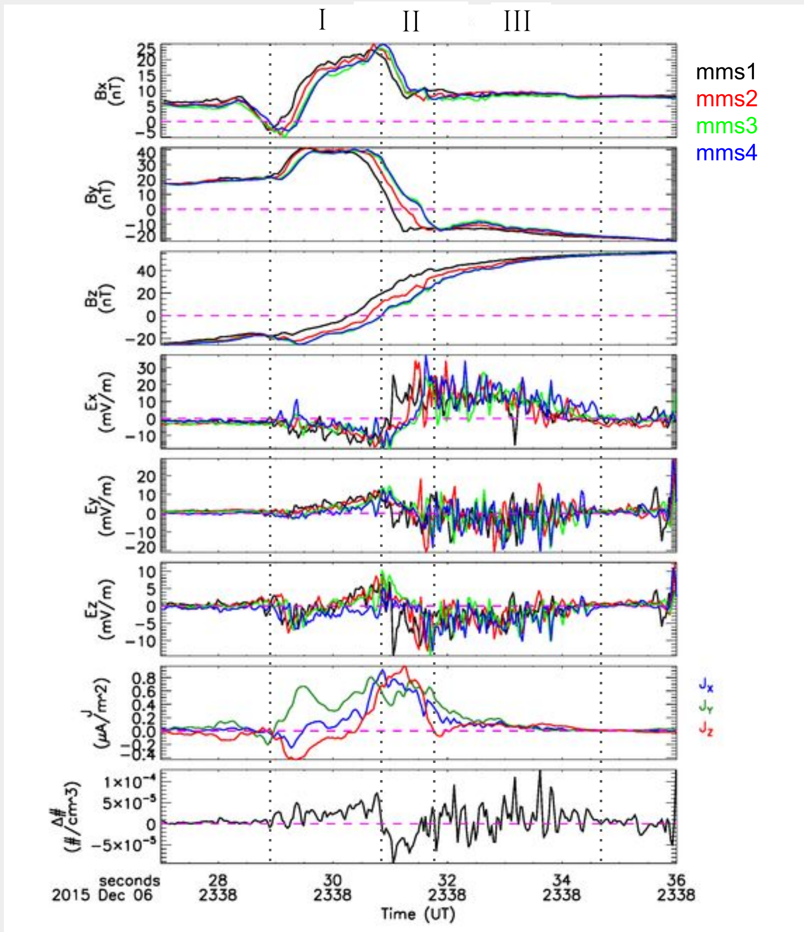
How Neutral is Quasi-Neutral: Charge Density in the Reconnection Diffusion Region Observed by MMS

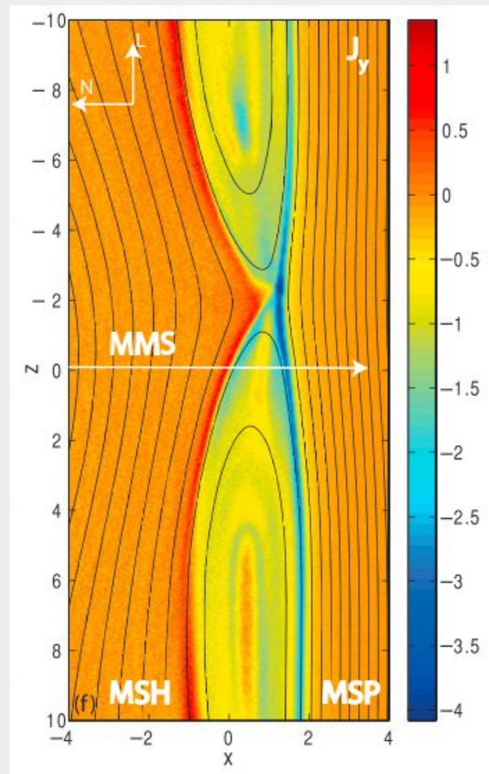
Matthew R. Argall[1] (matthew.argall@unh.edu), J. Shuster[2], I. Dors[1], K. J. Genestreti[3], T. K. M. Nakamura[4], R.B. Torbert[1,3], J. M. Webster[5], N. Ahmadi[6], R.E. Ergun[6], R. J. Strangeway[7], B. L. Giles[8], J. L. Burch[3]

[1]University of New Hampshire, Durham, NH, USA; [2]University of Maryland, College Park, MD; [3]EOS Southwest Research Institute, Durham, NH; [4]Space Research Institute, Austrian Academy of Sciences, Graz, Austria; [5]Rice University, Houston, TX; [6]Laboratory of Atmospheric and Space Physics, Boulder, CO, USA; [7]University of California, Los Angeles, Los Angeles, CA, USA; [8]Goddard Space Flight Center, Greenbelt, MD, USA; [9]Southwest Research Institute, San Antonio, TX, USA

Charge Density in Other Contexts

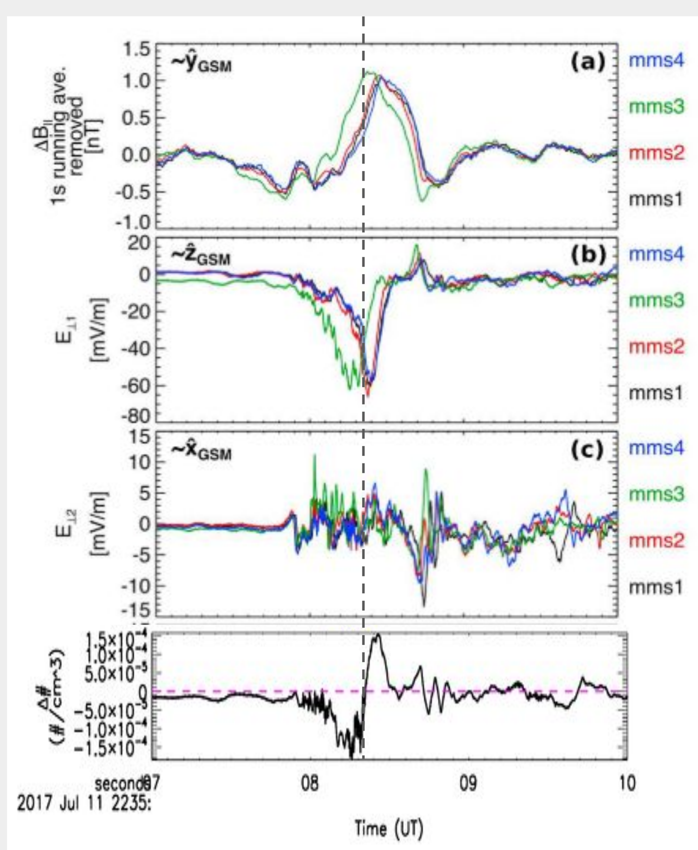
Asymmetric Reconnection

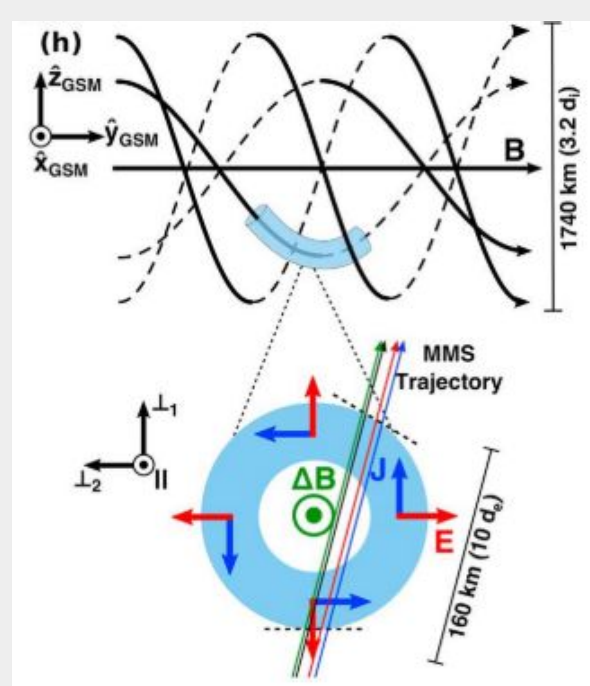




- Regions I, II, & III are the same as the symmetric case
- Hall fields and currents detected
- Ratio of charge density to background density is 10^{-3}%

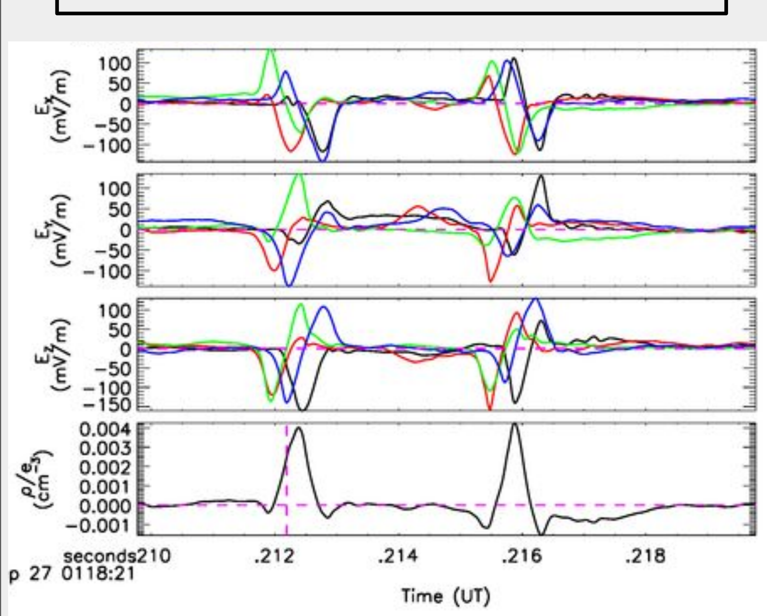
Magnetic Hole

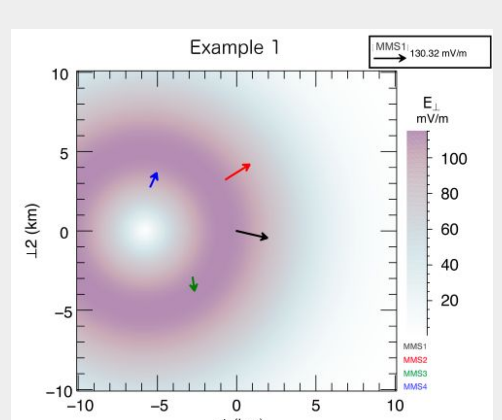


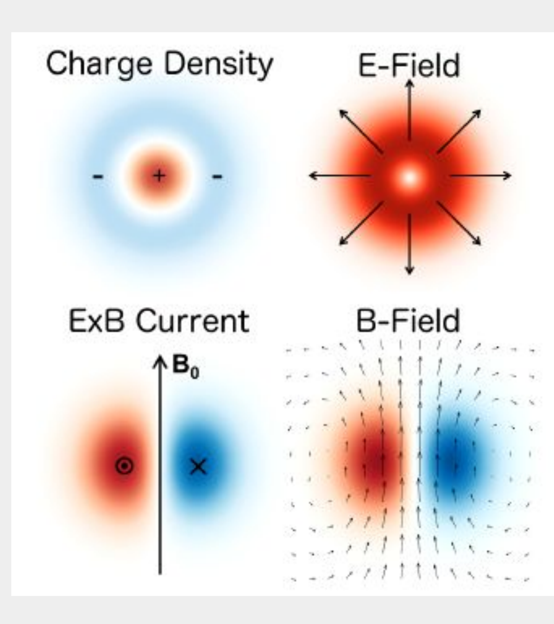


- ρ < 0 until all S/C are within the hole
- ρ > 0 inside the hole
- Suggests an electron sheath in vortex region
- Ratio of charge density to background density is 0.25%

Electron Phase-Space Hole

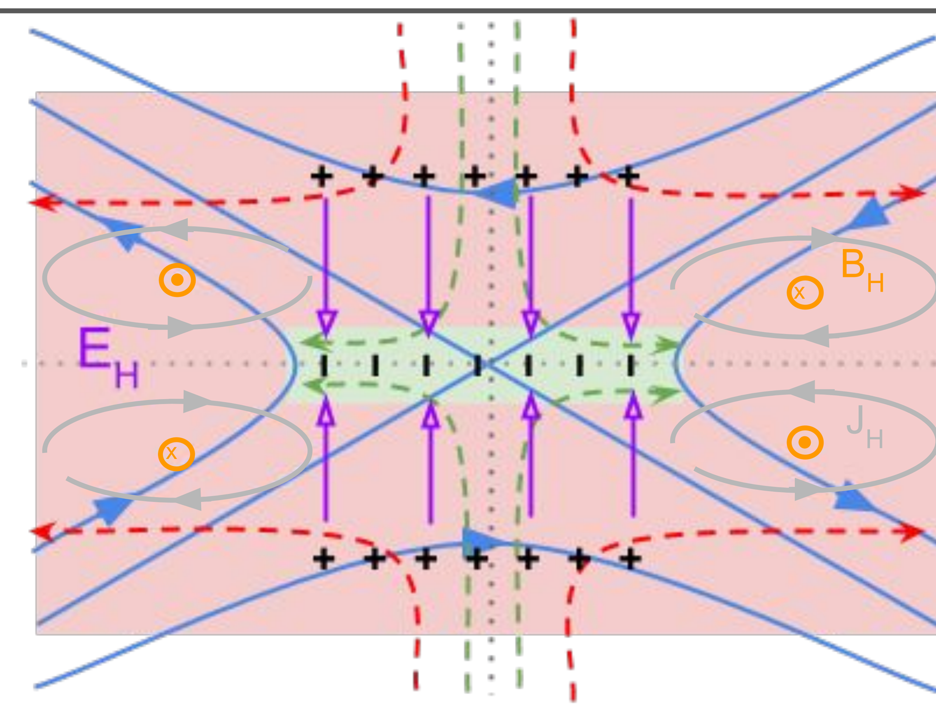






- *In-situ* observations match theory
  - ρ < 0 at edges of hole
  - ρ > 0 inside the hole
- Ratio of charge density to background density is 4%

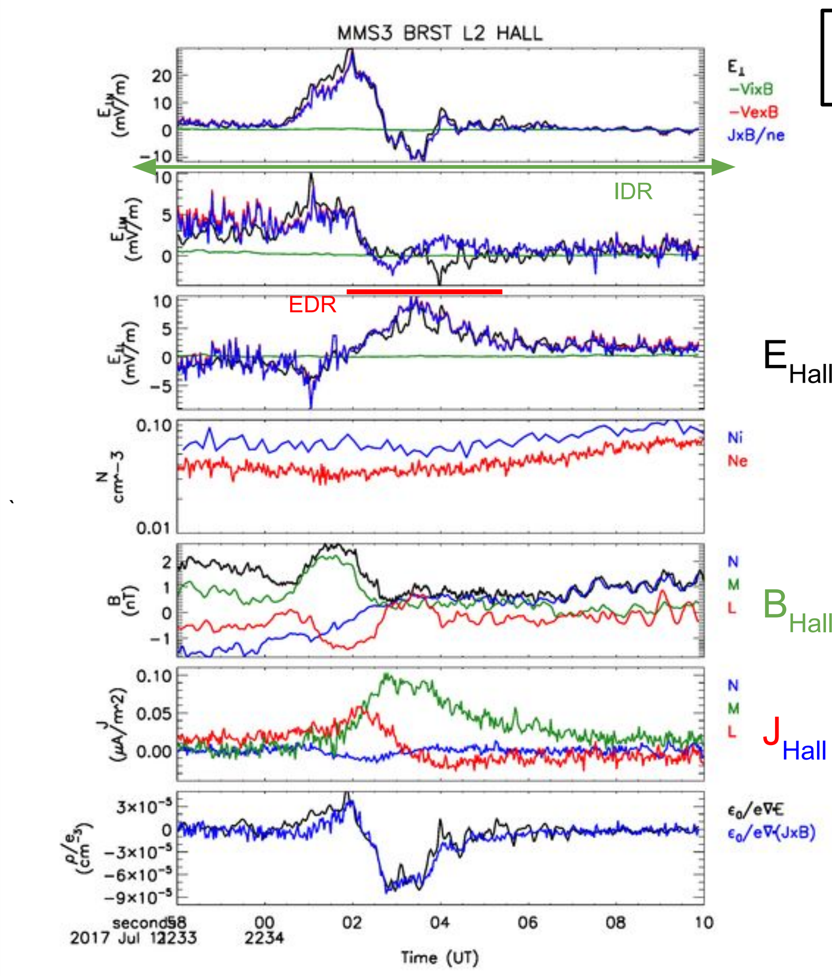
Charge Density in the Symmetric Reconnection Diffusion Region

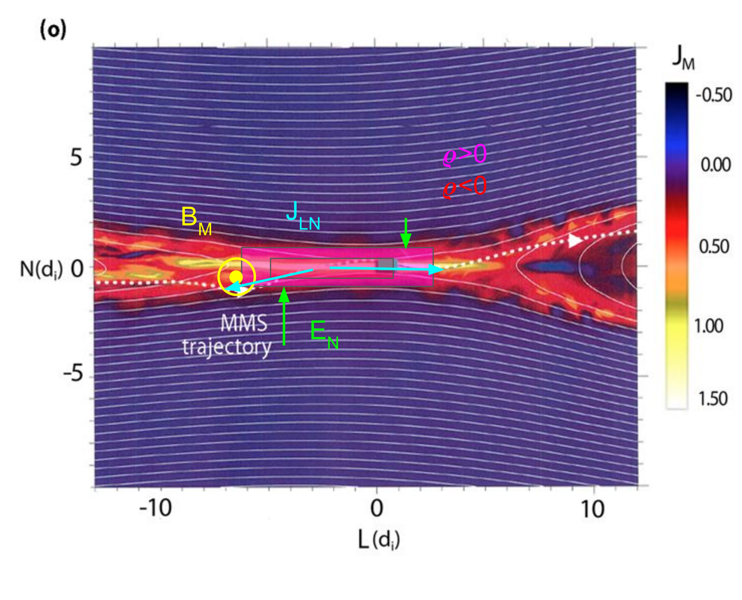


Charge density and the Hall system

- 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

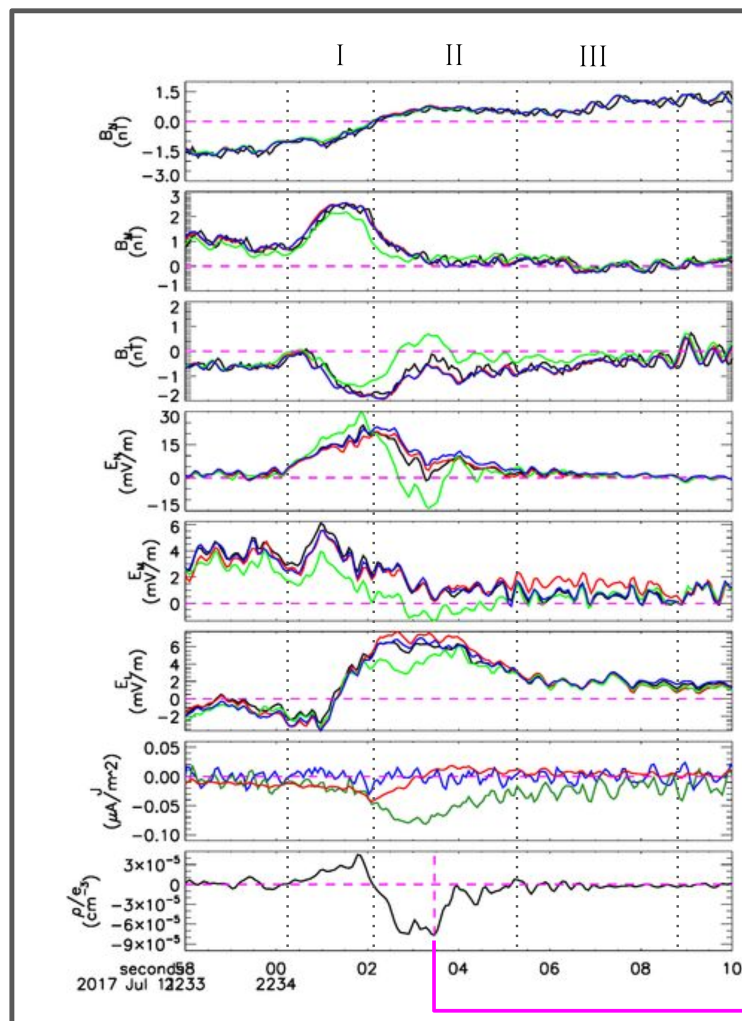
MMS Example 2017-07-17

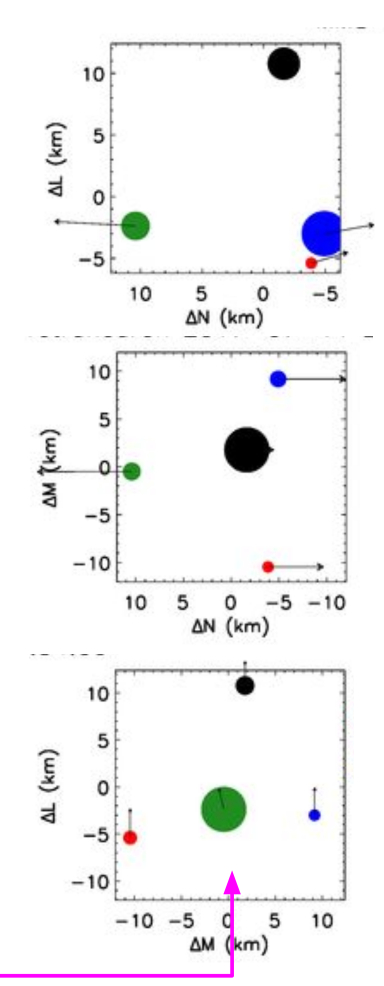




- E-field in S/C frame is dominated by **JxB**
- Hall fields and currents detected
- Ratio of charge density to background density is 1%

Multi S/C Perspective





Region I

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

Region II

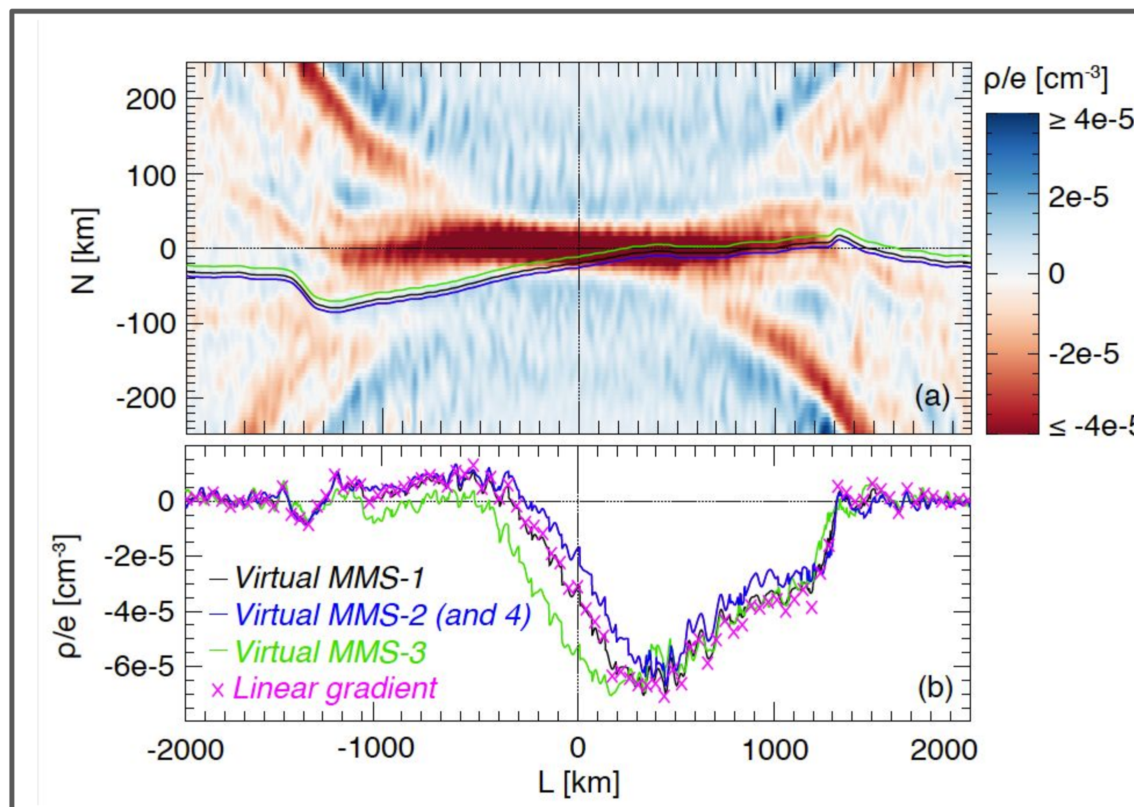
- S/C differences intensify in EDR
- Entry into EDR
- Net negative charge density

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

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

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 x 10^{-4} cm^{-3}

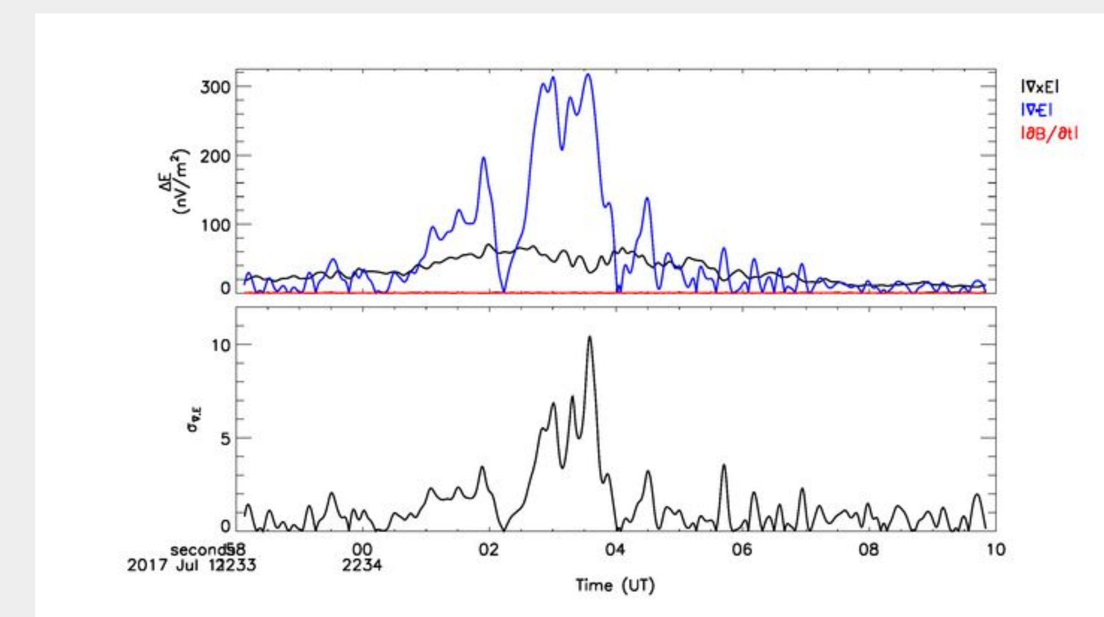
= 46 nV/m^2

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

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

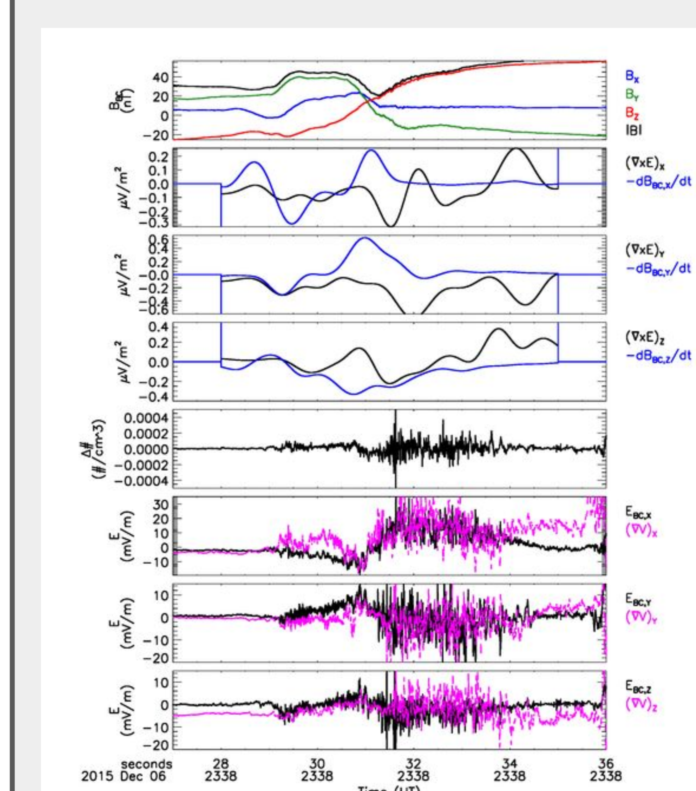
E is sampled 64x faster than B so averaging reduces the error by 8.

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

References

Torbert, R. B., Burch, J. L., Phan, T. D., Hesse, M., Argall, M. R., Shuster, J., … Saito, Y. (2018). Electron-scale dynamics of the diffusion region during symmetric magnetic reconnection in space. *Science*. https://doi.org/10.1126/science.aat2998

Nakamura, T. K. M., Genestreti, K. J., Liu, Y.-H., Nakamura, R., Teh, W.-L., Hasegawa, H., … Giles, B. L. (2018). Measurement of the Magnetic Reconnection Rate in the Earth's Magnetotail. *Journal of Geophysical Research: Space Physics*, *123*(11), 9150–9168. https://doi.org/10.1029/2018JA025713

Stawarz, J. E., Eastwood, J. P., Genestreti, K. J., Nakamura, R., Ergun, R. E., Burgess, D., … Torbert, R. B. (2018). Intense Electric Fields and Electron-Scale Substructure Within Magnetotail Flux Ropes as Revealed by the Magnetospheric Multiscale Mission. *Geophysical Research Letters*, *0*(0), 1–10. https://doi.org/10.1029/2018GL079095

Holmes, J. C., Ergun, R. E., Newman, D. L., Ahmadi, N., Andersson, L., Le Contel, O., … Burch, J. L. (2018). Electron Phase-Space Holes in Three Dimensions: Multispacecraft Observations by Magnetospheric Multiscale. *Journal of Geophysical Research: Space Physics*, *123*(12), 9963–9978. https://doi.org/10.1029/2018JA025750

Khotyaintsev, Y. V., Graham, D. B., Norgren, C., Eriksson, E., Li, W., Johlander, A., … Burch, J. L. (2016). Electron jet of asymmetric reconnection. *Geophysical Research Letters*, *43*(11), 5571–5580. https://doi.org/10.1002/2016GL069064