How neutral is quasi-neutral: Charge Density in the Reconnection Diffusion Region Observed by MMS

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November 22, 2022

Abstract

Magnetic reconnection is responsible for the major reconfigurations of the magnetosphere that lead to energy transport and deposition into the ionosphere. The fast rate at which magnetic energy is converted to plasma kinetic energy is likely enabled by the polarization Hall electric field that results from the separation of ions and electrons at small scales. Signatures of Hall fields have played a key role in identifying and studying reconnection, but the density of accumulated charge has not been quantified. We use the 4-point measurements of the Magnetospheric Multiscale mission to compute the divergence of the electric field and present the first observations of charge density in the diffusion region of magnetic reconnection. We show how it ties into the Hall system, discuss measurement uncertainties, analyze quality estimates, and make comparisons to 2D simulations. Charge density is briefly presented for other phenomena, and ranges from 2% or less of the background plasma density for magnetic reconnection and electron-scale magnetic holes and peaks to upwards of 4% for electron phase space holes.

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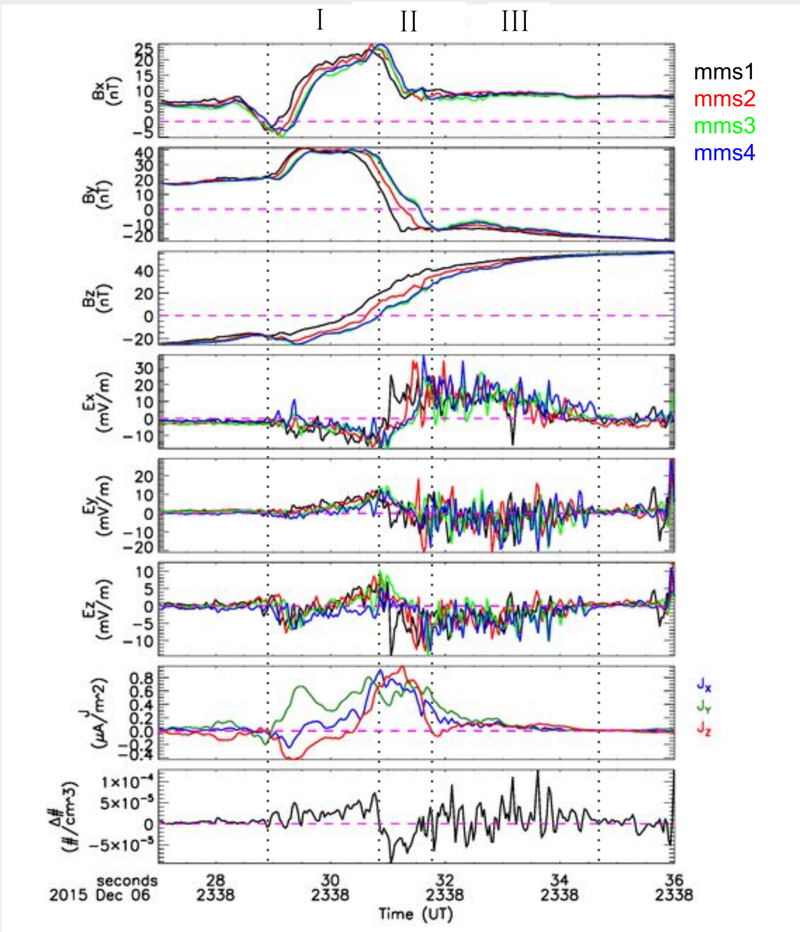
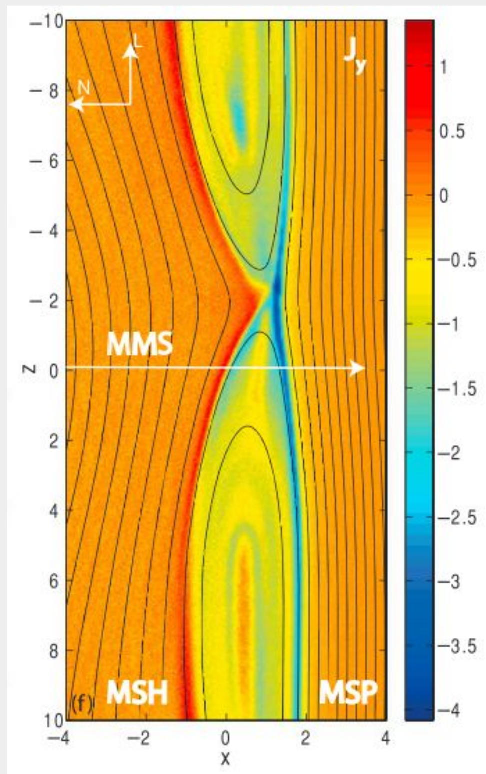
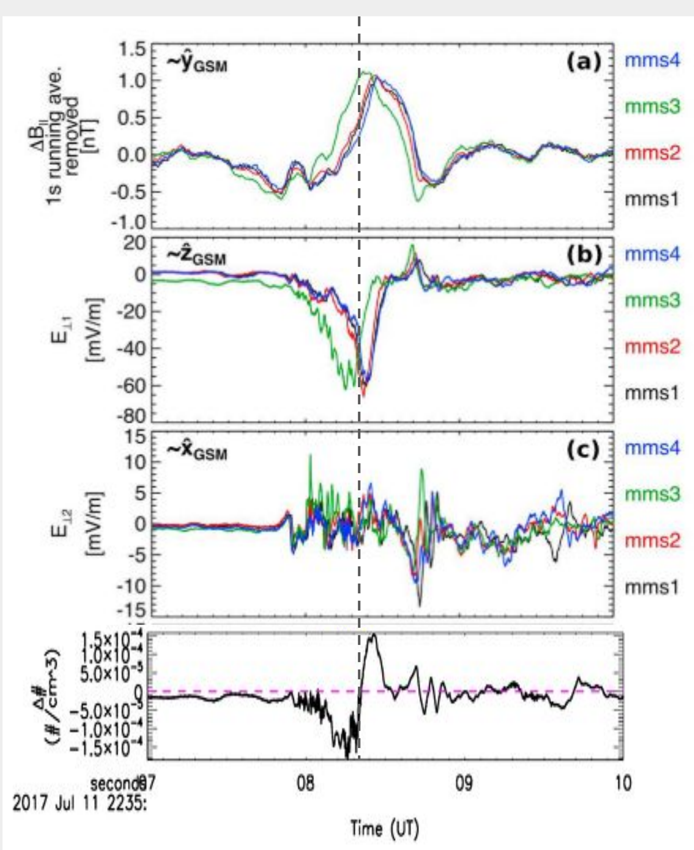
Charge Density in Other Contexts



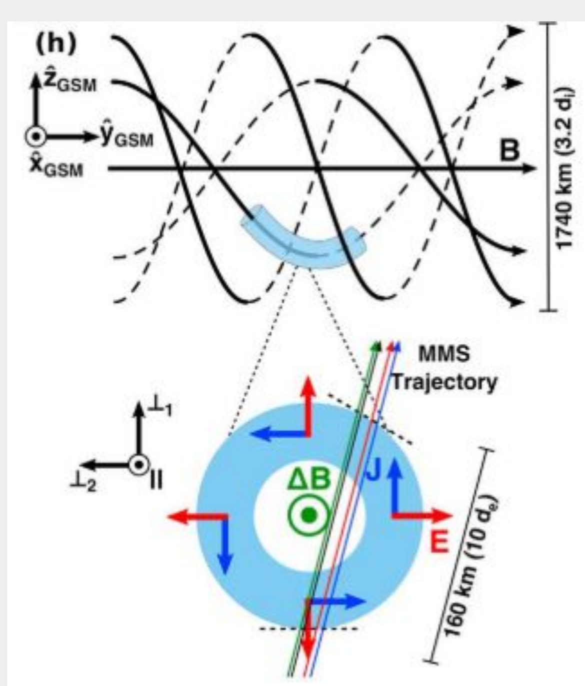
Asymmetric Reconnection



- Regions I, II, & III are the same as the symmetric case
- Hall fields and currents detected
- Ratio of charge density to background density is 10^{-3}%

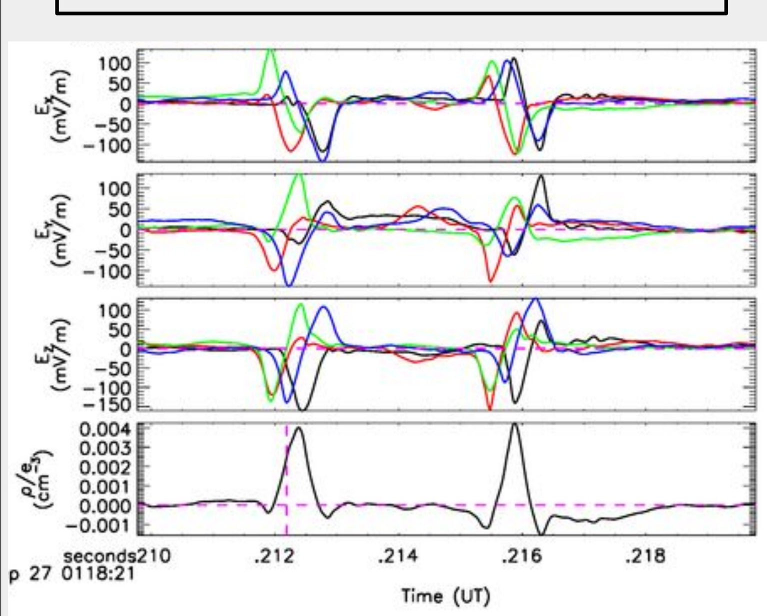


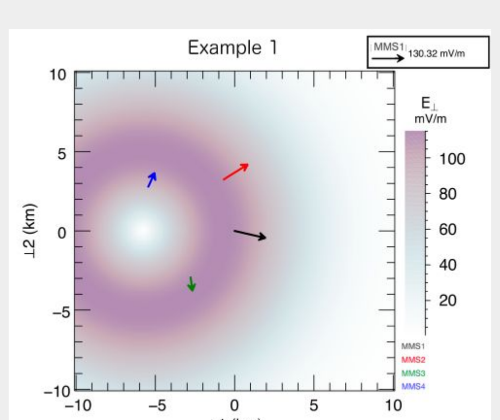
Magnetic Hole

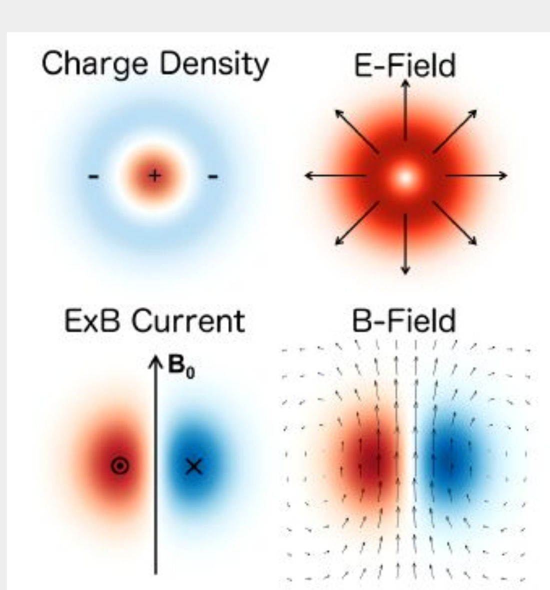


- ρ < 0 until all S/C are within the hole
- ρ > 0 inside the hole
- Suggests an electron sheath in vortex region
- Ratio of charge density to background density is 0.25%

Electron Phase-Space Hole

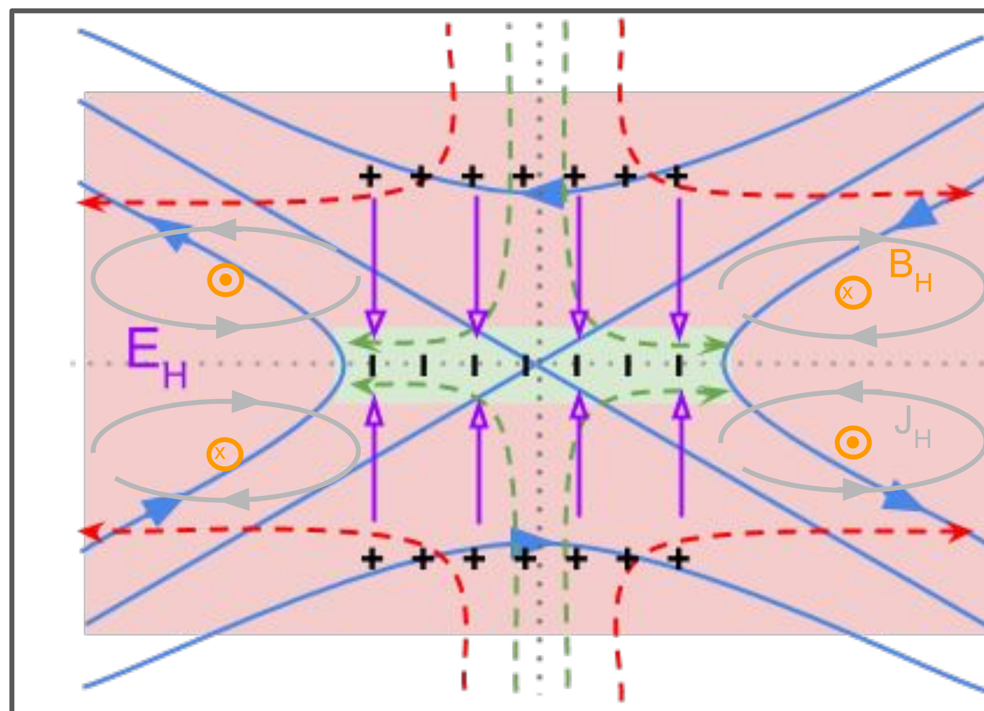






- *In-situ* observations match theory
  - ρ < 0 at edges of hole
  - ρ > 0 inside the hole
- Ratio of charge density to background density is 4%

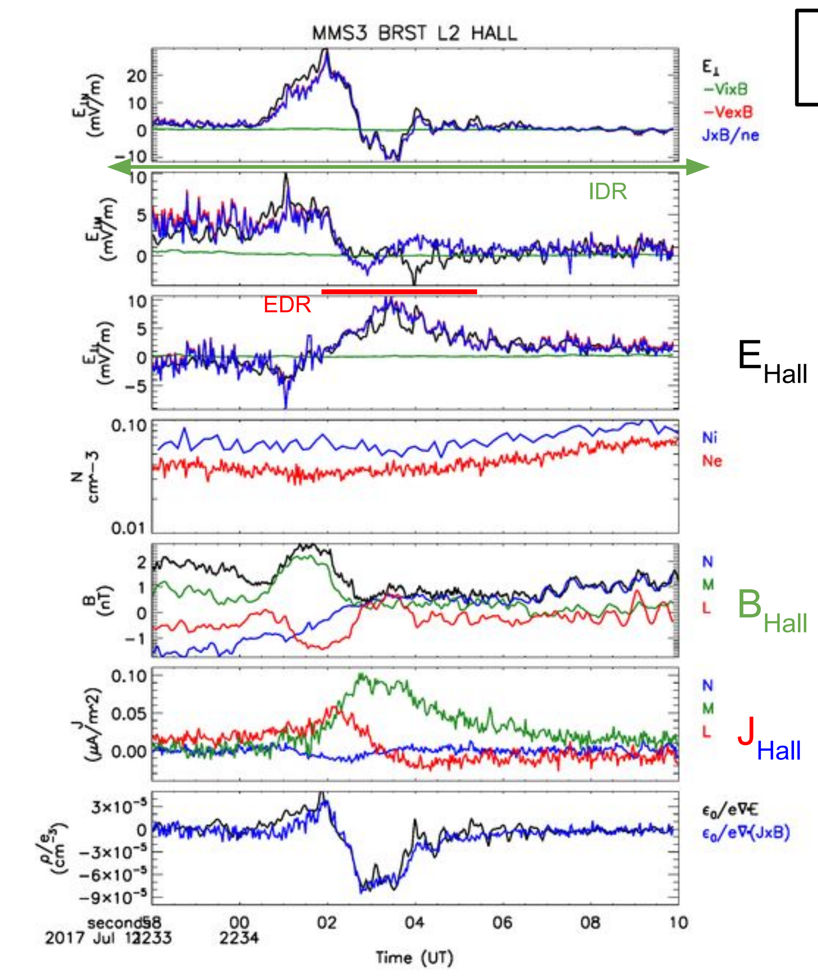
Charge Density in the Symmetric Reconnection Diffusion Region

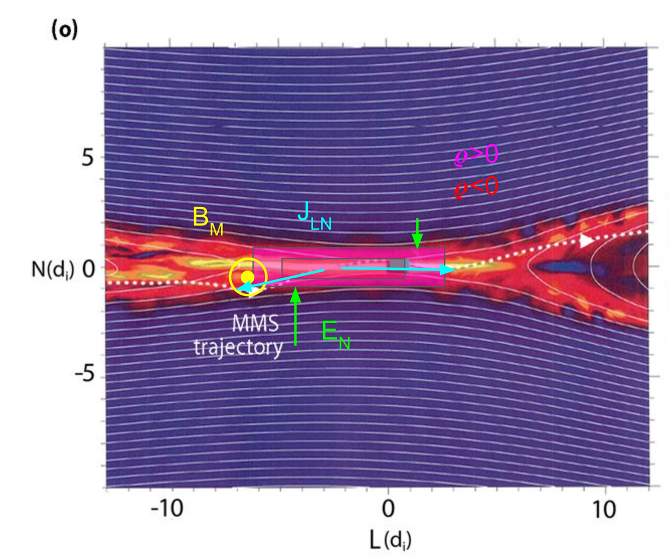


Charge density and the Hall system

- Inflow: Ions and electrons ExB drift inward
- IDR: B curvature radius < ion gyroradius: $R_C < r_{ion}$
- EDR: $R_C < r_{e-}$
- Charge Density: Separation of IDR & EDR
- Outflow: Plasma is energized and diverted
- Hall J: Created by ion and electron outflow
- Hall B: Formed from Hall currents
- Hall E: Due to charge separation

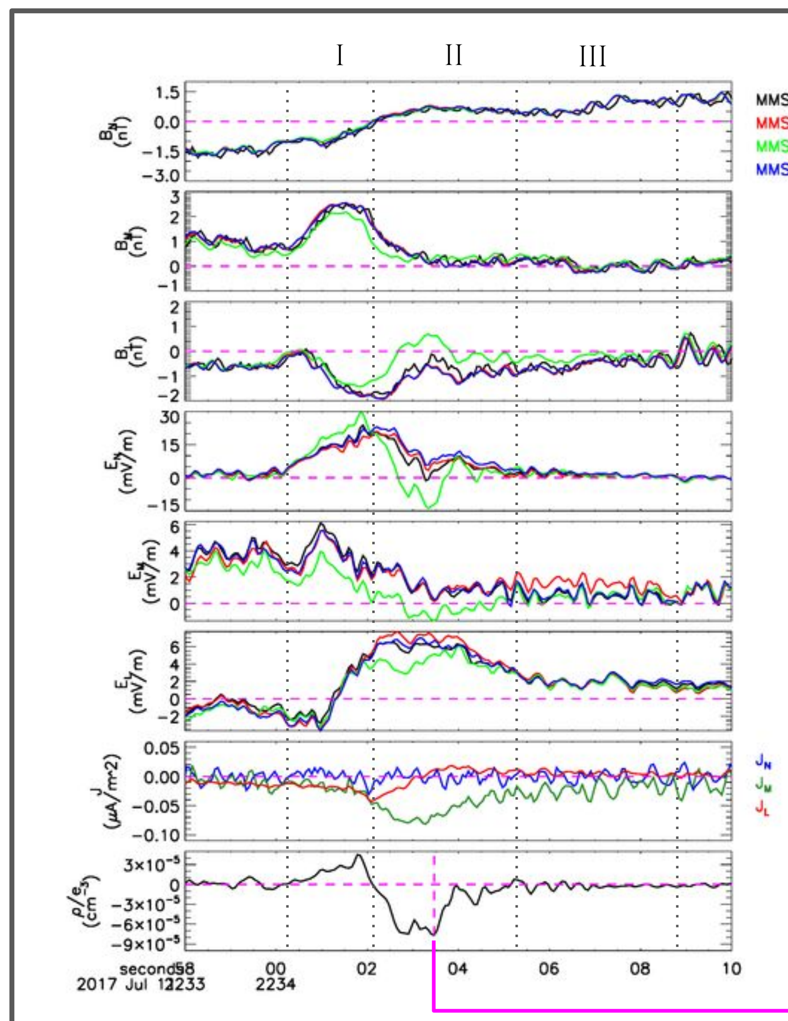
MMS Example 2017-07-17

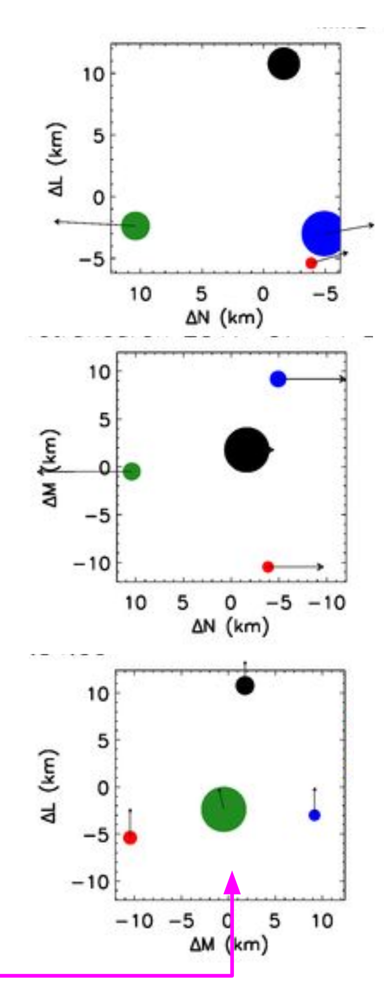




- E-field in S/C frame is dominated by **JxB**
- Hall fields and currents detected
- Ratio of charge density to background density is 1%

Multi S/C Perspective



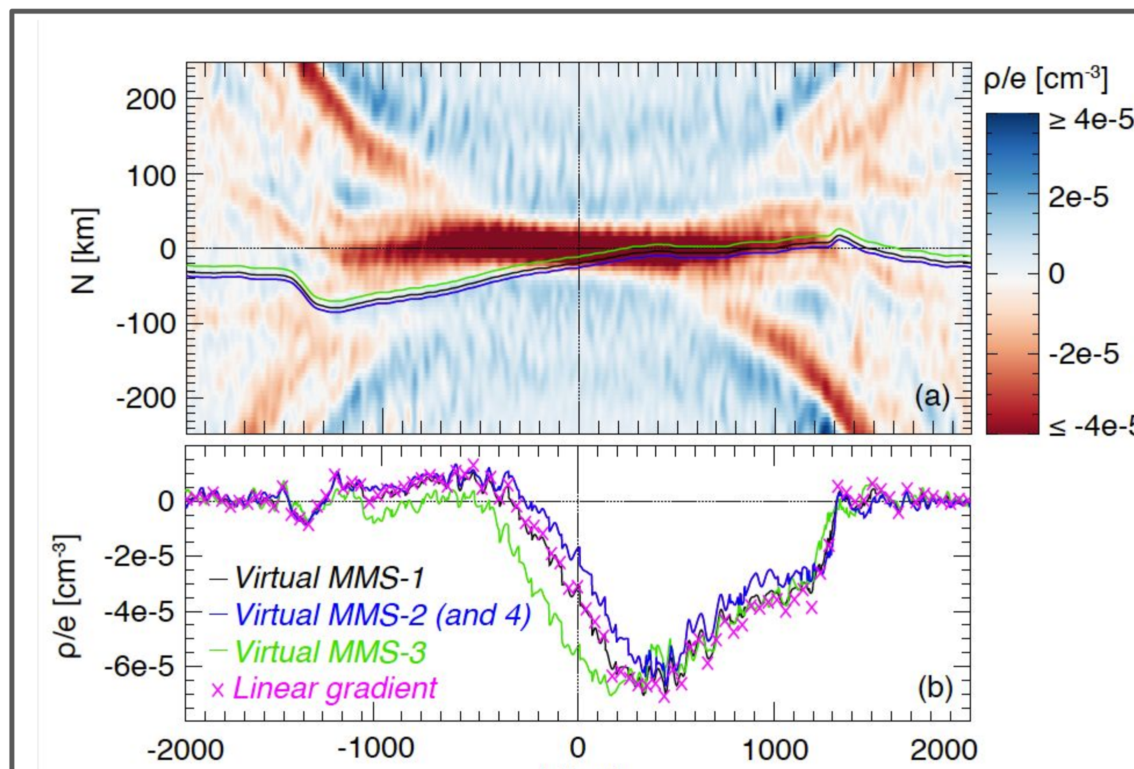


Region I
- E- and B-fields diverge, J finite
- Entry into IDR
- Net positive charge density

Region II
- S/C differences intensify in EDR
- Entry into EDR
- Net negative charge density

Region III
- E- and B-fields converge
- Exit EDR then IDR
- Net positive charge density

E-Field at peak charge density is divergent



Comparison to Simulations

- Simulation matches qualitatively and quantitatively with the data
  - Positive (negative) in IDR (EDR)
  - $|\rho/e|_{max} = 1\times10^{-5}\ cm^{-3}$
- Linear gradient ∇•E matches local measurements of ρ
- ρ is nonuniform across the tetrahedron

Error Analysis and Implications

Expected Errors

General Error Formula

$$\sigma^2_{f(x_1,x_2,\ldots)} = \left(\frac{\partial f}{\partial x_1}\sigma_{x_1}\right)^2 + \left(\frac{\partial f}{\partial x_2}\sigma_{x_2}\right)^2 + \ldots$$

Variance of ∇•E, ∇×E, -∂B/∂t: gradient approximated as average of unique s/c-to-s/c differences

$$\sigma_{\rho/e} = \frac{\epsilon_0}{e}\sqrt{2}\frac{0.5\,mV/m}{15\,km} = 2.6\times10^{-6}cm^{-3}$$

$<< 1.0 \times 10^{-4}\ cm^{-3}$

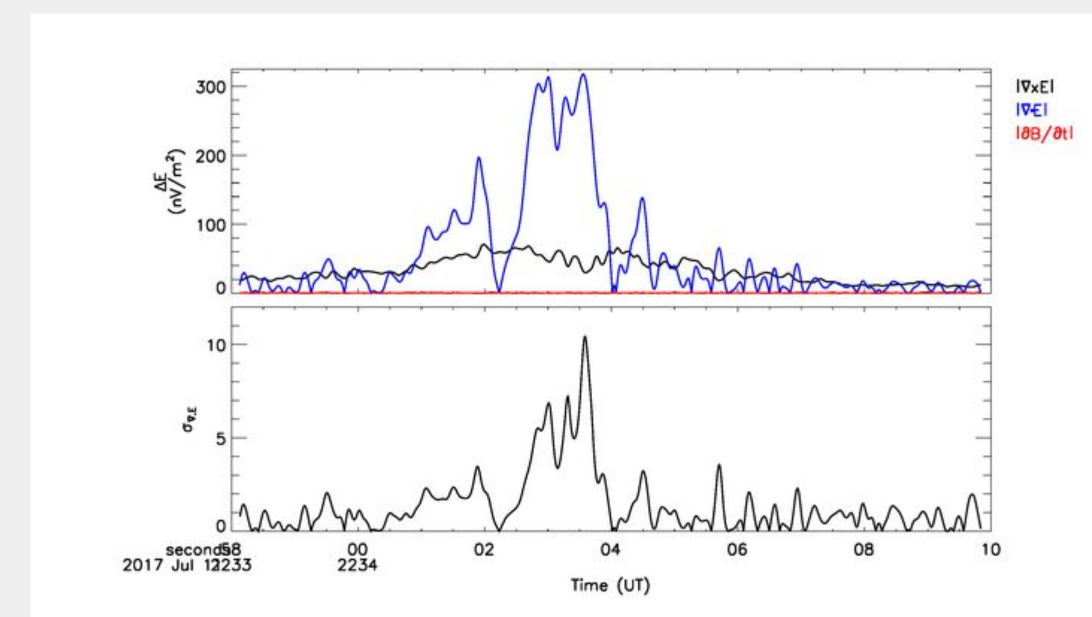
$= 46\ nV/m^2$

$$\sigma_{(\nabla\times E)_1} = \sqrt{\frac{4}{3}}\frac{0.5\,mV/m}{15\,km} = 3.8\times10^{-8}\,V/m = 38\,nT/s$$

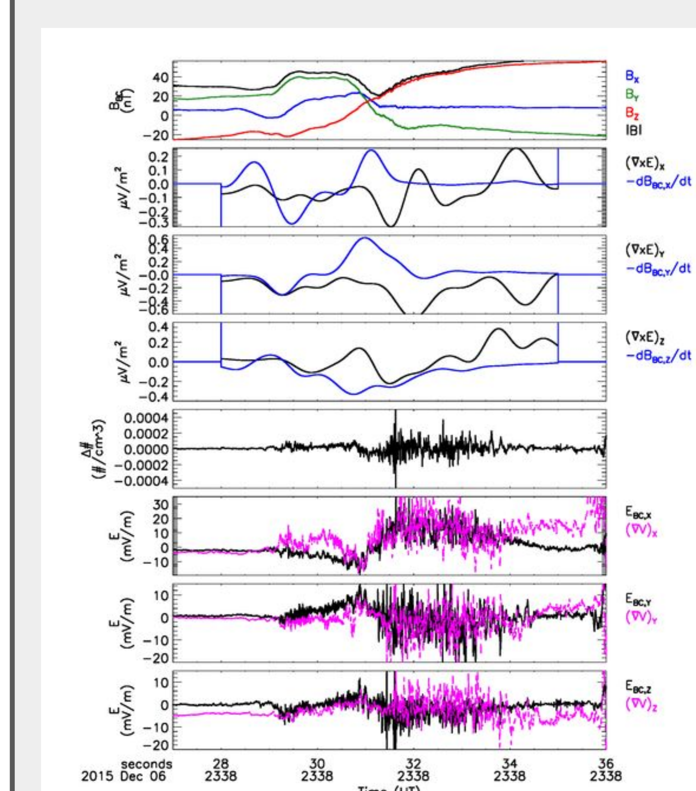
$$\sigma_{\dot{B}} = \sqrt{2}\frac{0.05\,nT}{0.008\,s} \approx 9\,nT/s$$

E is sampled 64x faster than B so averaging reduces the error by 8.

Quality Estimate



|∇×B| / |∇•B| → à la Curlometer Technique → |∇·E| / |∇×E - ∂B/∂t|



Implications

Steady-State Reconnection
- ∂B/∂t = ∇×E = 0
- 0-th order diffusion region can be expressed as a scalar potential
  - E = -∇V

Wave Generation
- Quasi-neutrality assumptions simplify wave generation mechanisms
- Could serve as an additional means of carrying charge away from EDR

Summary

- ρ ≠ 0 in the diffusion region
- ρ is supported by the Hall system
- Qualitative and quantitative agreement with simulations
- ρ/N varies by context
  - Symmetric reconnection: 1%
  - Asymmetric Reconnection 10^{-3}%
  - Magnetic Hole: 0.25%
  - Phase-Space Hole: 4%
- Electron plasma and ion acoustic waves
  - Both affected by charge imbalance
  - Both have been observed during reconnection

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