Kinetic-Scale Turbulence in Laboratory and Space Plasmas: Empirical Constraints, Fundamental Concepts and Unsolved Problems
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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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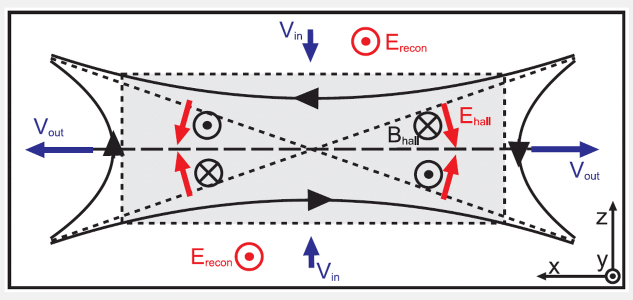
Summary

Magnetic reconnection is a universal plasma process, important in many different physical phenomena
- The plasma decouples from the magnetic field in the central diffusion region;
- In collisionless reconnection the diffusion region has a characteristic two-scale structure

The Earth's magnetotail is a natural reconnection laboratory

Key questions and results:
- *What are the average experimental properties of the diffusion region?*
  - **Reconnection is fast, with peak normalized Hall fields: b = 0.39 ± 0.16 e = 0.33 ± 0.18**
- *How does a guide field alter the diffusion region?*
  - **Even a 20% guide field significantly distorts the structure of the diffusion region**
- *What are the properties of turbulence inside the diffusion region?*
  - **Anti-parallel reconnection exhibits whistler turbulence**

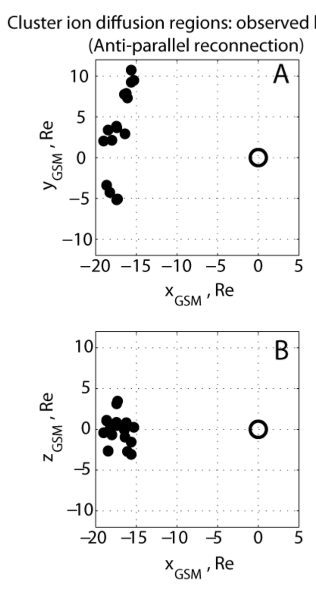


Average properties of the Hall fields

- In-situ observations of the diffusion region in space are rare
- Most analysis is therefore based on case studies
- Are these case studies representative? A more comprehensive study is required
- We used five years of Cluster data to perform a systematic survey for diffusion region encounters
- This allows statements to be made concerning the average properties of the diffusion region
- This will also enable the next generation of satellites (particularly Magnetospheric Multi-Scale) to automatically detect diffusion region encounters

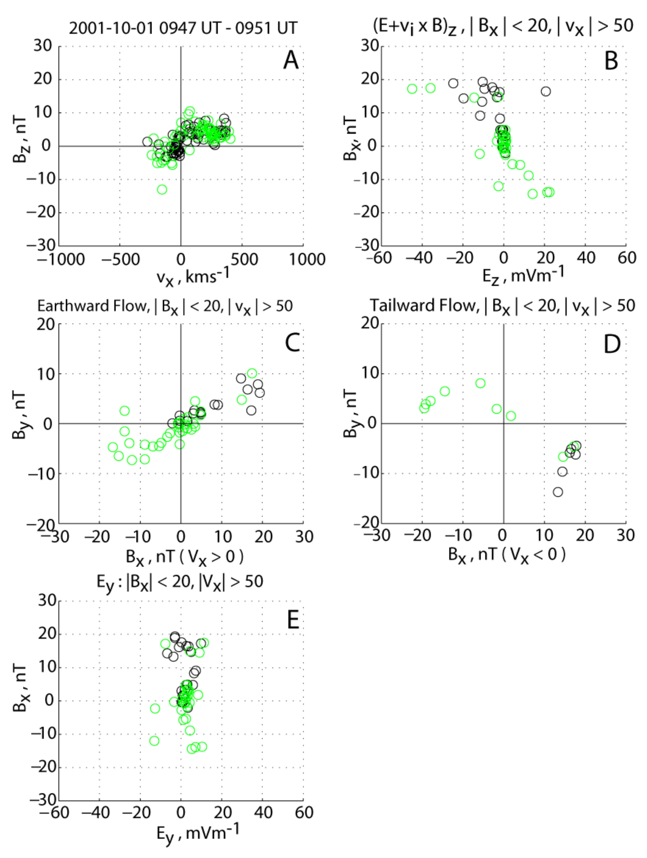
- **Key result: peak normalized Hall fields: b = 0.39 ± 0.16 e = 0.33 ± 0.18**
- **Avg reconnection E field e_{recon} = 0.04**

Diffusion region locations

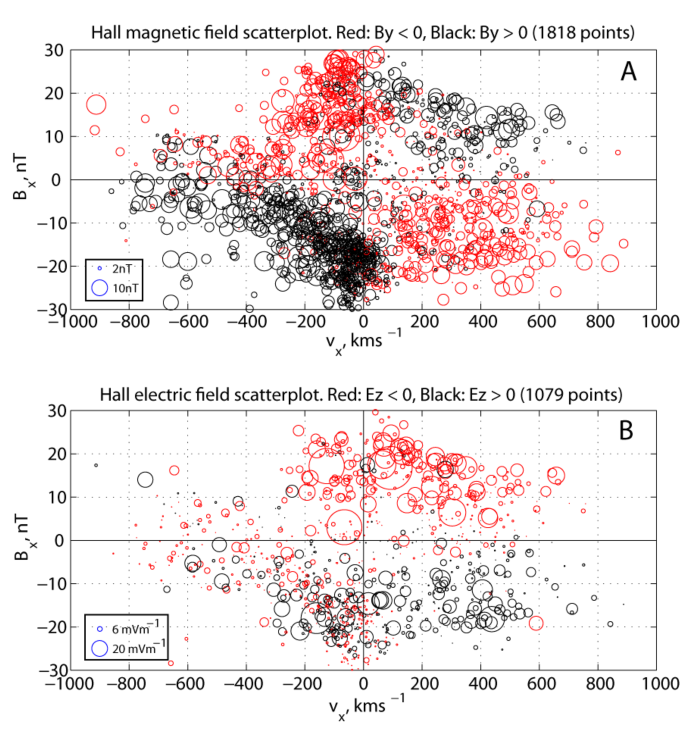


- A survey of 5 years of Cluster data resulted in a sample of 18 diffusion region encounters associated with antiparallel reconnection (note strong function of Cluster orbit)

Example of a diffusion region encounter

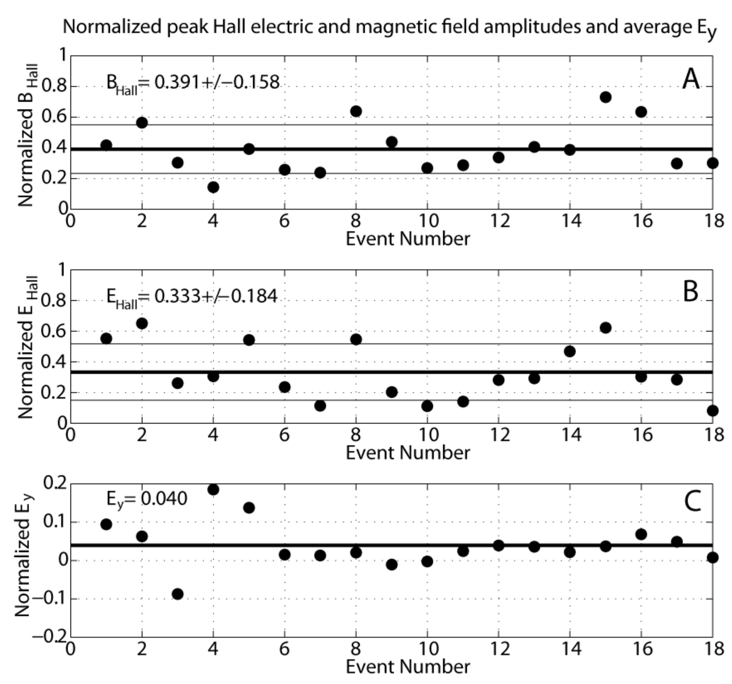


Hall field pattern: all data, all encounters



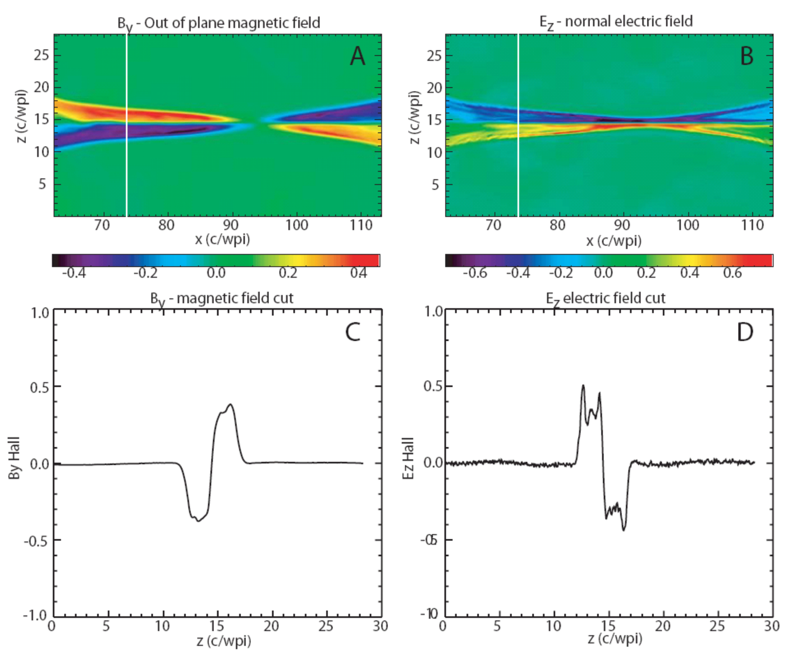
- The Hall field pattern naturally emerges from the Geocentric Solar Magnetospheric coordinate system

Normalized results



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

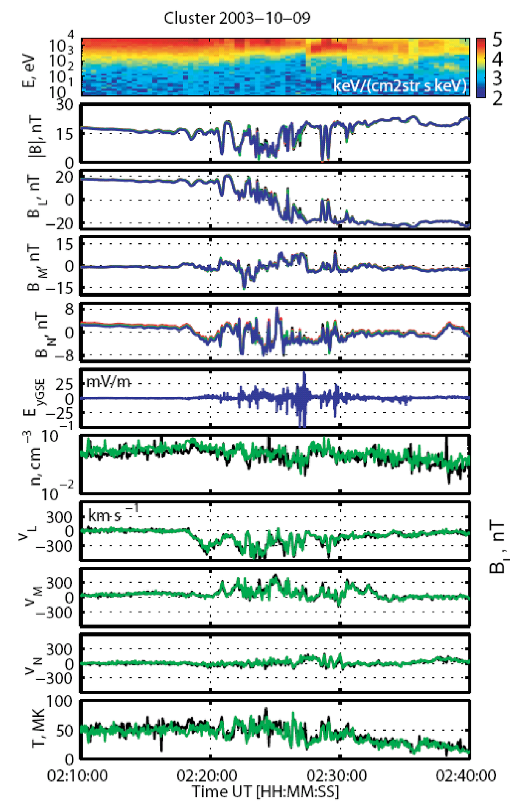
Comparison with simulations

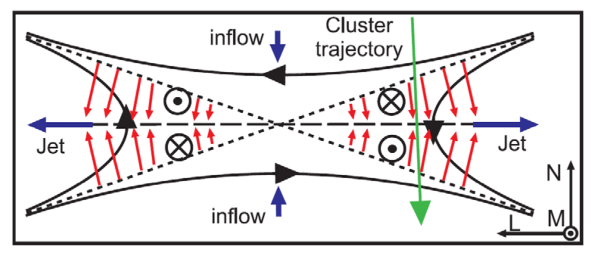


- PIC code P3D;
  - [*Shay et al.*, Phys. Rev. Lett., 2007]
- A small part of the simulation, centered on one of the X-lines at a time when reconnection has established is shown
- Normalized in the same way as the data
- (Location of cut is not of specific importance)

Turbulence in the diffusion region

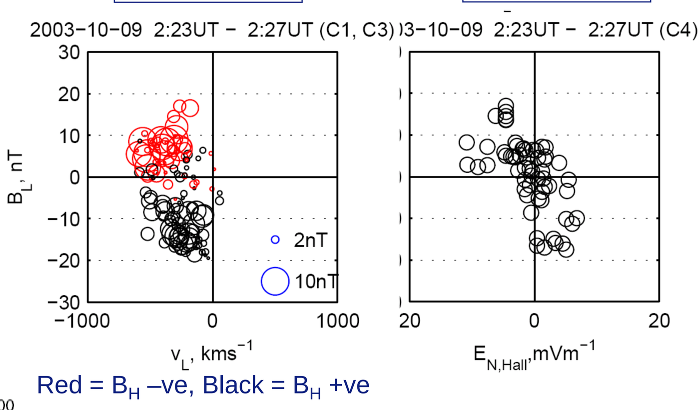
- It is thought that Hall fields play a key role in fast reconnection [*Birn et al.*, J. Geophys. Res., 2001]
- Recent laboratory experiments appear to show reconnection rate positively correlated with magnitude of electro-magnetic fluctuations up to the lower hybrid frequency [*Ji et al.*, Phys. Rev. Lett., 2004]
- Small 3D hybrid simulations: although a turbulent configuration can arise in three dimensions, this does not significantly enhance the reconnection rate [*Rogers et al.*, Geophys. Res. Lett., 2000]
- To establish the role of fluctuations vs Hall physics in controlling reconnection, use new Cluster observations of diffusion regions in the Earth's magnetotail current sheet





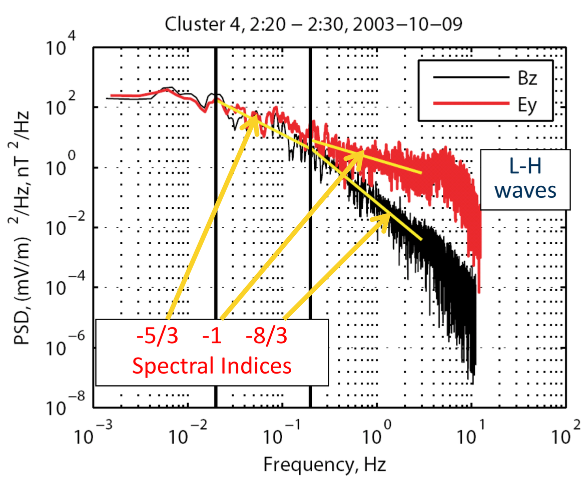
Hall B field

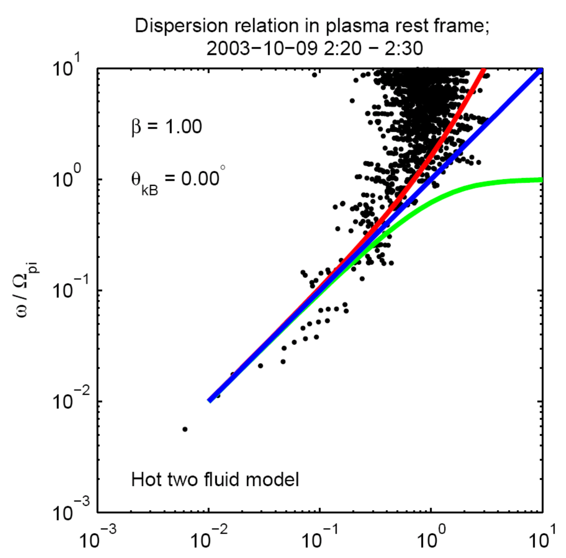
Hall E field



Red = B_H −ve, Black = B_H +ve

- Cluster encounter with a diffusion region in the Earth's magnetotail on 9 October 2003. The spacecraft cut through the exhaust from top to bottom, and observed the Hall magnetic and electric field





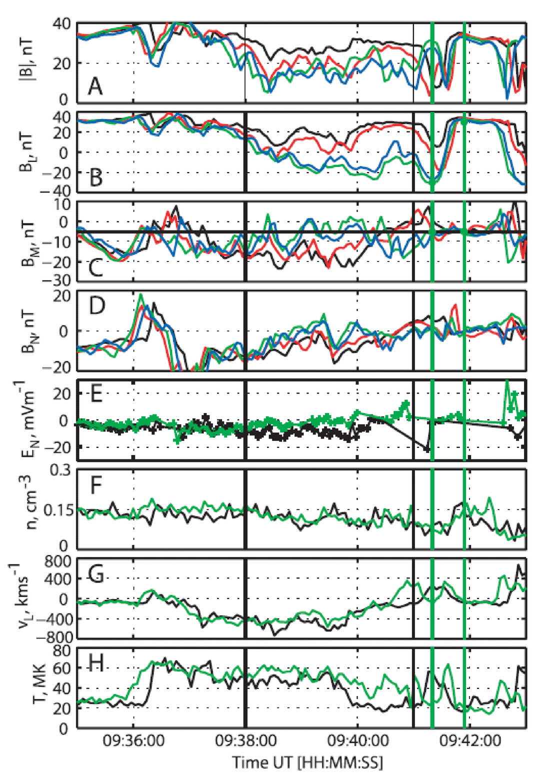
- Applying an analysis similar to that of *Ji et al.* [Phys. Rev. Lett., 2004], to the magnetic fluctuations, we find that the associated electric field is ~ 0.3 mVm^{-1}
- Lower hybrid waves in the 3 – 8 Hz frequency range
- Whistler waves can scatter off plasma density variations and convert into LH waves [e.g. *Bell & Ngo*, J. Geophys. Res., 1990]
- LH wave fluctuations correspond to a reconnection electric field of ~ 0.01 mVm^{-1}
- Modification of the overall reconnection rate is negligible

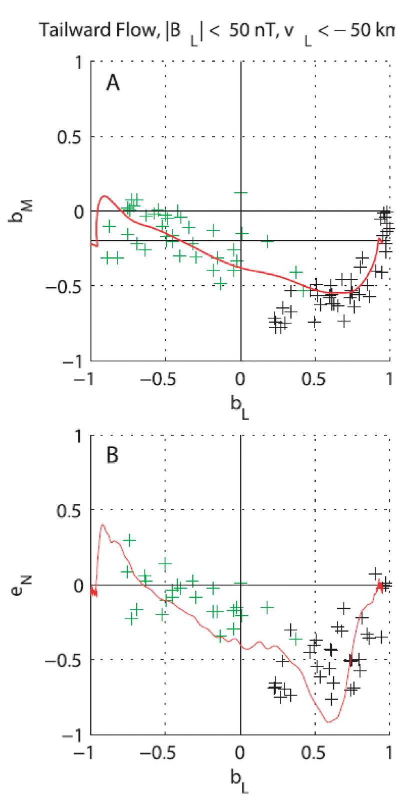
- Using wave telescope/ k-filtering technique, k vector thought to lie along outflow, parallel to B.
- Transform to plasma frame
- Compare to hot two fluid dispersion relations [*Formisano and Kennel*, J. Plasma Phys., 1969]
- **Appears to be consistent with whistler/ fast mode waves**

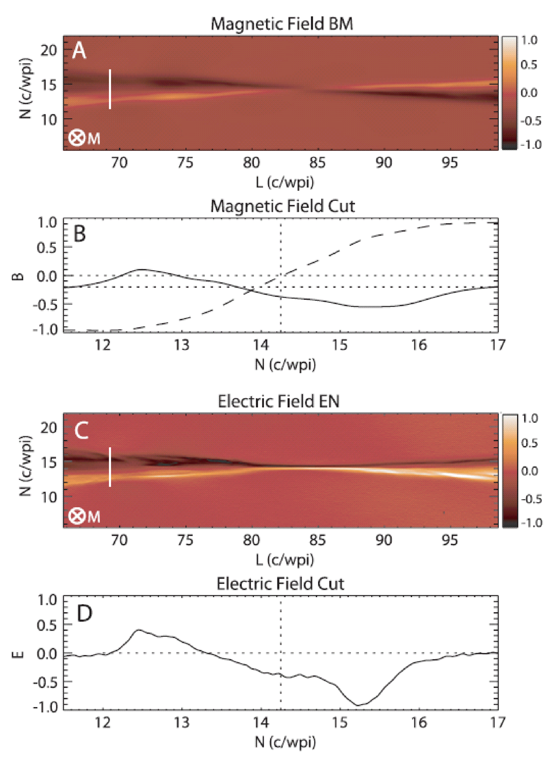
Guide field Reconnection

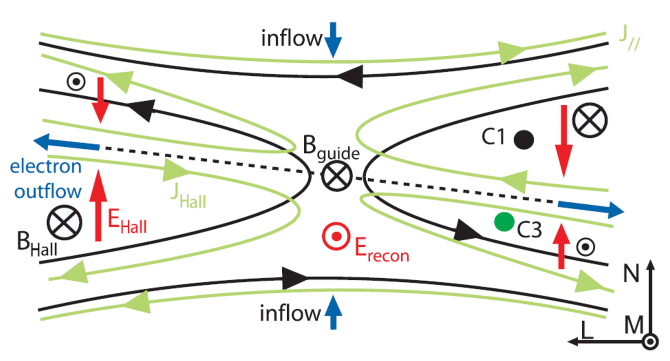
- (Most) reconnection is not anti-parallel
- Here we examine the structure of the diffusion region during guide field reconnection
- Guide field alters the pattern of the Hall currents by enabling the reconnection electric field to induce electron motion and currents along the magnetic field
- Displaces electron outflow in N direction due to $\mathbf{j}_{Hall} \times \mathbf{B}_g$ forces
- Asymmetry in N direction, not in L direction

- **Even a small guide field can significantly alter the structure of the diffusion region**









- Data rotated into current sheet coordinate system (close to GSM)
- Guide field ~ 20%
- Shear = 159°
- Examine interval of tailward flow
  - Cluster 1 above current sheet
  - Cluster 3 below current sheet

- PIC simulation with code P3D – 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)
- Good agreement between the data and the simulation
- Fairly insensitive to the location of the cut downstream

Publications

- Eastwood, J. P., T. D. Phan, M. Øieroset and M. A. Shay (2010), Average properties of the magnetic reconnection ion diffusion region in the Earth's magnetotail: 2001–2005 Cluster observations and comparison with simulations, *J. Geophys. Res.*, **115**, doi:10.1029/2009JA014962.
- Eastwood, J. P., M. A. Shay, T. D. Phan and M. Øieroset (2010), Asymmetry of the Ion Diffusion Region Hall Electric and Magnetic Fields during Guide Field Reconnection: Observations and Comparison with Simulations. *Phys. Rev. Lett.*, **104**, 205001.
- Eastwood, J. P., T. D. Phan, S. D. Bale and A. Tjulin (2009), Observations of turbulence generated by magnetic reconnection, *Phys. Rev. Lett.*, **102** 035001.

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