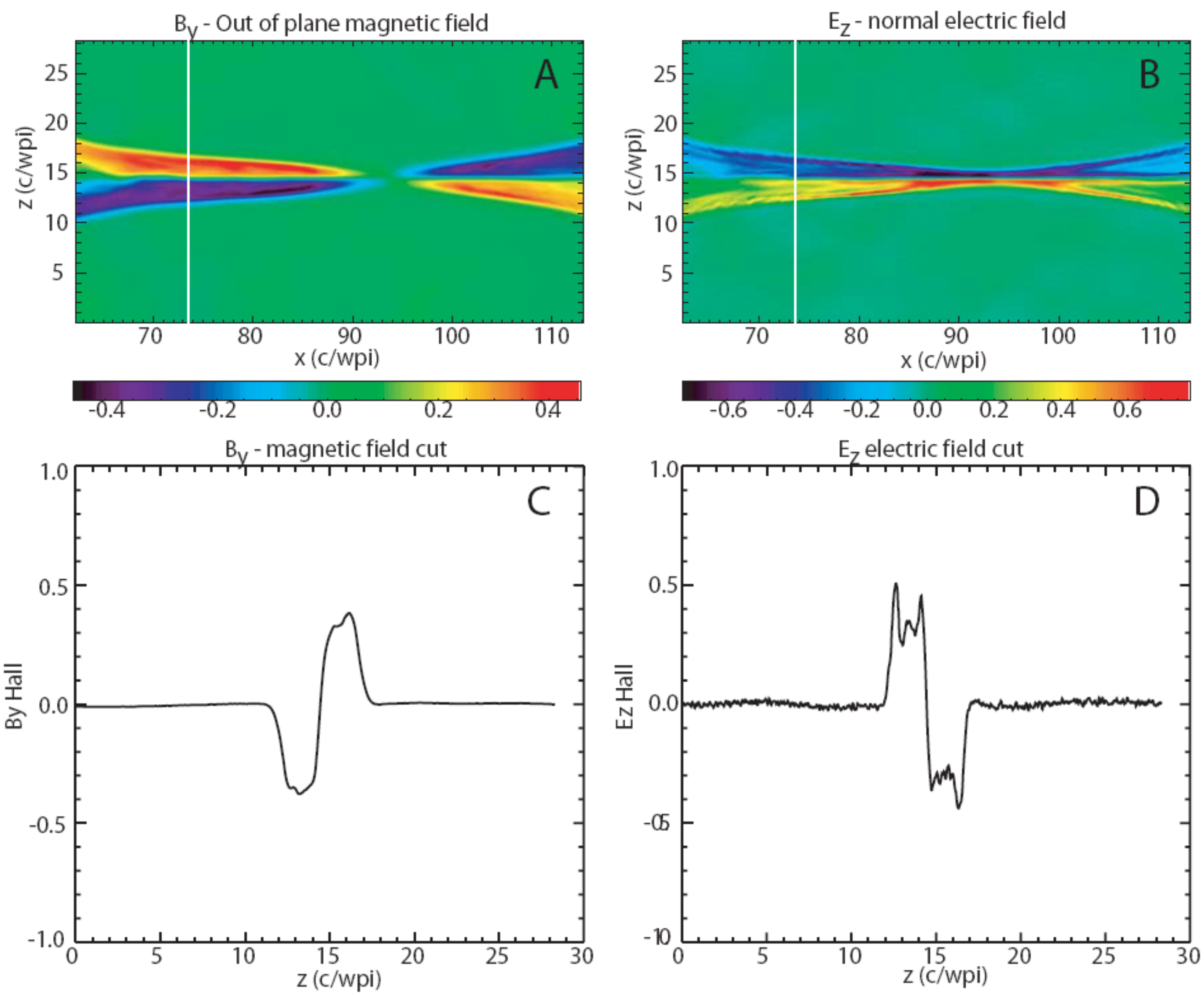
PIC code P3D

(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)



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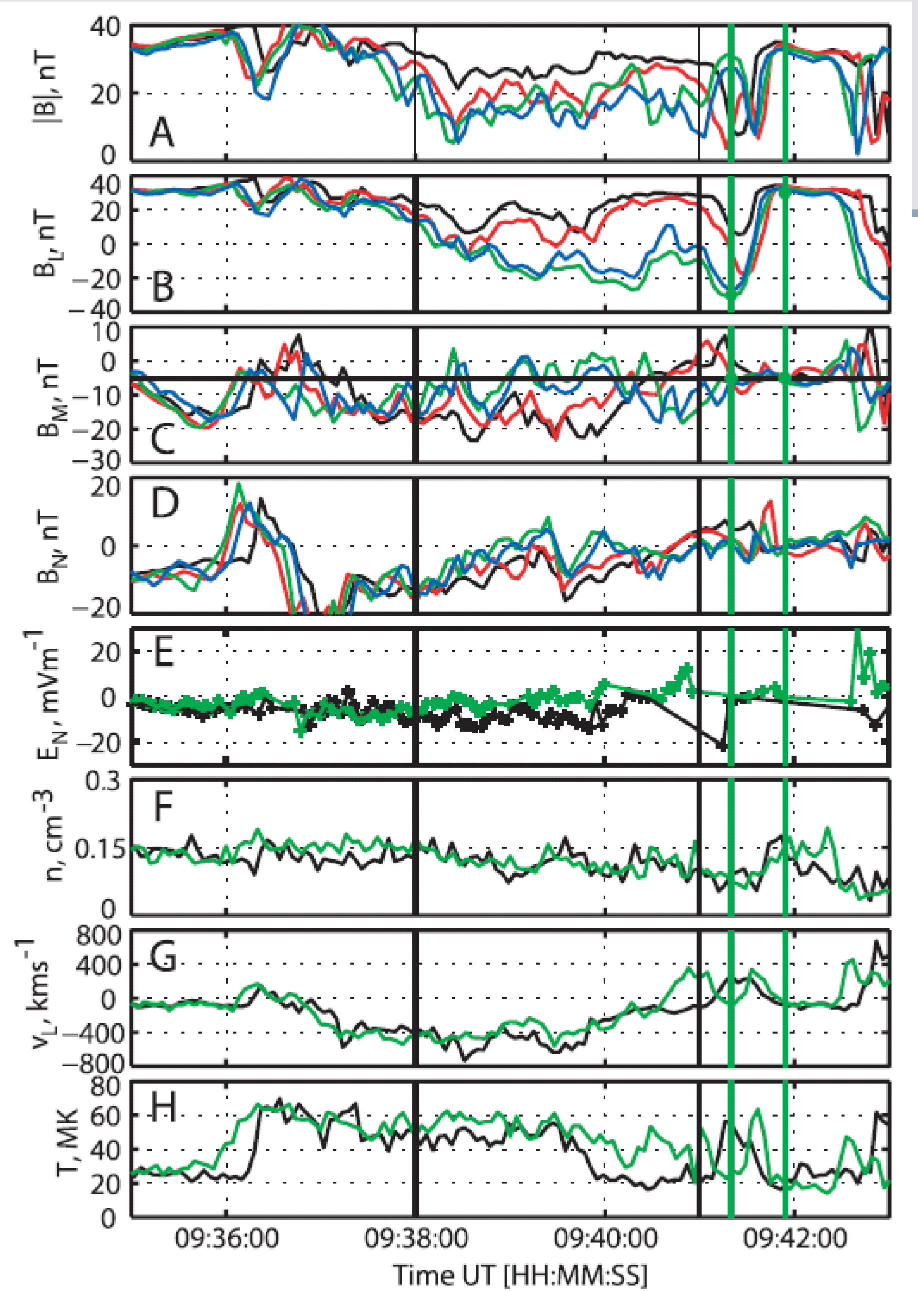
Guide field?

- (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



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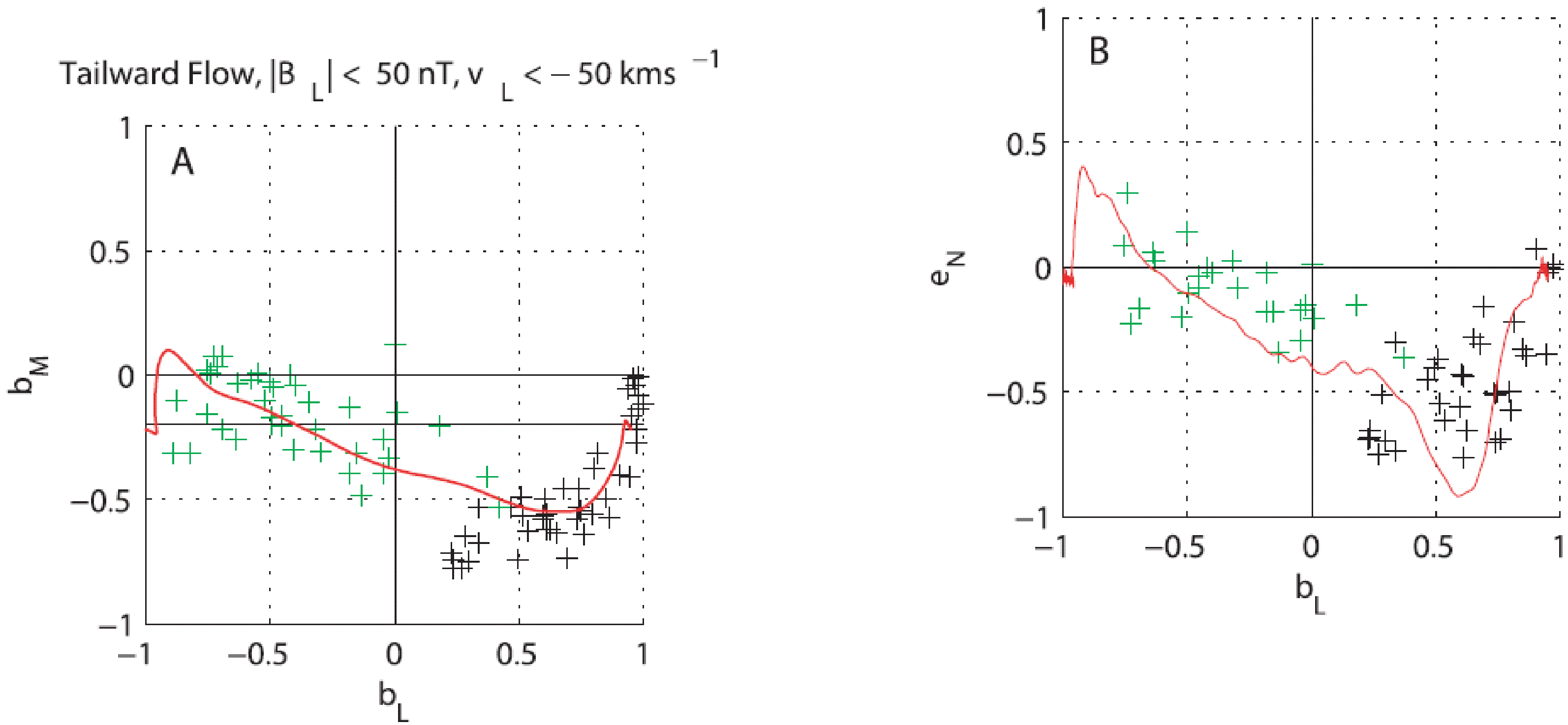
Hall fields



- 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

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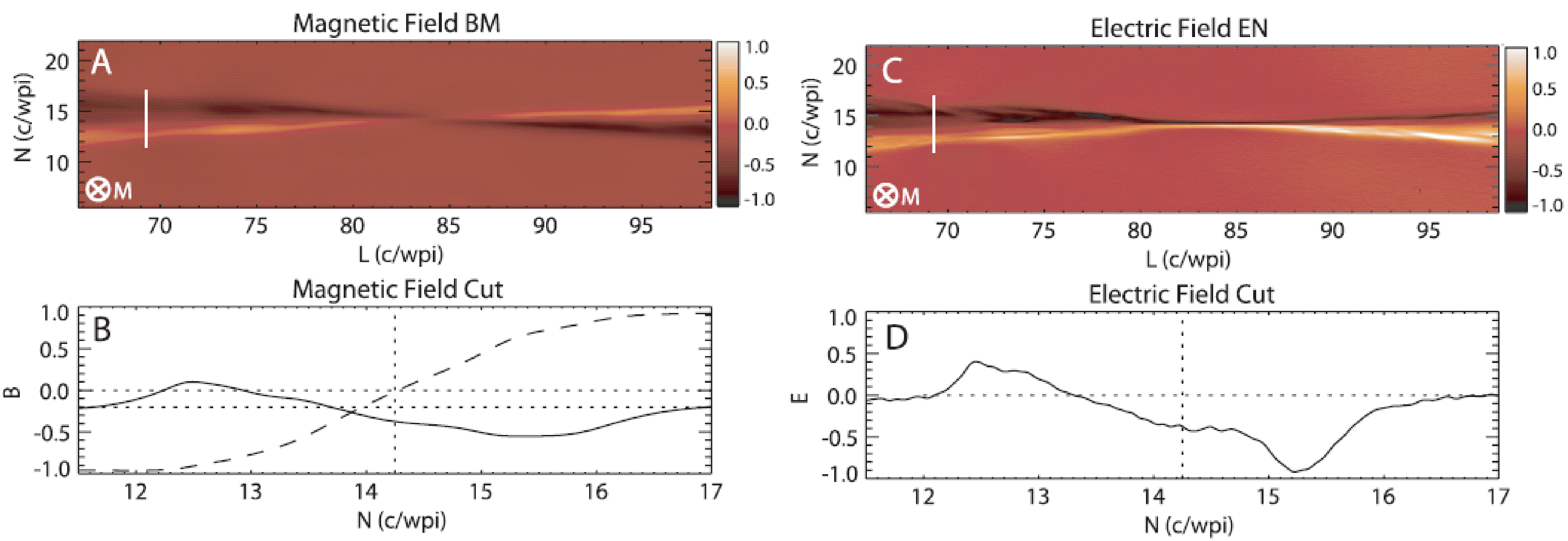
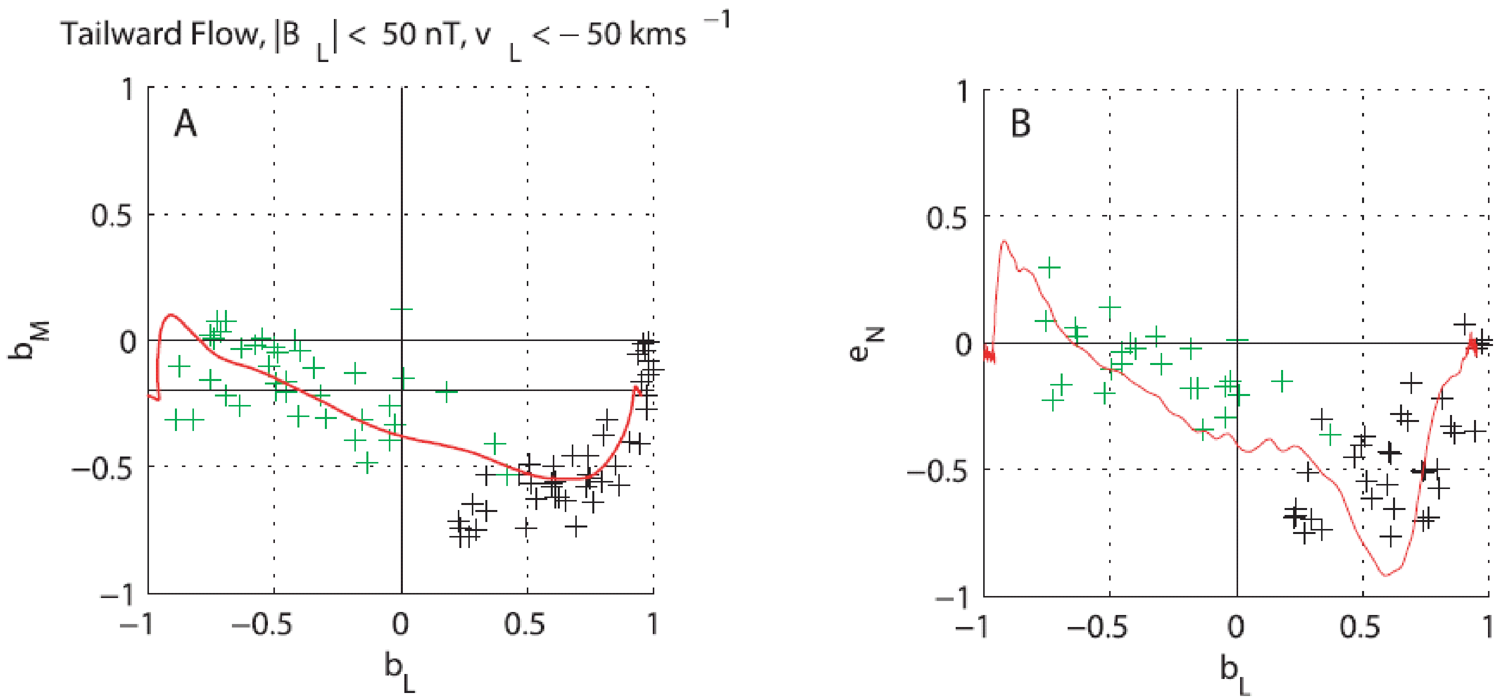
Particle in cell simulation



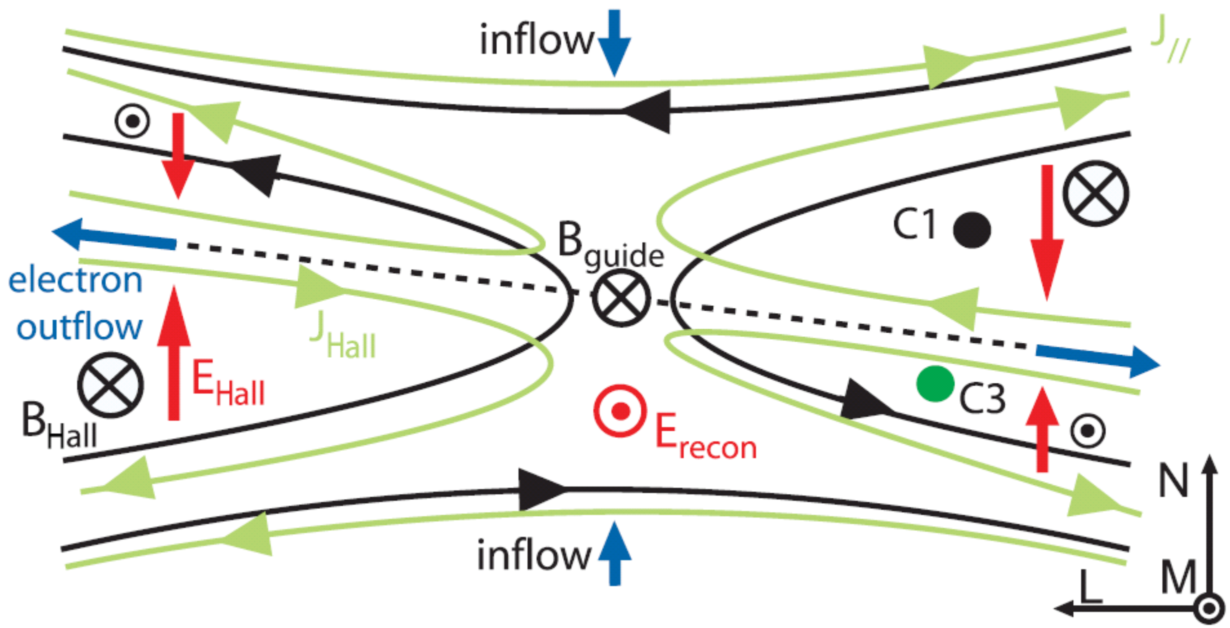
- PIC simulation with code P3D (Mike Shay)
- Guide field = 0.2
- Cuts taken through outflow in same geometry as Cluster measurements
- Reversal in B_M relative to the guide field does not occur at the center of the current sheet (reversal in B_L)

Comparison with simulations



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

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 $\mathbf{j}_{Hall}$ x $\mathbf{B}_g$ forces
- Asymmetry in N direction, not in L direction
- Even a small guide field can significantly alter the structure of the diffusion region

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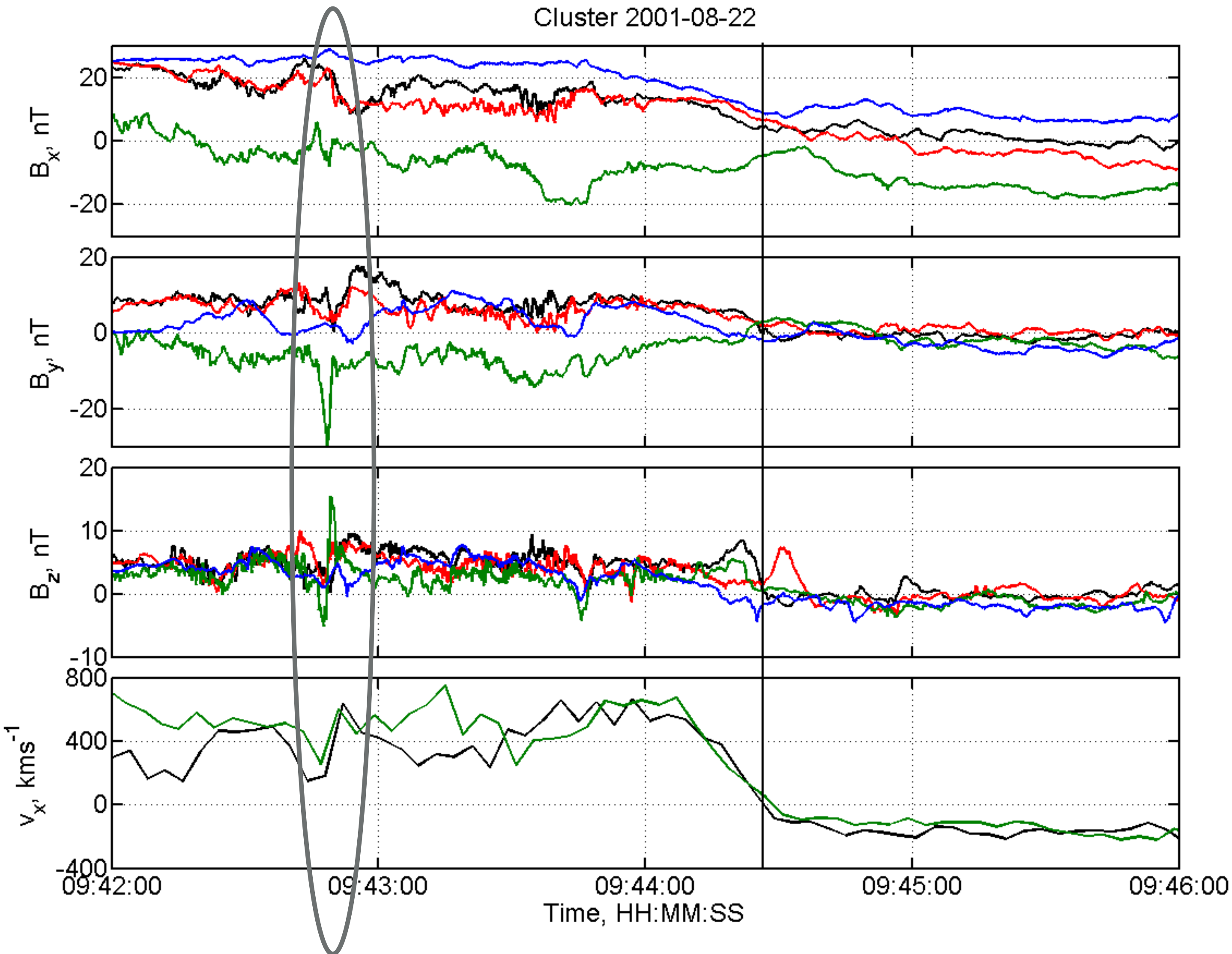
Example of a secondary island in the ion diffusion region



"Secondary island
Plasmoid
Flux rope
O-line
Nightside FTE"

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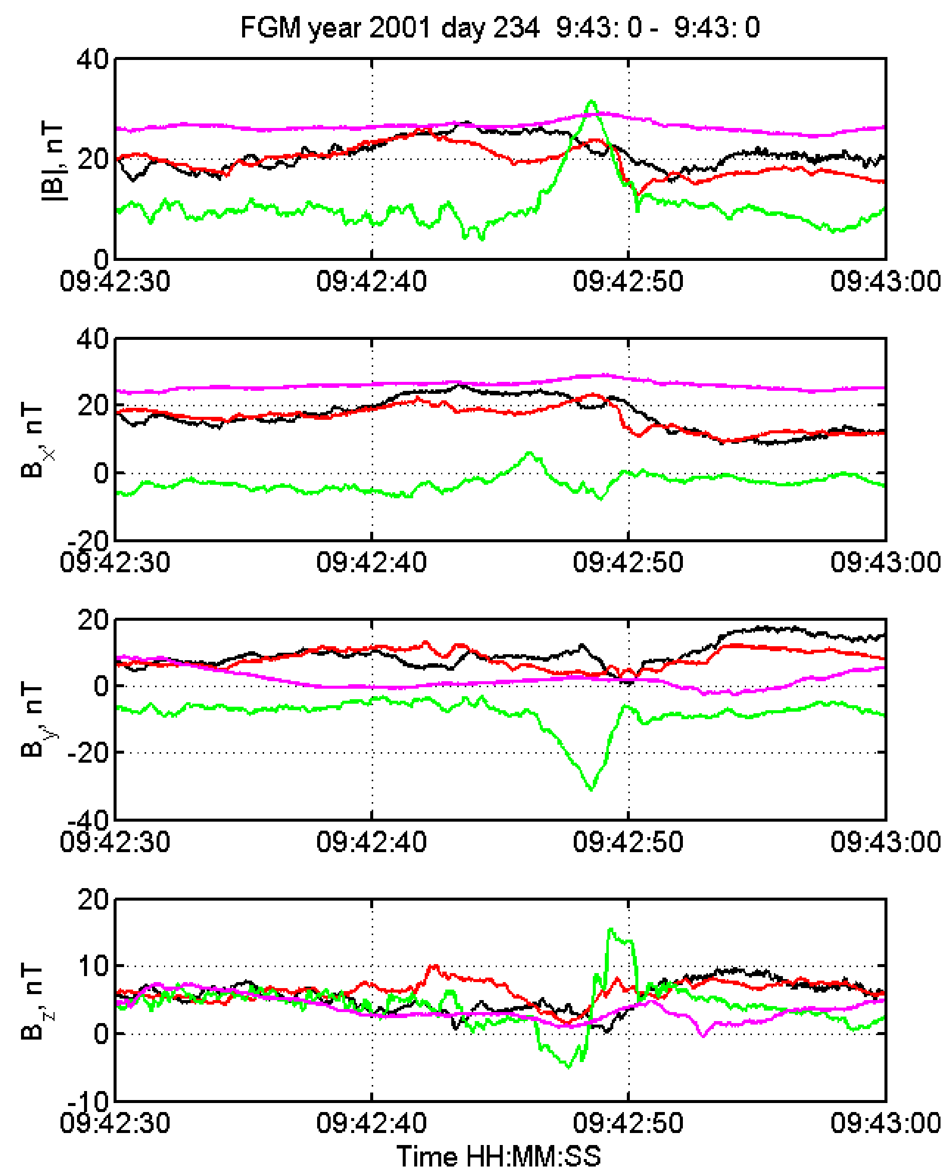
Secondary island



Secondary Island

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

Traveling Compression Region

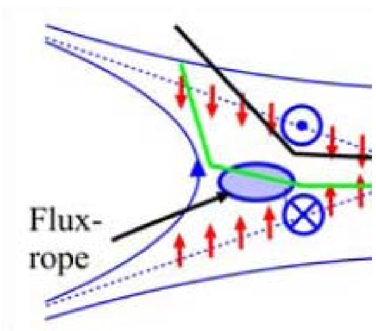
- seen by e.g. Cluster 4 (magenta)

Vertical radius = 1300 km

- A few c/ω_{pi}

Ion flow speed is 500 kms^{-1}

- But we are in ion diffusion region



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Secondary Island – Internal Electric Field

Magnetic Field:

- Core B_y ~ 32 nT
- External B_y ~ 10 nT
- Lobe guide field ~ 0

There is no guide field

Large core B field, but negligible lobe guide field, unexplained by conventional theory

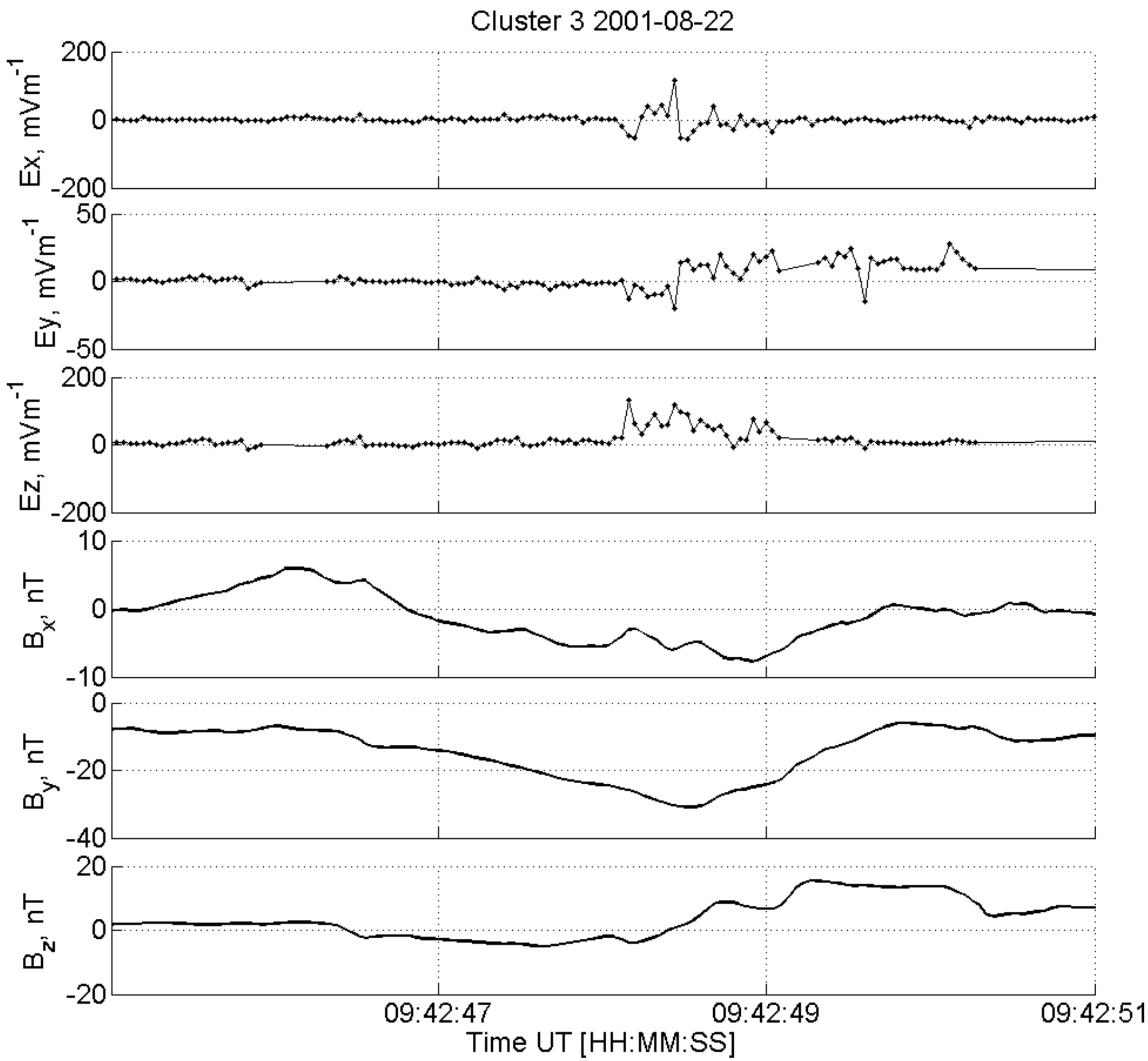
Electric Field

- Core E_z ~ 150 mVm^{-1}
- Peak to Peak E_x ~ 100 mVm^{-1}

V_x ~ 3000 kms^{-1}

Island length

- 10 – 20 c/ω_{pi}



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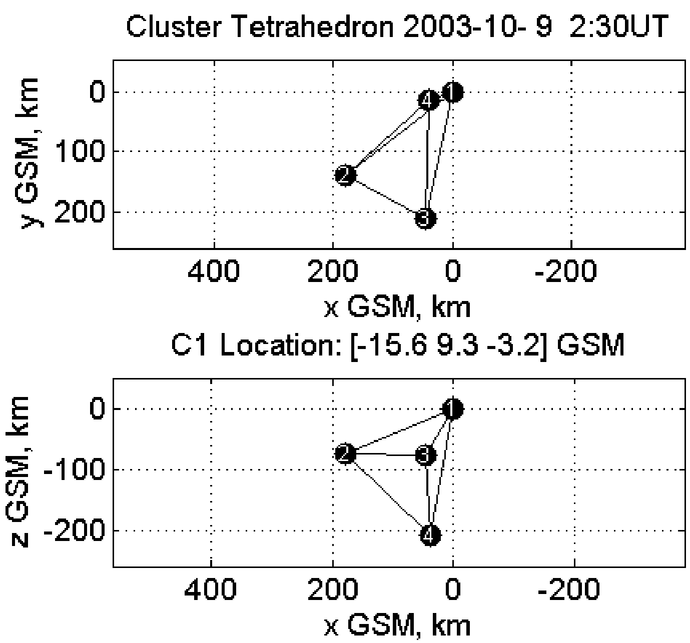
Cluster - magnetotail

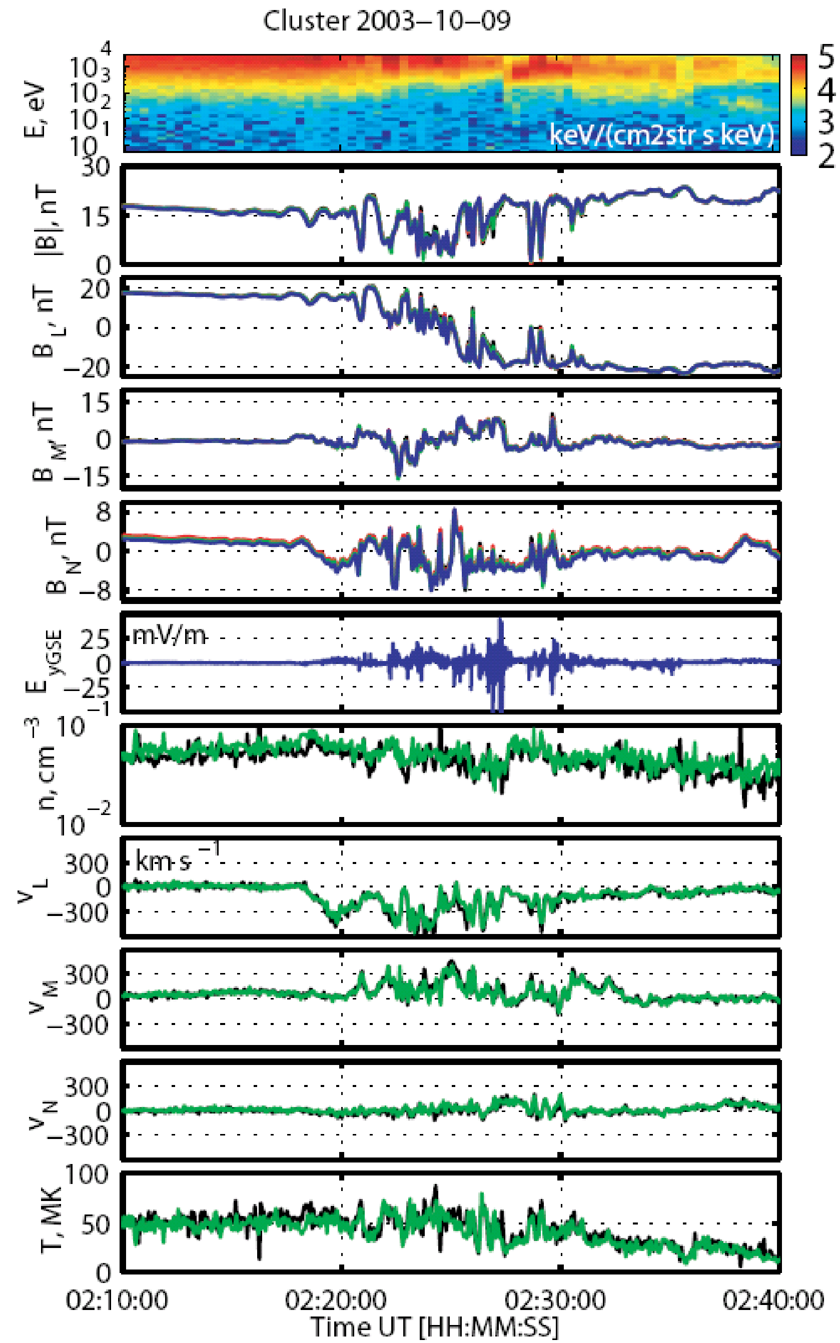
9 October 2003

300 km scale tetrahedron

Data shown in current sheet co-ordinate system

L = (0.895, −0.441, 0.068)
M = (0.445, 0.892, −0.072)
N = (−0.029, 0.094, 0.994)





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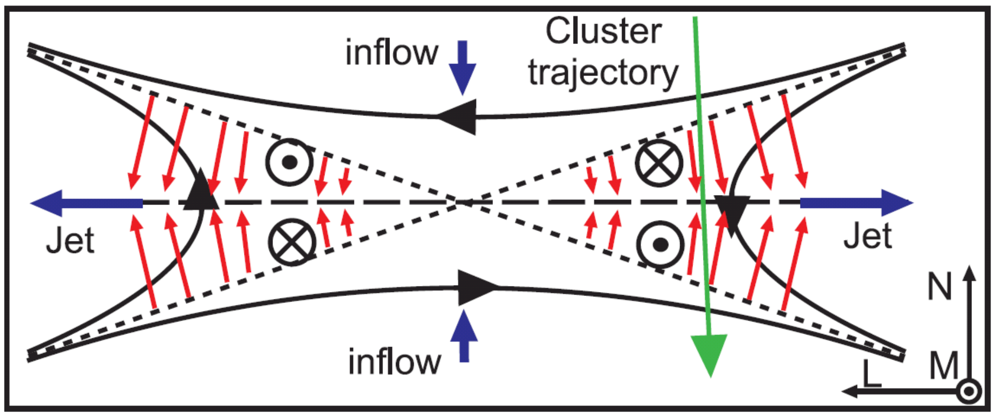
Cluster - magnetotail

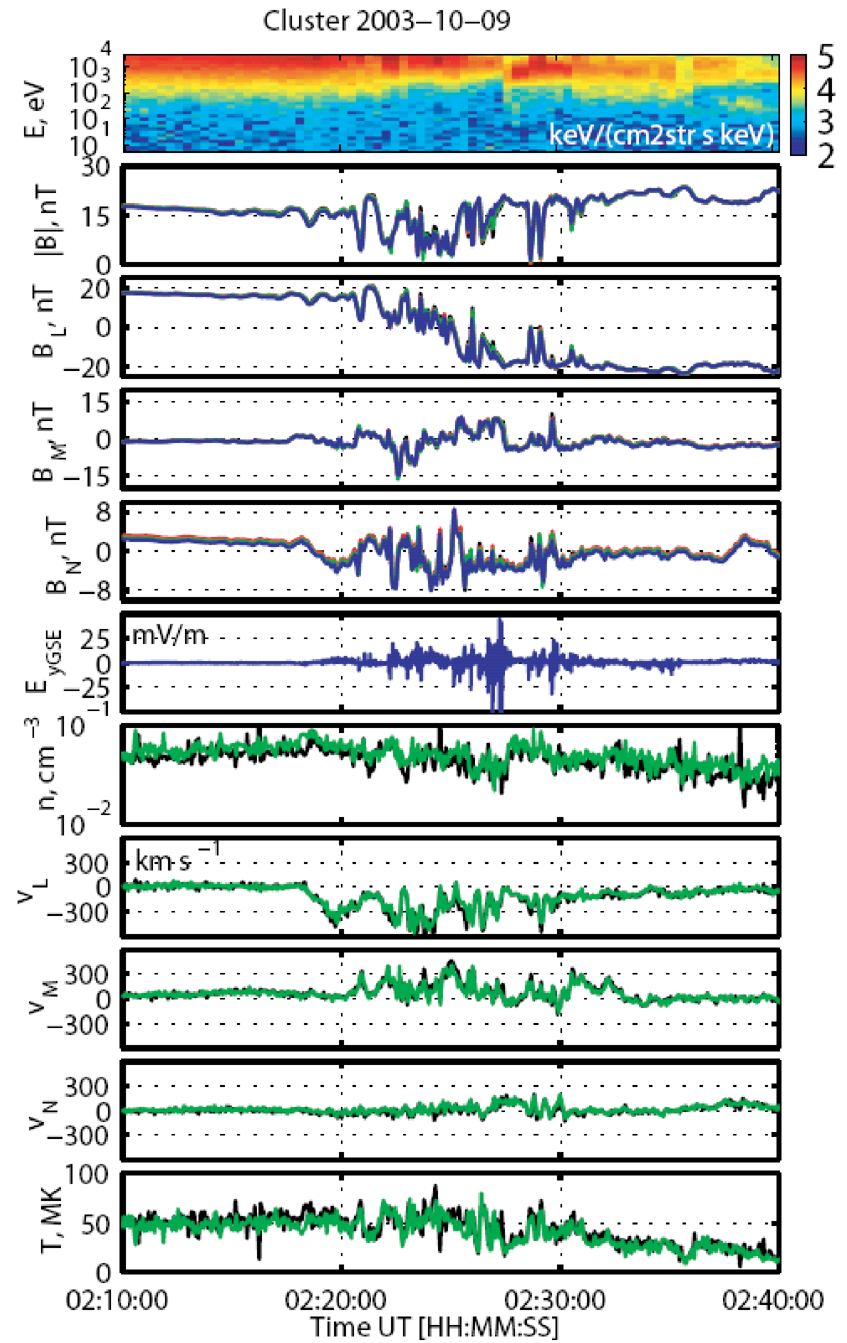
Data indicate Cluster crossed a tailward jet from north to south

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

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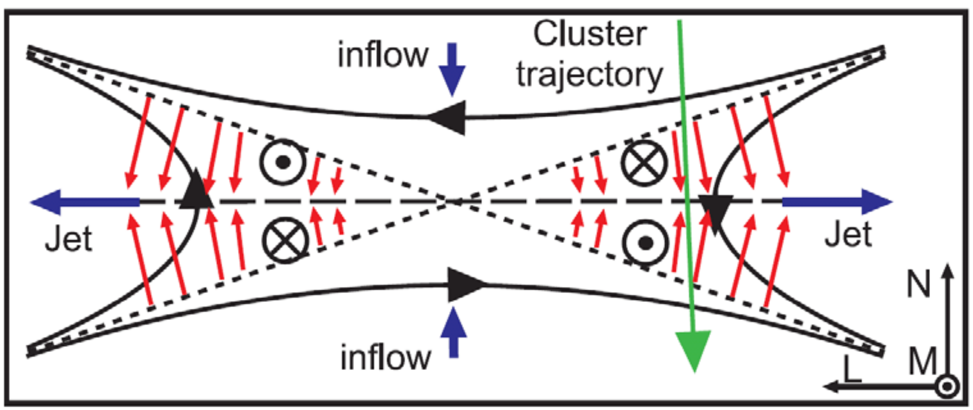
Hall field signatures

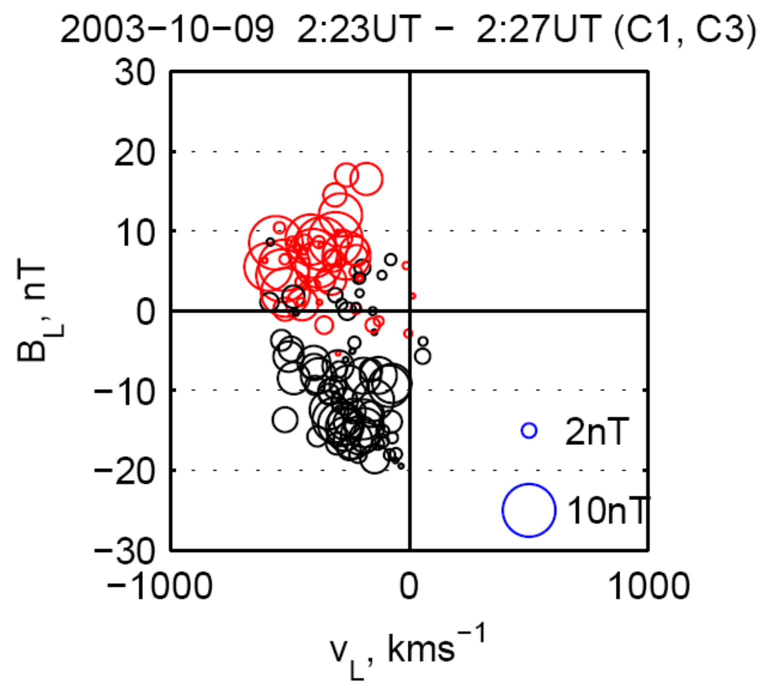
Hall magnetic field
- Red = B_M negative
- Black = B_M positive

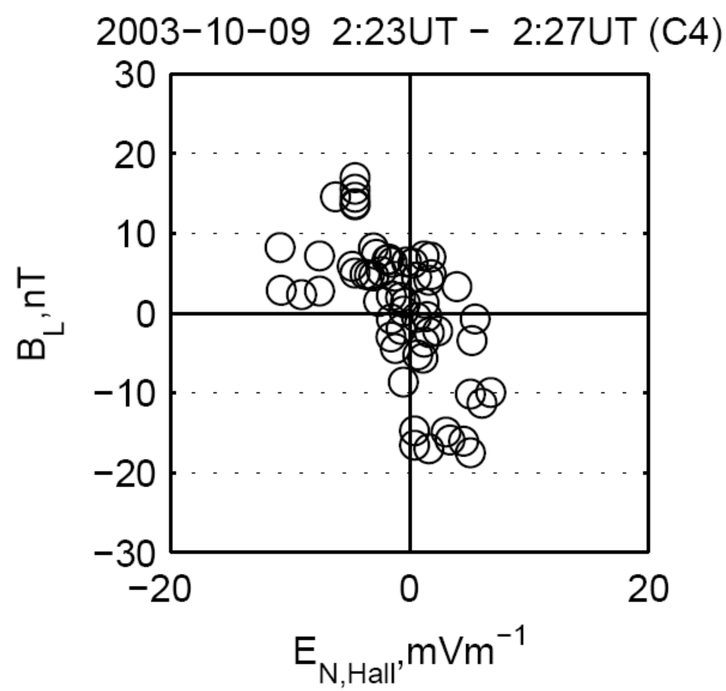
Hall electric field
- Points into current sheet on both sides
- Larger than reconnection electric field (E_M)

Hall fields fill jet
- Outer Electron Diffusion Region

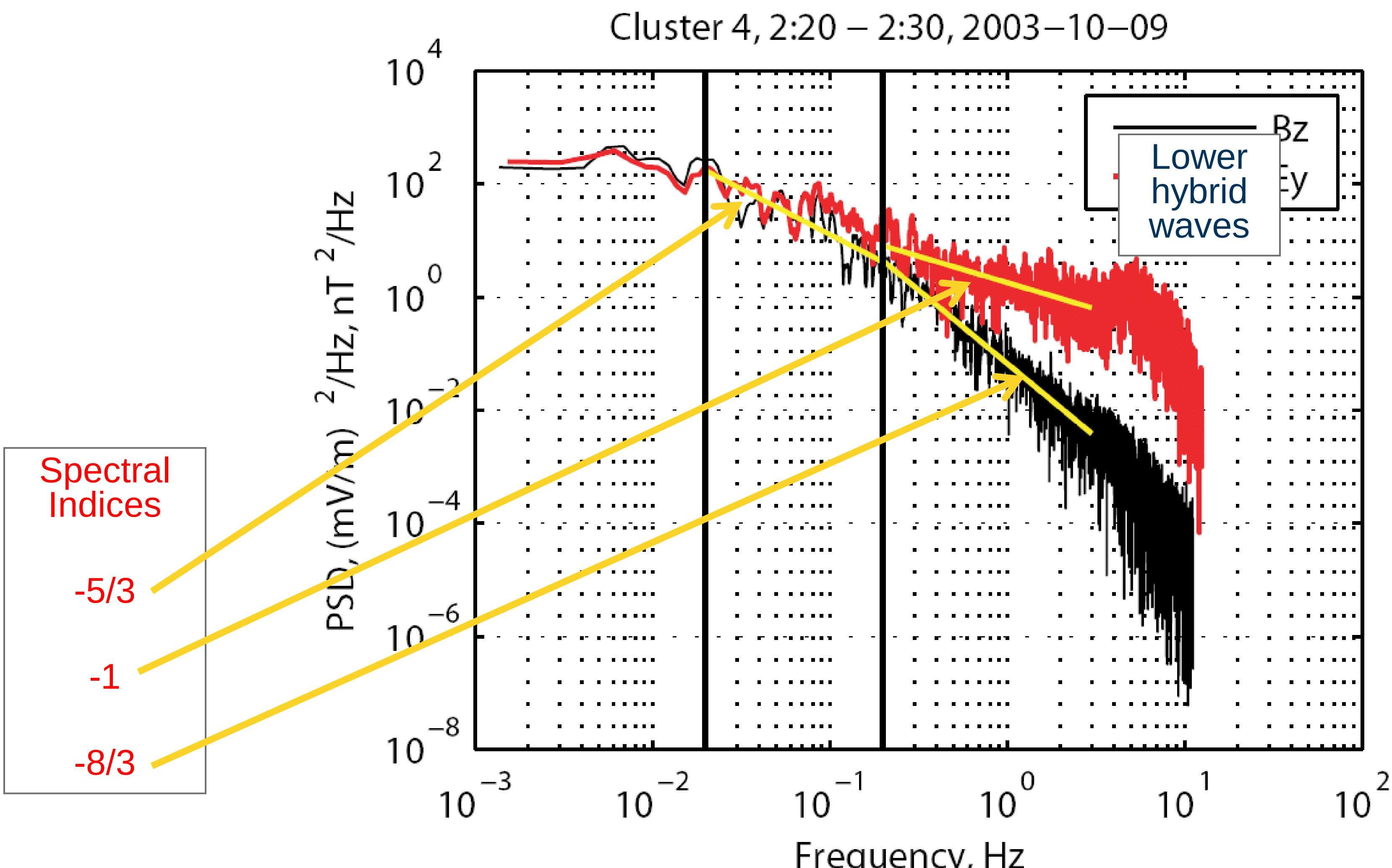
Minimal guide field





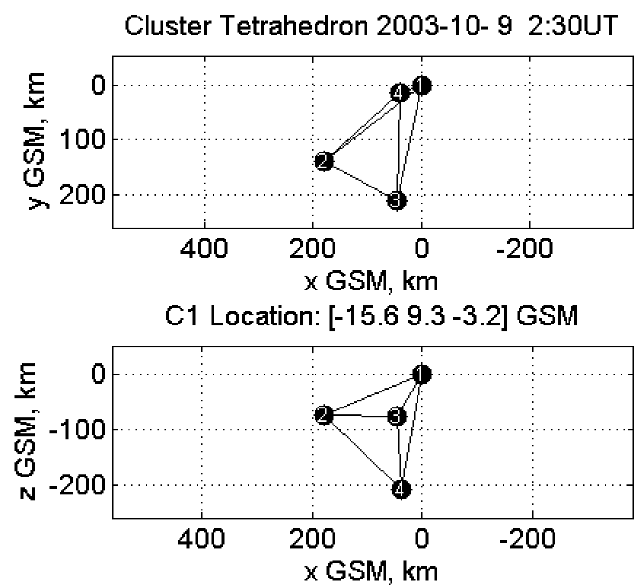


Power spectra



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

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

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

$$\mathbf{P}(\omega,\mathbf{k}) = \langle\mathbf{A}(\omega,\mathbf{k})\mathbf{A}^{\dagger}(\omega,\mathbf{k})\rangle,$$

Fourier transform data from N spacecraft

$$\mathbf{A}(\omega) = \begin{pmatrix}\mathbf{A}(\omega,\mathbf{r}_1)\\ \mathbf{A}(\omega,\mathbf{r}_2)\\ \vdots\\ \mathbf{A}(\omega,\mathbf{r}_N)\end{pmatrix}.$$

Define M

$$\mathbf{M}(\omega) = \langle\mathbf{A}(\omega)\mathbf{A}^{\dagger}(\omega)\rangle.$$

Define the locations of the N spacecraft

$$\mathbf{H}(\mathbf{k}) = \begin{pmatrix}\mathbf{I}_L e^{i\mathbf{k}\cdot\mathbf{r}_1}\\ \mathbf{I}_L e^{i\mathbf{k}\cdot\mathbf{r}_2}\\ \vdots\\ \mathbf{I}_L e^{i\mathbf{k}\cdot\mathbf{r}_N}\end{pmatrix},$$

'It can be shown that' an estimate of P is:

$$P(\omega,\mathbf{k}) = \mathrm{Tr}\left\{\left(\mathbf{H}^{\dagger}(\mathbf{k})\mathbf{M}^{-1}(\omega)\mathbf{H}(\mathbf{k})\right)^{-1}\right\}.$$

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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 x 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 .r = 2pi 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.

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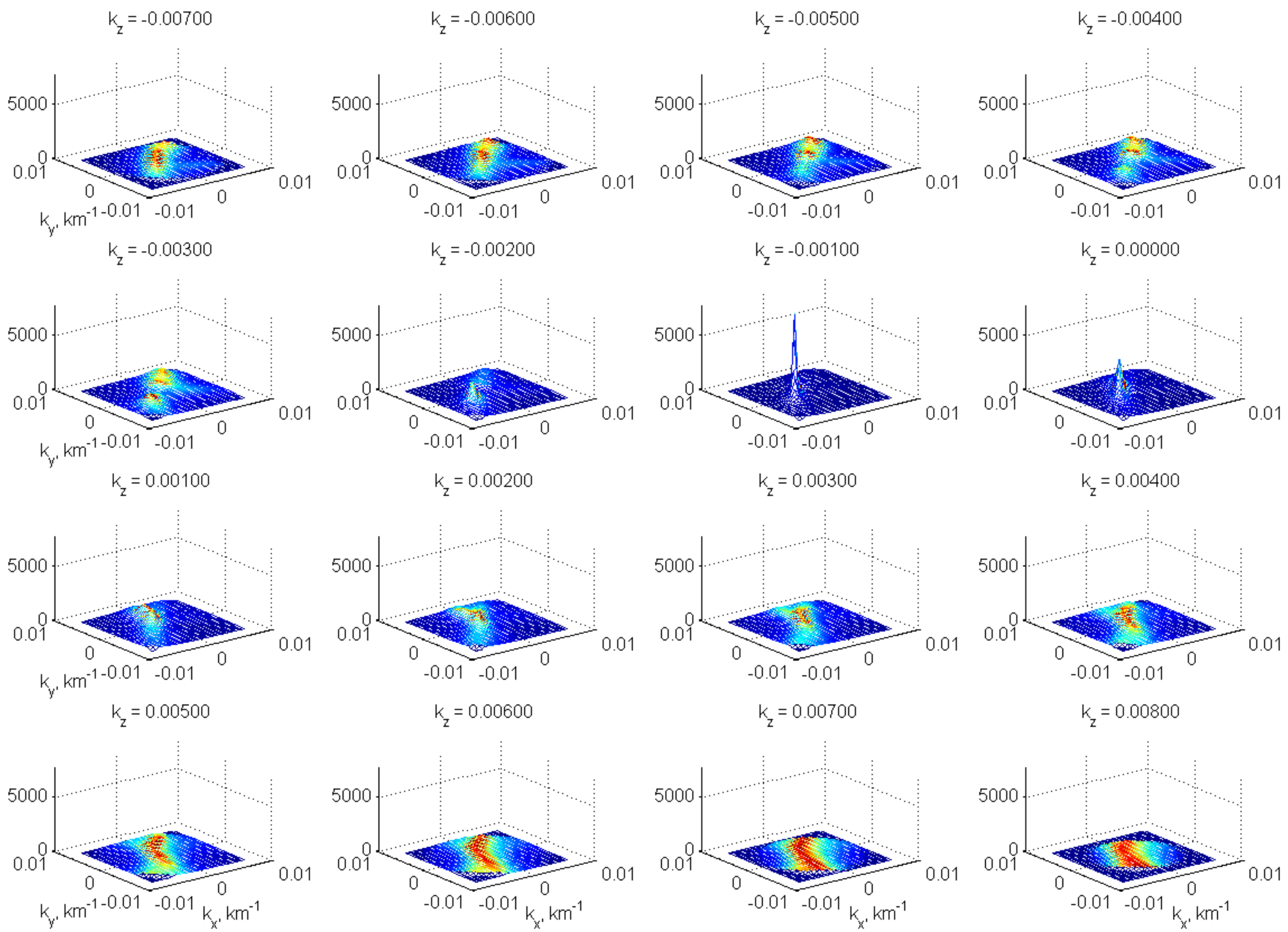
k-filtering results (f = 0.281 Hz; cuts in k_z)



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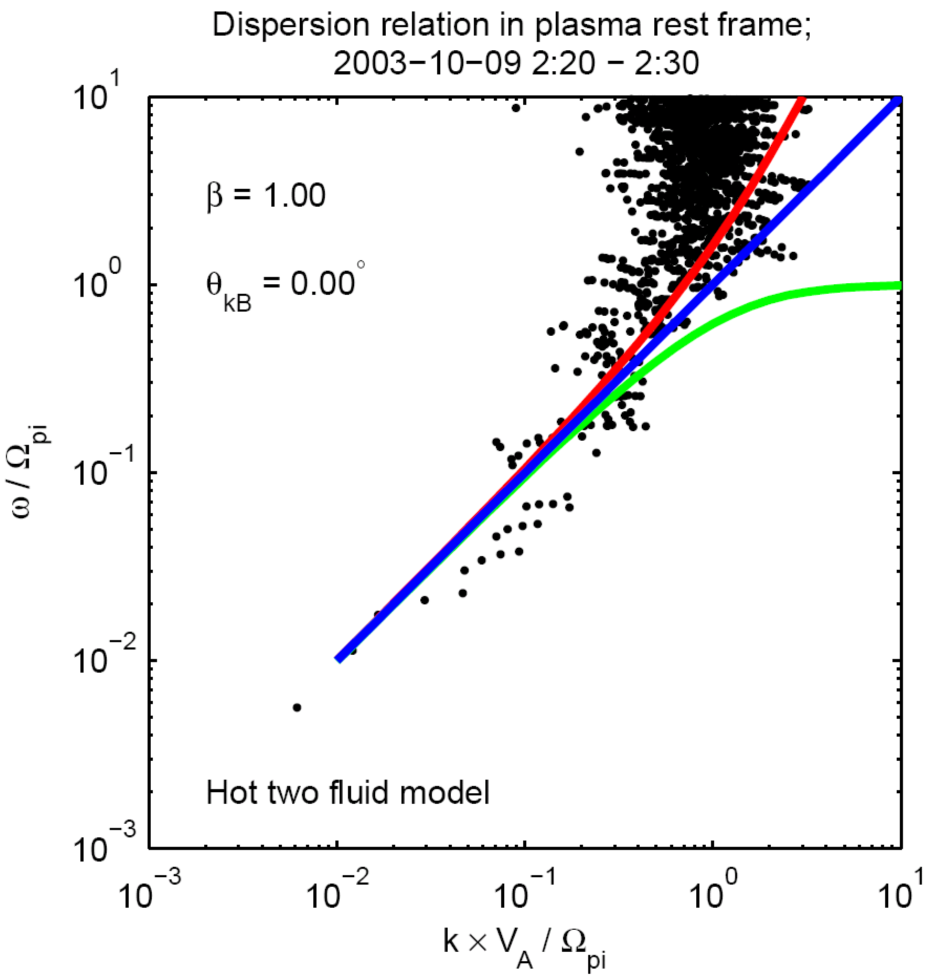
Dispersion relation



Assume k vector along outflow, parallel to B. Then:

$$k_x = \frac{\omega_{sc}}{v^{ph}_{sc,x}} = 2\pi f_{sc} \times \frac{\delta B_z(f)}{\delta E_y(f)}$$

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

Contribution to the reconnection electric field

Applying an analysis similar to that of *Ji et al.* [PRL, 2004], to the magnetic fluctuations, we find that the associated electric field is ~0.3 mVm^{-1}

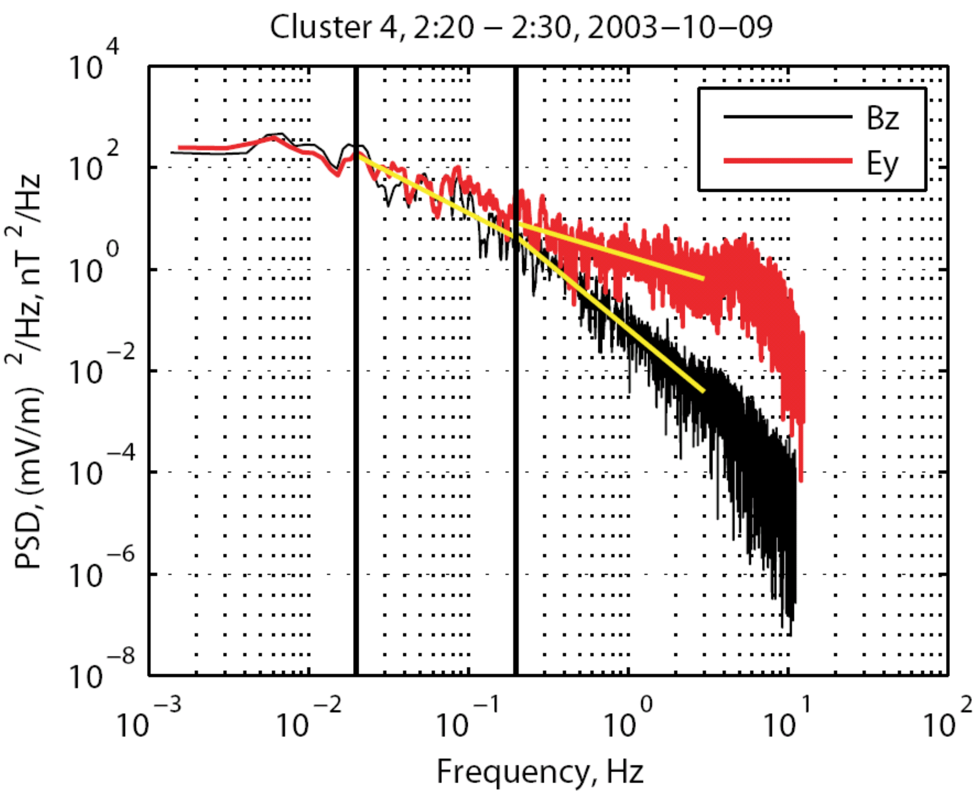
Lower hybrid waves in the 3 – 8 Hz frequency range

- f_{LH} = 4 Hz for B = 6 nT
- f_{LH} = 6.5 Hz for B = 10 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 ~0.01 mVm^{-1}

Modification of the overall reconnection rate is negligible.



Conclusions

Survey [Eastwood et al., J. Geophys. Res., 2010]

- 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

Guide field [Eastwood et al., Phys. Rev. Lett., 2010]

- 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 [Eastwood et al., J. Geophys. Res., 2007]

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

Turbulence in the diffusion region [Eastwood et al., Phys. Rev. Lett., 2009]

- 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