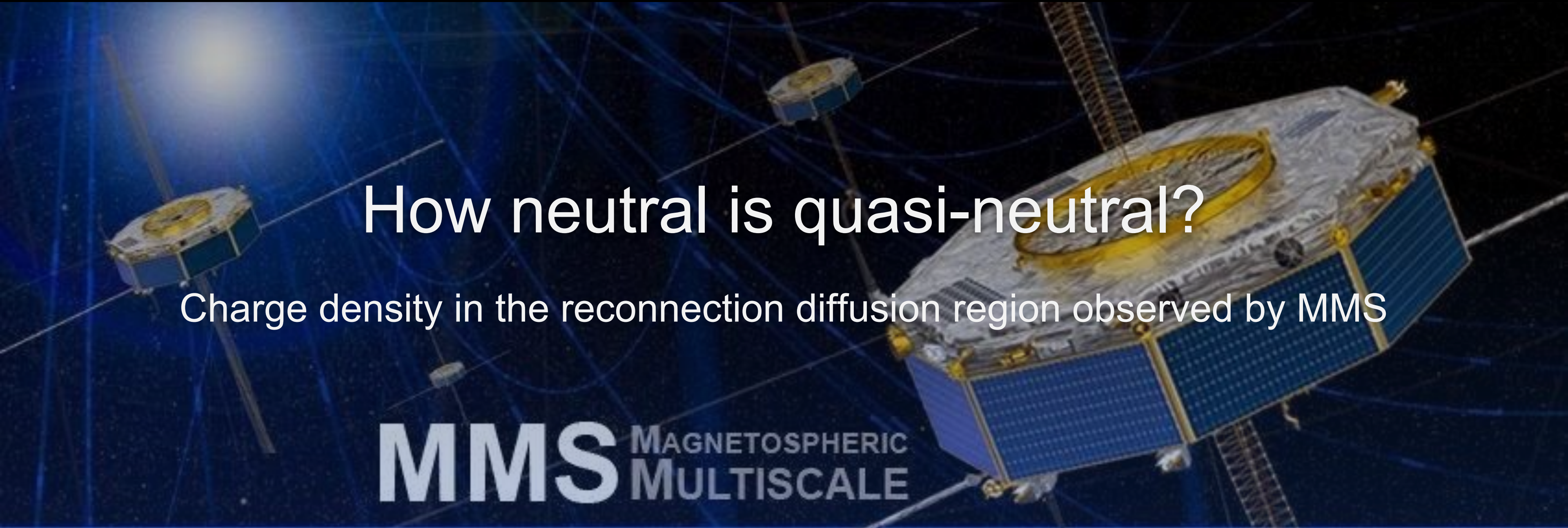
How neutral is quasi-neutral?

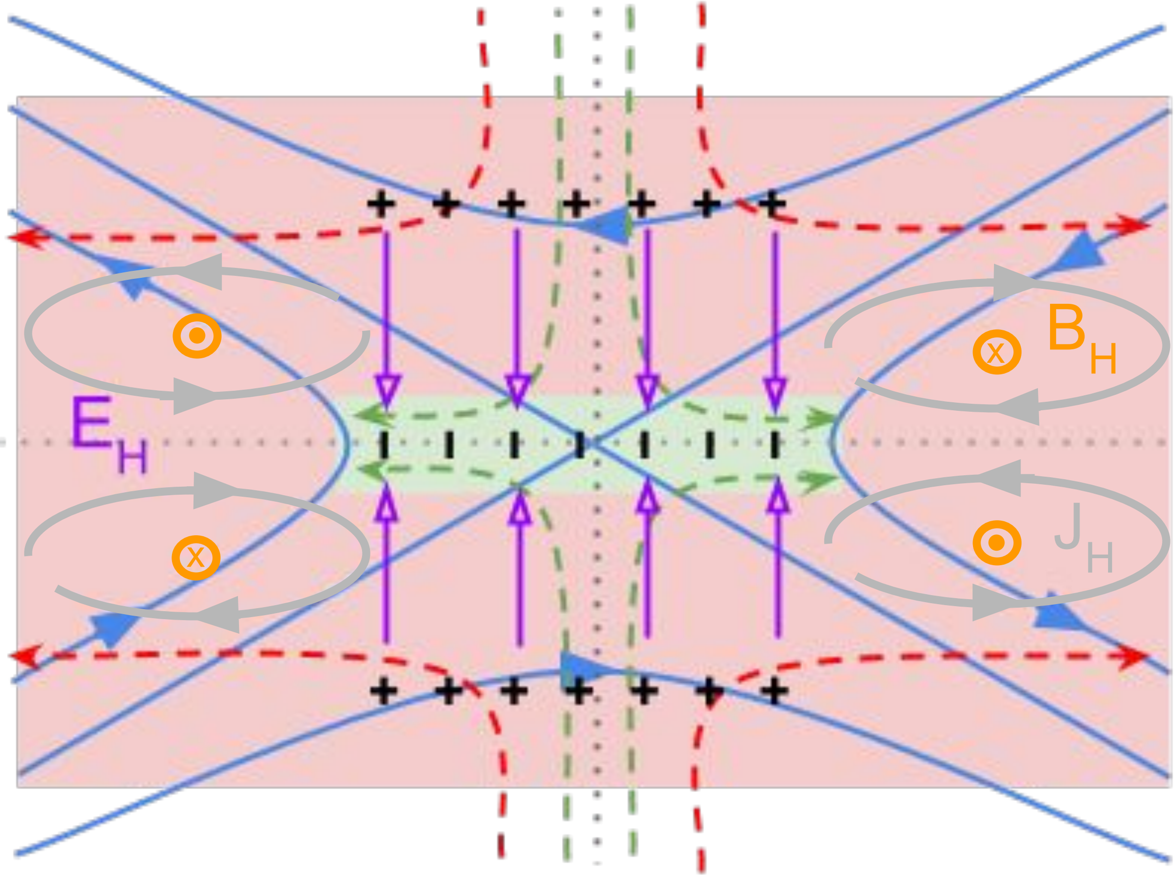
Charge density in the reconnection diffusion region observed by MMS



M. R. Argall, J. R. Shuster, I. Dors, K. J. Genestreti, T. K. M. Nakamura, R. B. Torbert, J. M. Webster, N. Ahmadi, R. E. Ergun, R. J. Strangeway, B. L. Giles, and J. L. Burch

Outline

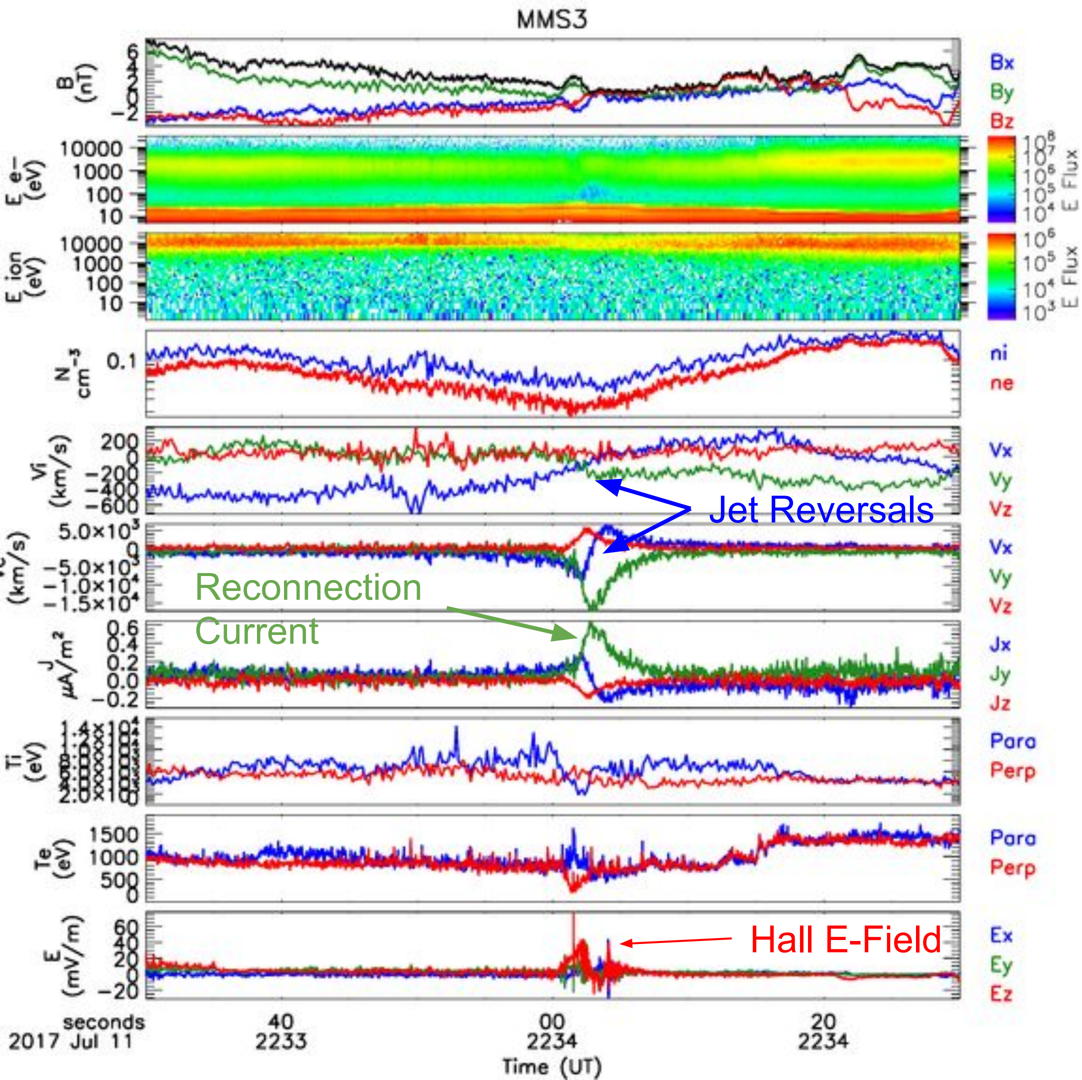
- Picture of ϱ in the Hall system
- ϱ in the magnetotail diffusion region
- ϱ in other contexts
  - Magnetopause reconnection
  - Electron-scale magnetic peak
  - Electron phase space hole
- Errors
- Scalar potential
- Summary

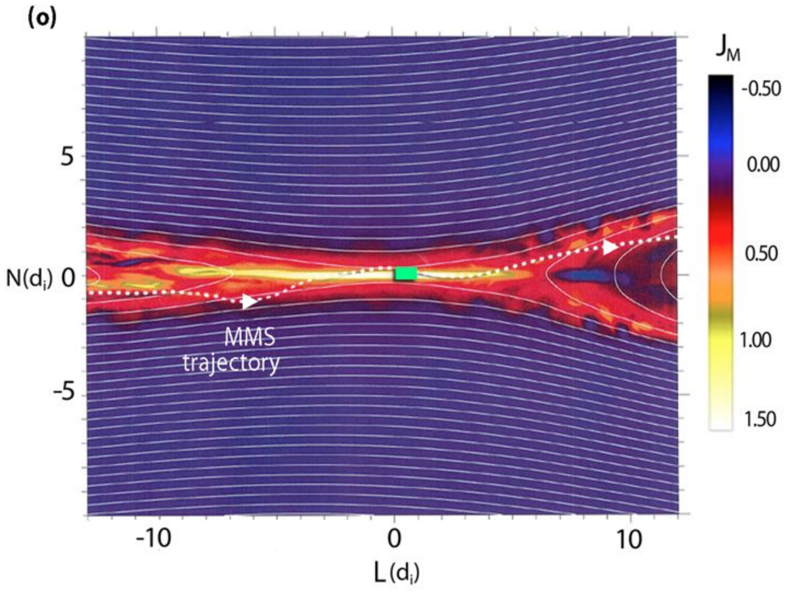

B H
E H
J H

ϱ

Magnetotail EDR

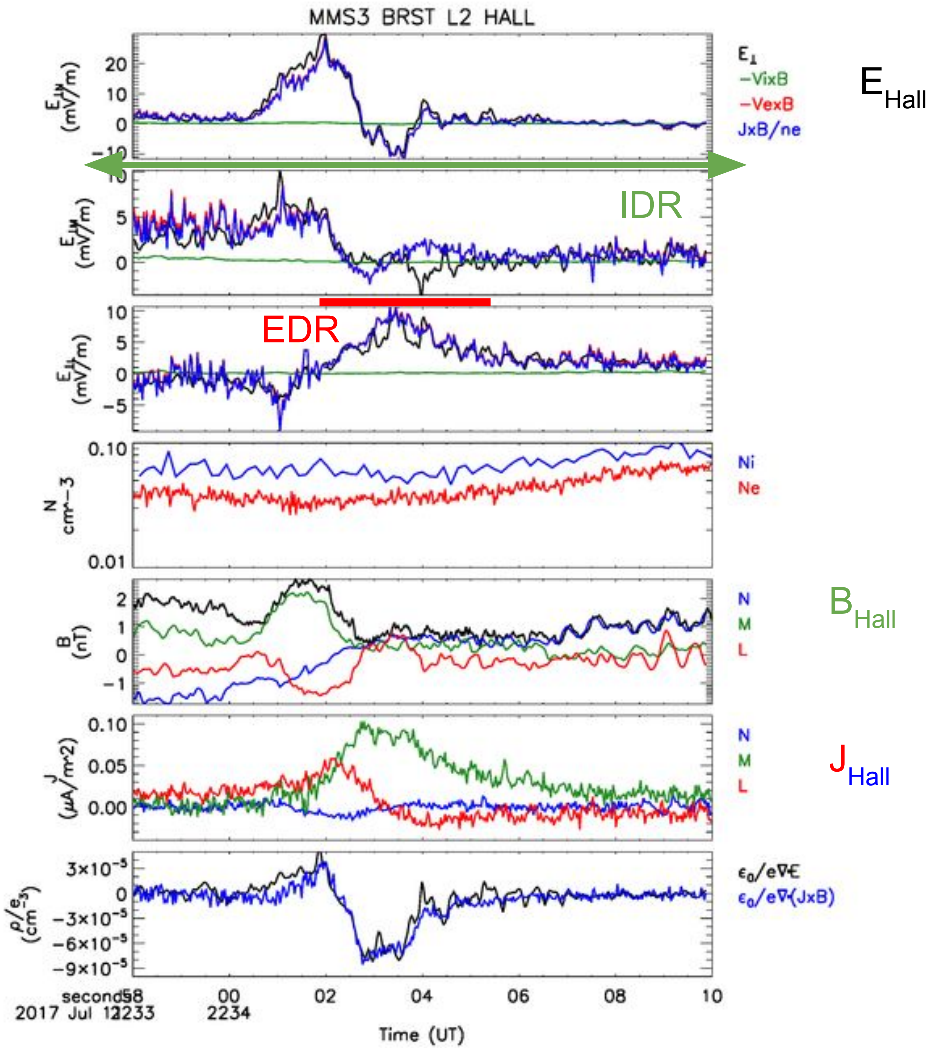
Trobert, et al., Science 2018

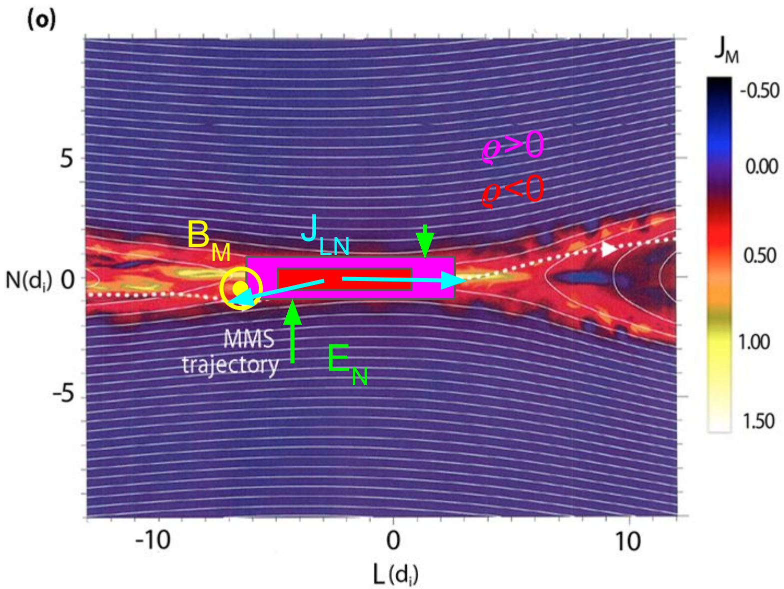


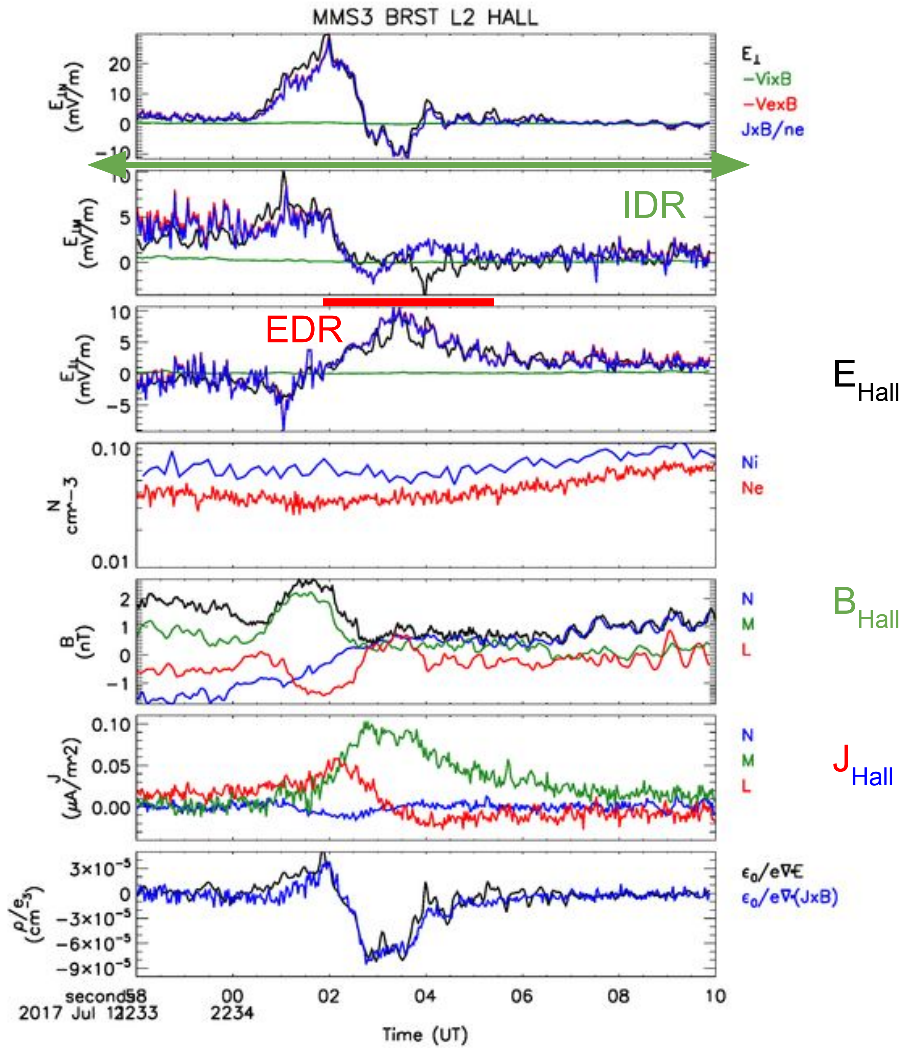


Hall System

- **E** balanced largely by **J**x**B**/ne
  - E_{Hall} weak at edges of IDR
- **J** supports $+B_Y$
  - $-J_Z$ as e- flow into X-line,
  - $+J_X$ as e- jet into tail exhaust
- $\varrho > 0$ ($\varrho < 0$) in outer (inner) diffusion region
- ~1×10^{-4} excess electrons




(o)
J_M
B_M
J_{LN}
$\varrho>0$
$\varrho<0$
MMS trajectory
E_N
N(d_i)
L(d_i)


MMS3 BRST L2 HALL
IDR
EDR
E_{Hall}
B_{Hall}
J_{Hall}
Ni
Ne
$E_\perp$
-VixB
-VexB
JxB/ne
Time (UT)
2017 Jul 12

ñ/N ~ 1%

CS Encounter

Region I

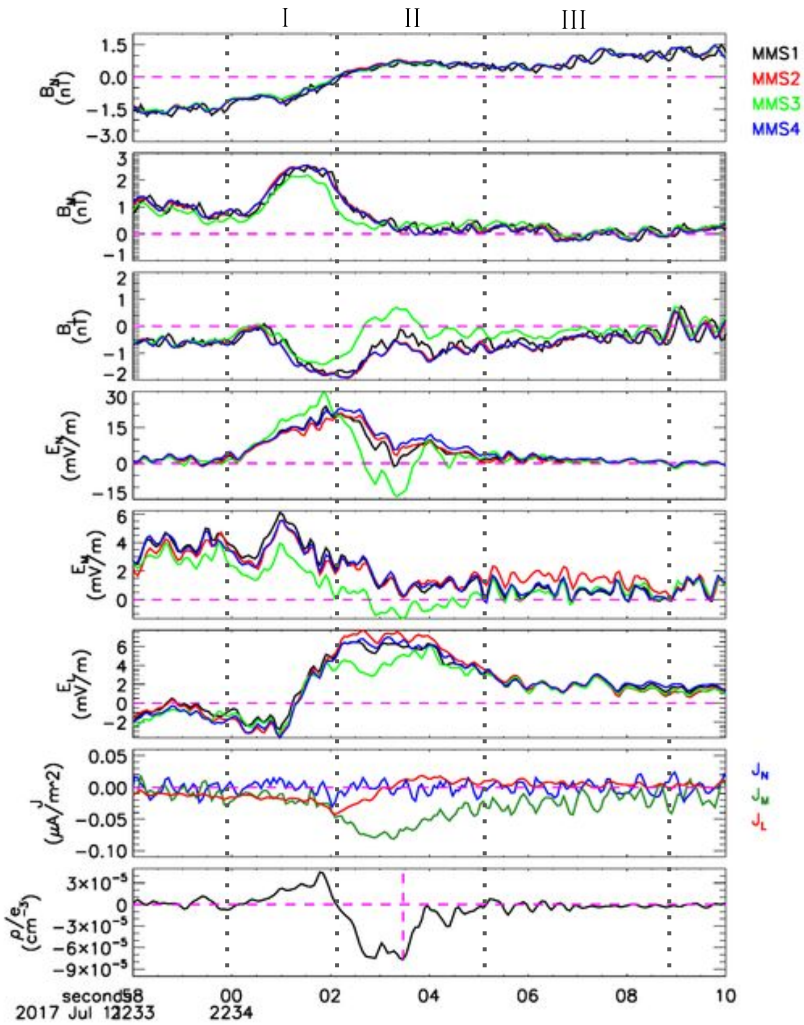
- **E** & **B** among spacecraft diverge -> enter IDR
- $\varrho > 0$

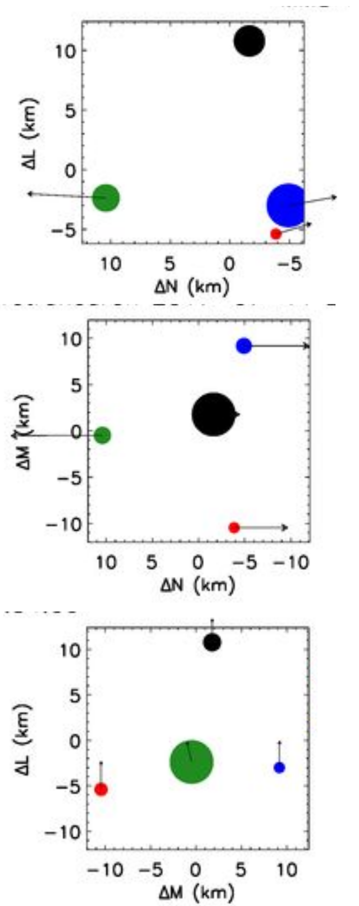
Region II

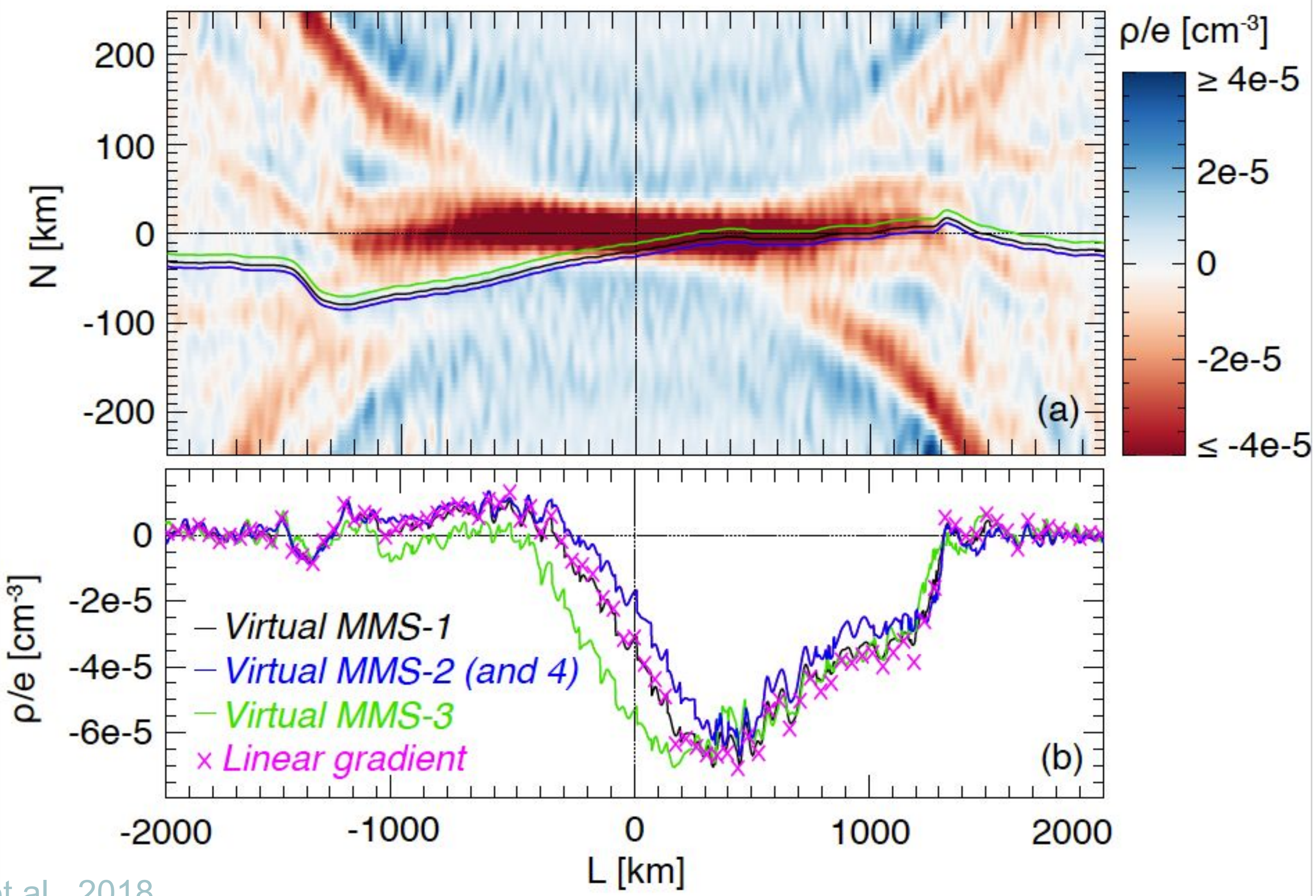
- Current peaks in EDR
- ϱ becomes negative

Region III

- **E** & **B** among spacecraft converge -> exit IDR
- $\varrho > 0$





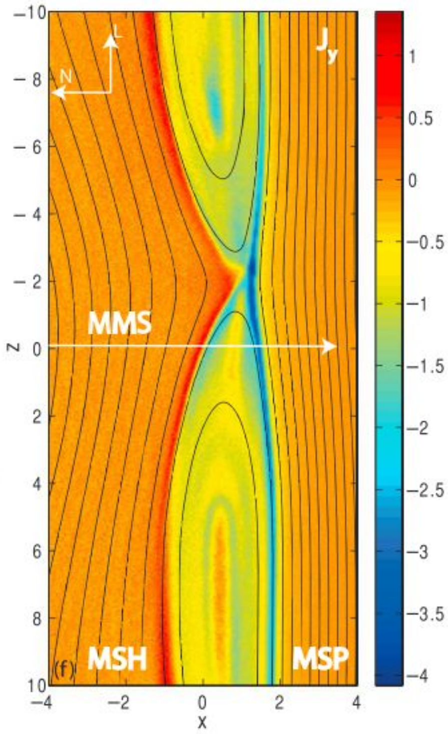


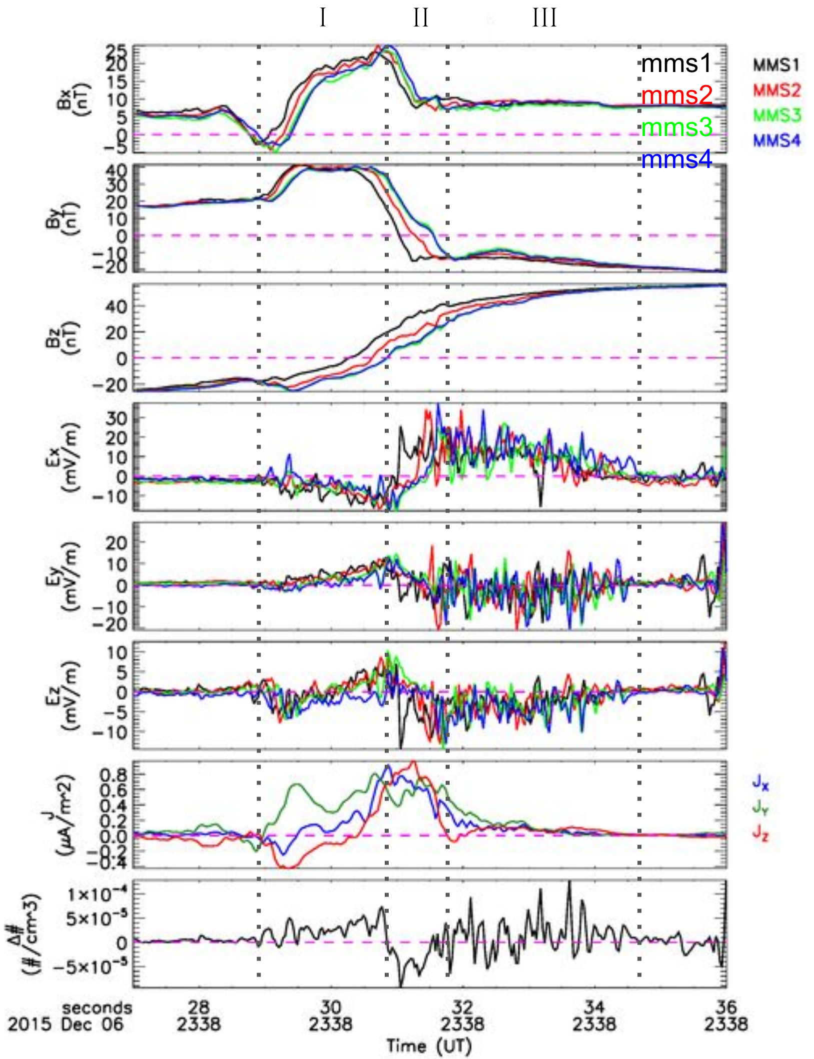
Nakamura, et al., 2018

$$\varrho$$

In Other Contexts

MP Encounter

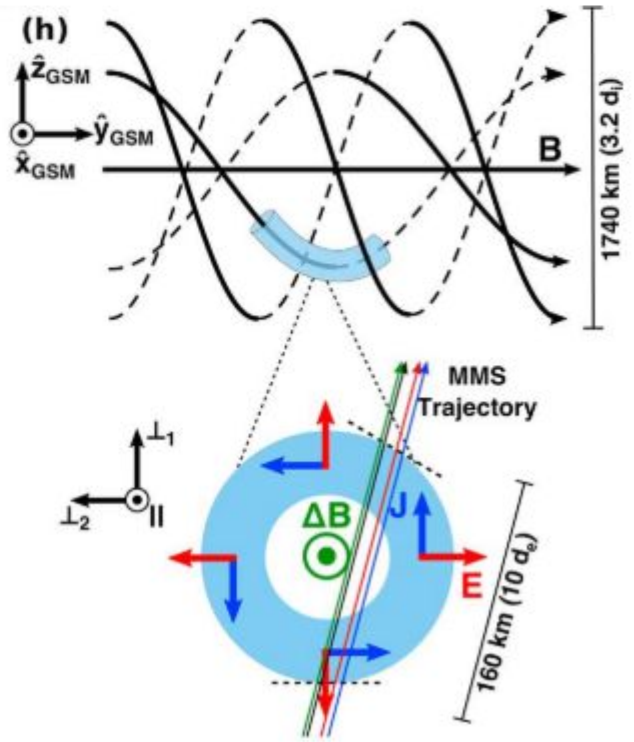


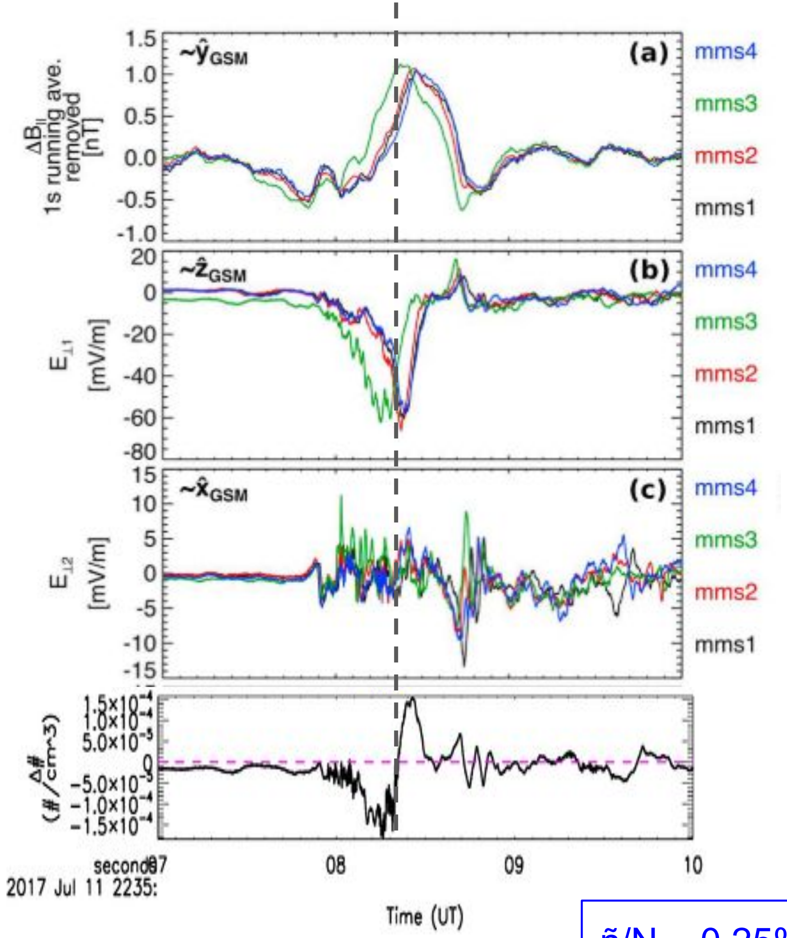


$\tilde{n}/N \sim 1\text{x}10^{-3}$ %

Khotyaintsev, et al., 2015

Magnetic Peak

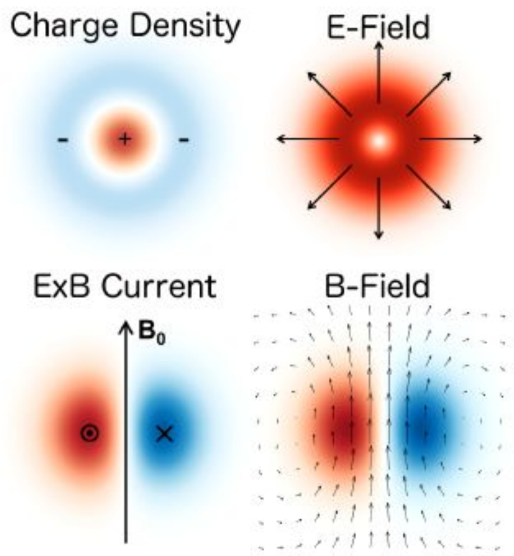


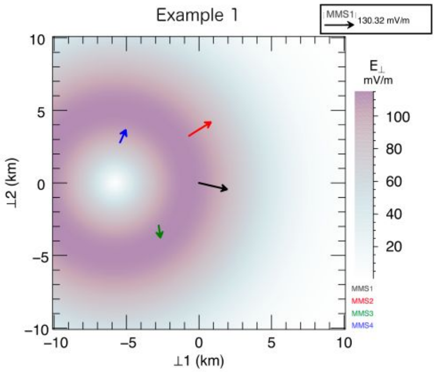


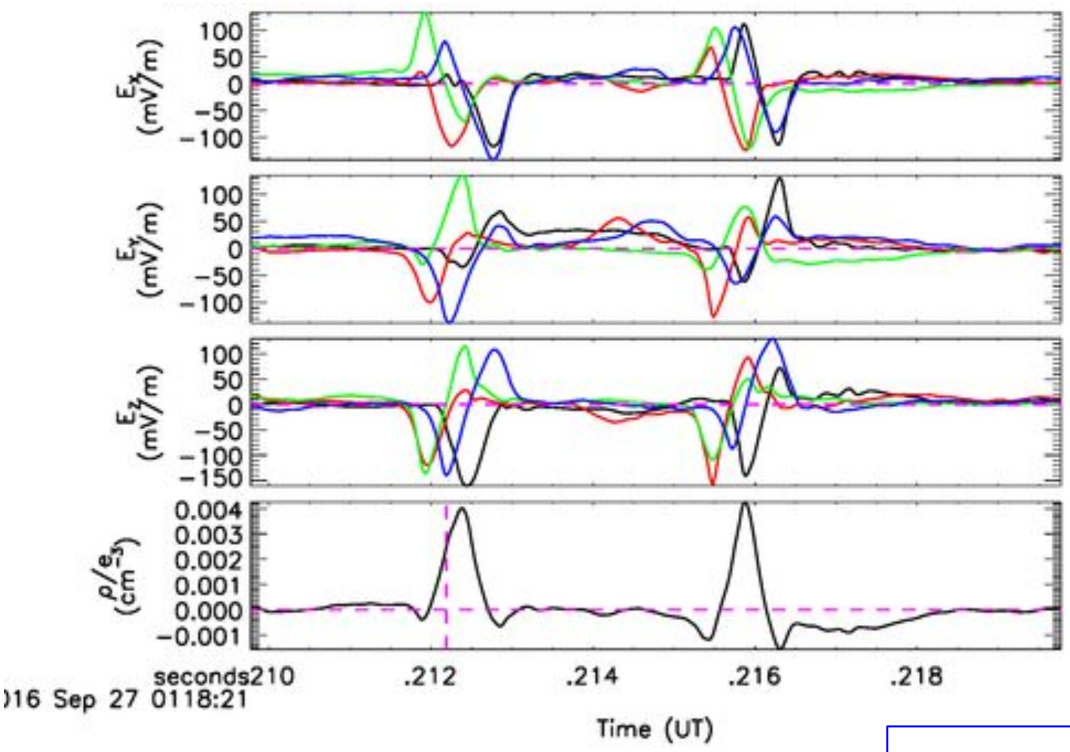
ñ/N ~ 0.25%

Stawarz, et al., GRL 2018

Electron Phase Space Hole







ñ/N ~ 4%

Holmes, et al., JGR 2018

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

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

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

$= 46\ nV/m^2$

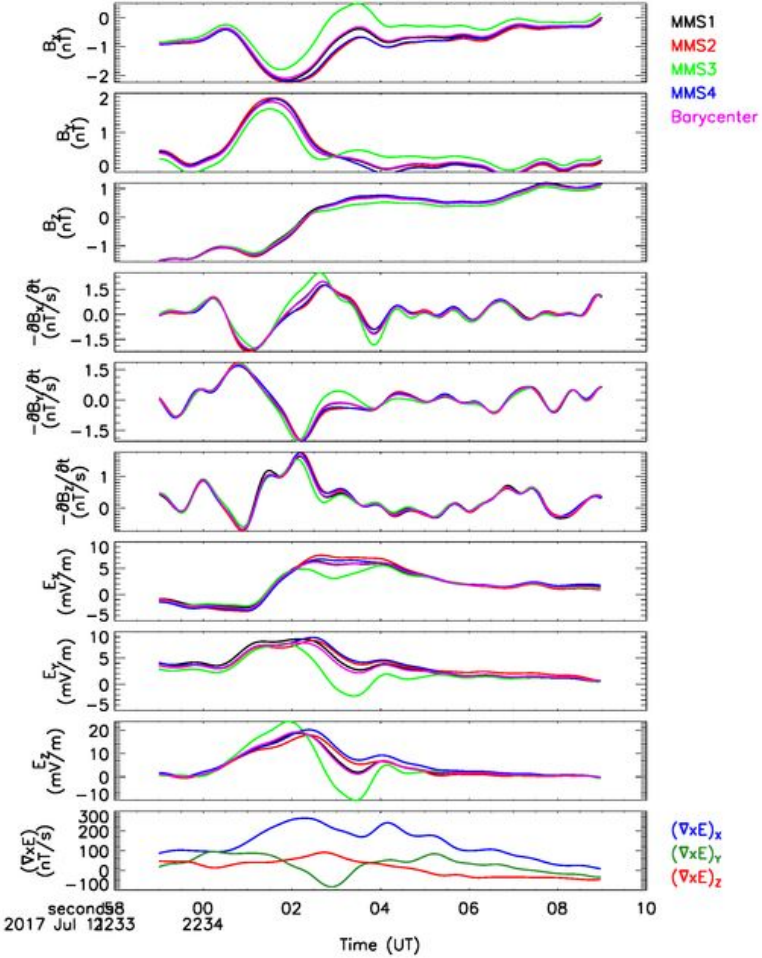
$$\sigma_{(\nabla\times E)_1} = \sqrt{\frac{4}{3}}\frac{0.5\,mV/m}{15\,km} = 3.8\times10^{-8}\,V/m = 38\,nT/s$$

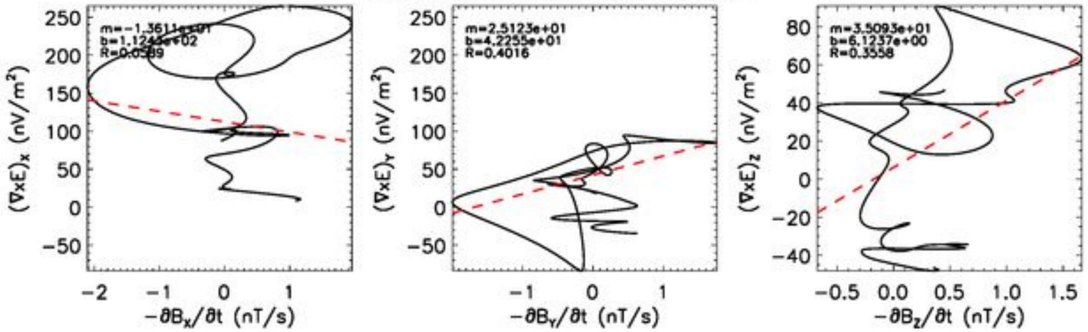
$$\sigma_{\dot{B}} = \sqrt{2}\frac{0.05\,nT}{0.008\,s} \approx 9\,nT/s$$

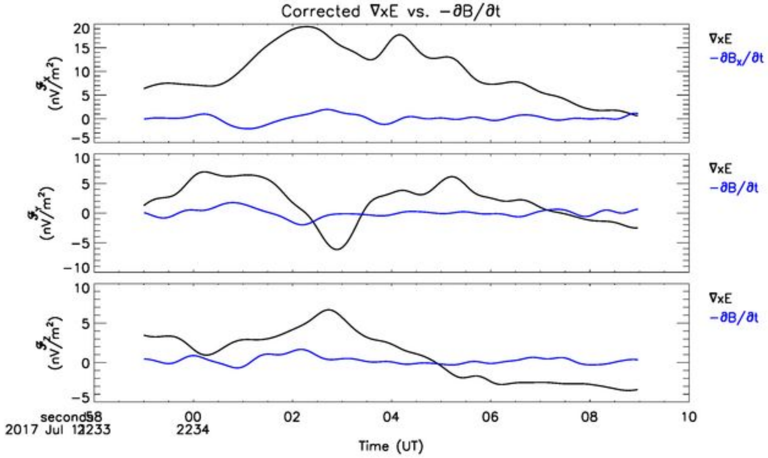
E is sampled 64x faster than B so averaging reduces the error by 8.

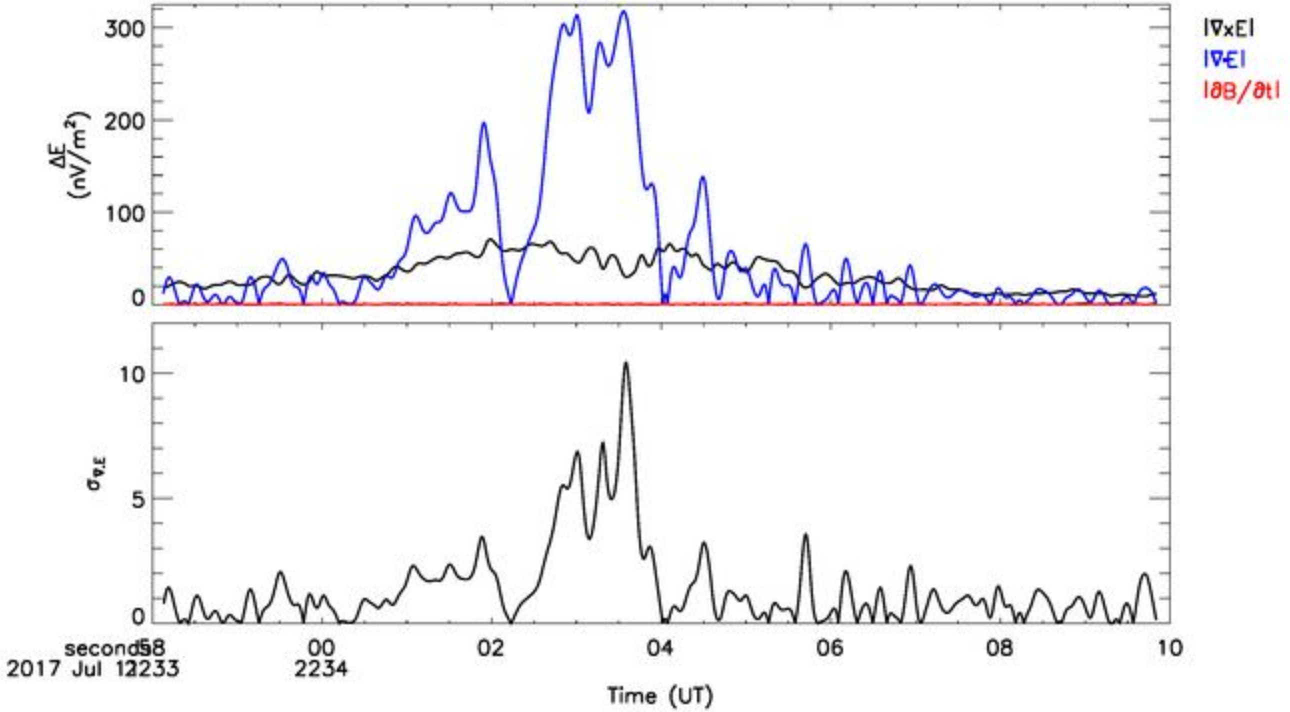
$$|\nabla \times B| \,/\, |\nabla \bullet B|$$

$$= |\nabla \cdot E| \,/\, |\nabla \times E - \partial B/\partial t|$$


MMS1
MMS2
MMS3
MMS4
Barycenter
(∇xE)x
(∇xE)y
(∇xE)z
seconds 58
2017 Jul 12 2233
00
2234
Time (UT)

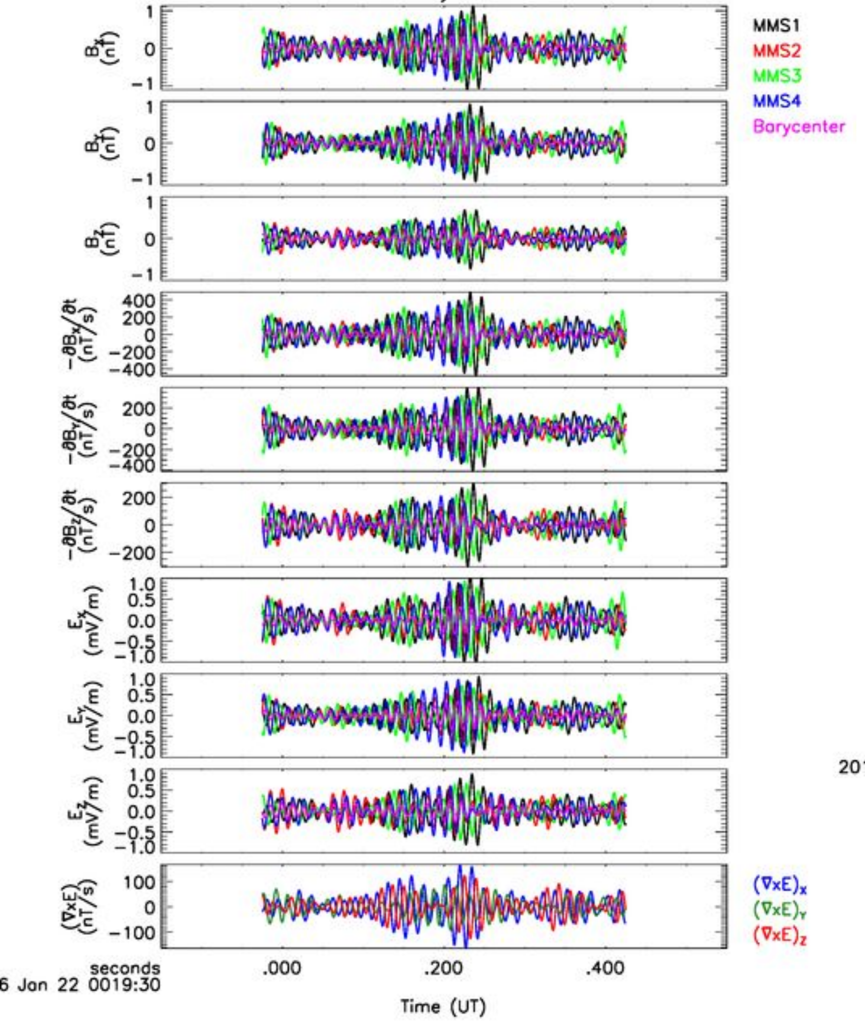

m=2.5123e+01
b=4.2255e+01
R=0.4016
m=3.5093e+01
b=6.1237e+00
R=0.3558
−∂Bx/∂t (nT/s)
−∂By/∂t (nT/s)
−∂Bz/∂t (nT/s)
(∇xE)x (nV/m²)
(∇xE)y (nV/m²)
(∇xE)z (nV/m²)

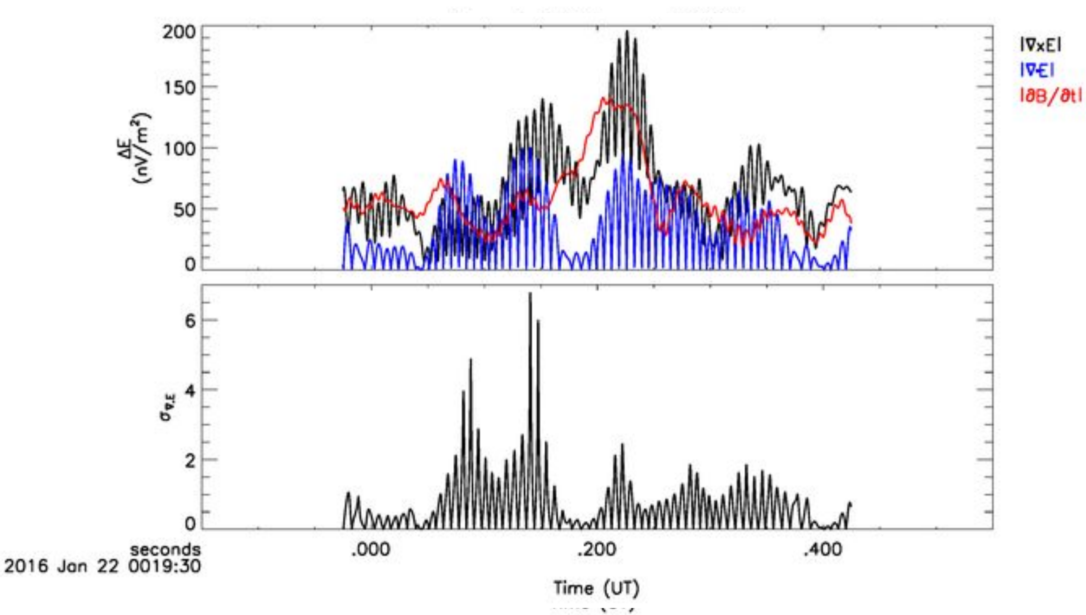

Corrected ∇xE vs. −∂B/∂t
∇xE
−∂Bx/∂t
∇xE
−∂B/∂t
∇xE
−∂B/∂t
seconds 58
2017 Jul 12 2233
00
2234
Time (UT)



300
200
100
0
ΔE (nV/m²)
|∇xE|
|∇·E|
|∂B/∂t|
10
5
0
σ∇,E
seconds 58
2017 Jul 12 2233
00
2234
02
04
06
08
10
Time (UT)

Magnetosheath Lion Roar

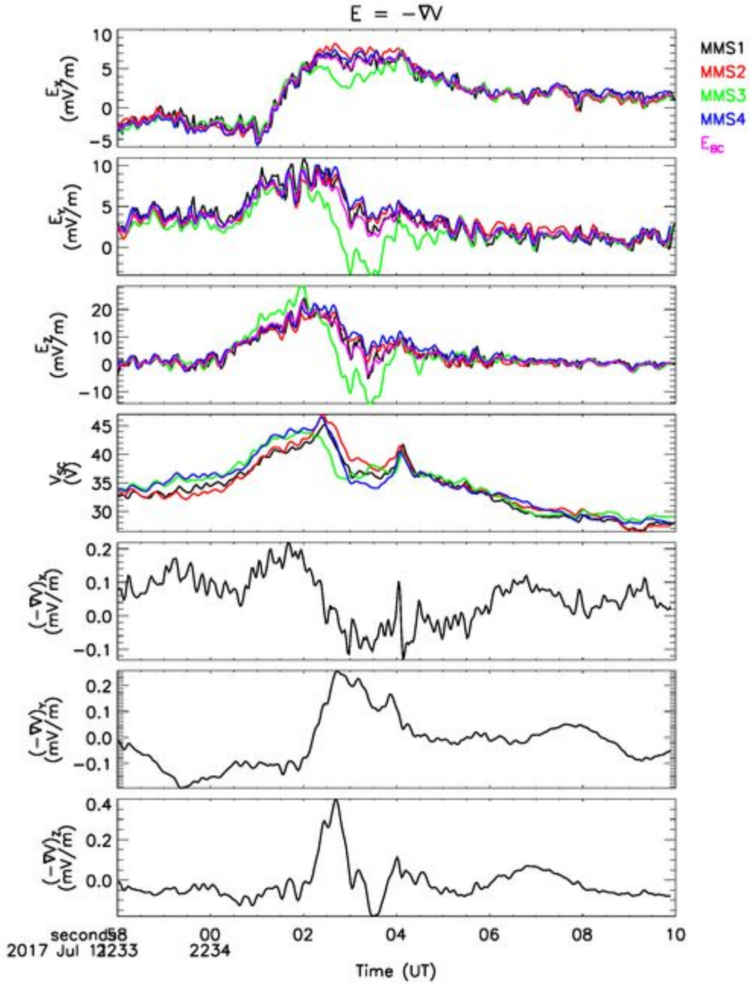


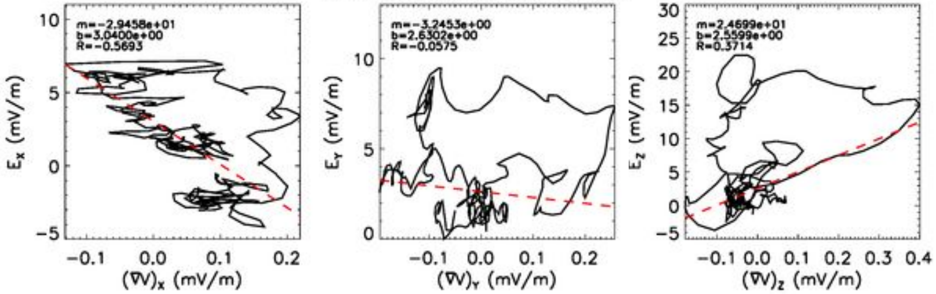


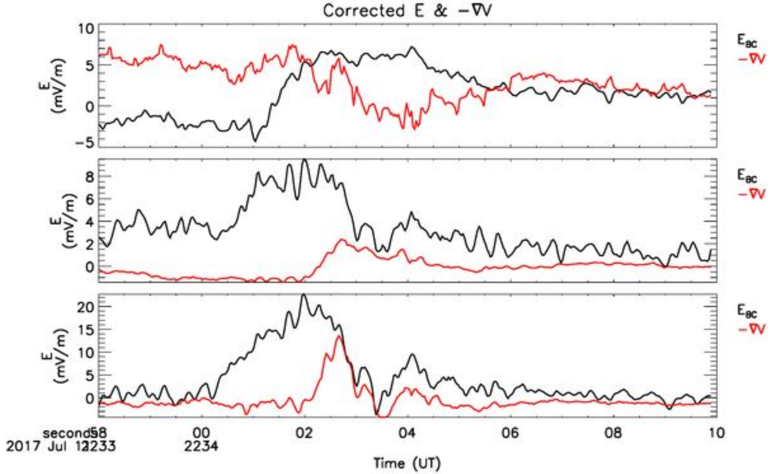
Scalar Potential

$$\nabla \cdot E \gg |\nabla \times E| = -|\partial B/\partial t| \approx 0?$$

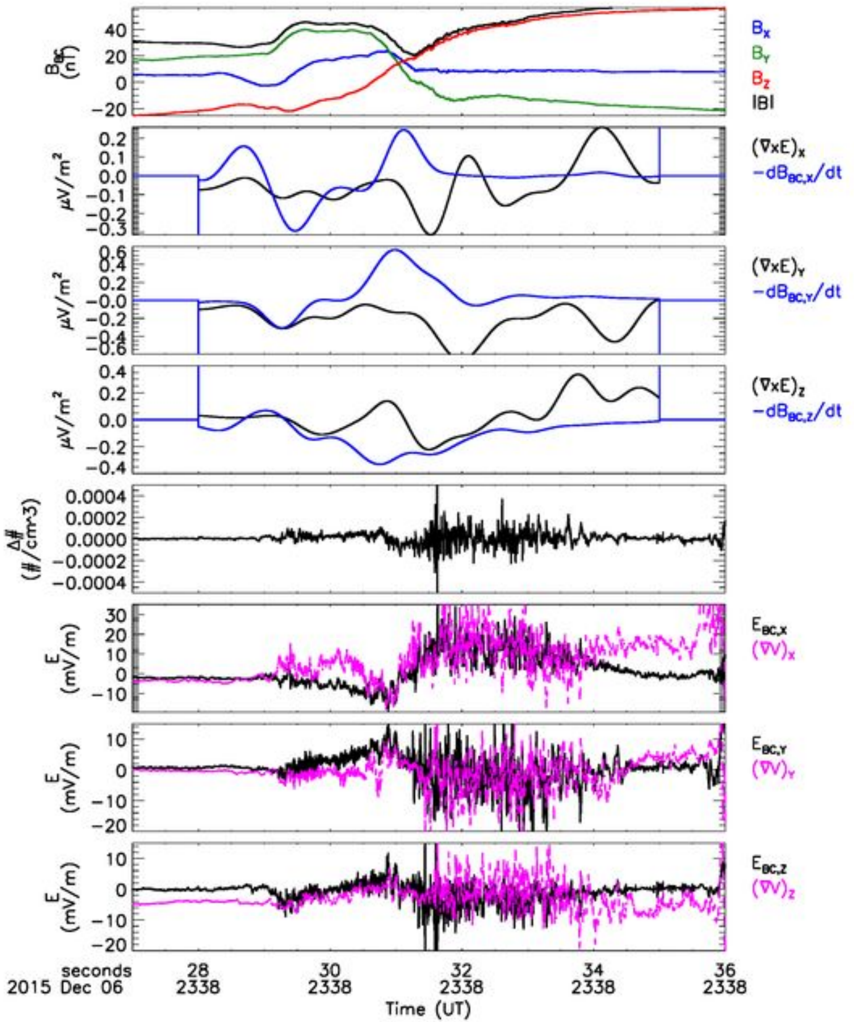
$$E = -\nabla V_{sc}$$


E = −∇V
MMS1
MMS2
MMS3
MMS4
E_BC
Time (UT)


m=−2.9458e+01
b=3.0400e+00
R=−0.5693
m=−3.2453e+00
b=2.6302e+00
R=−0.0575
m=2.4699e+01
b=2.5599e+00
R=0.3714


Corrected E & −∇V
Time (UT)

Magnetopause



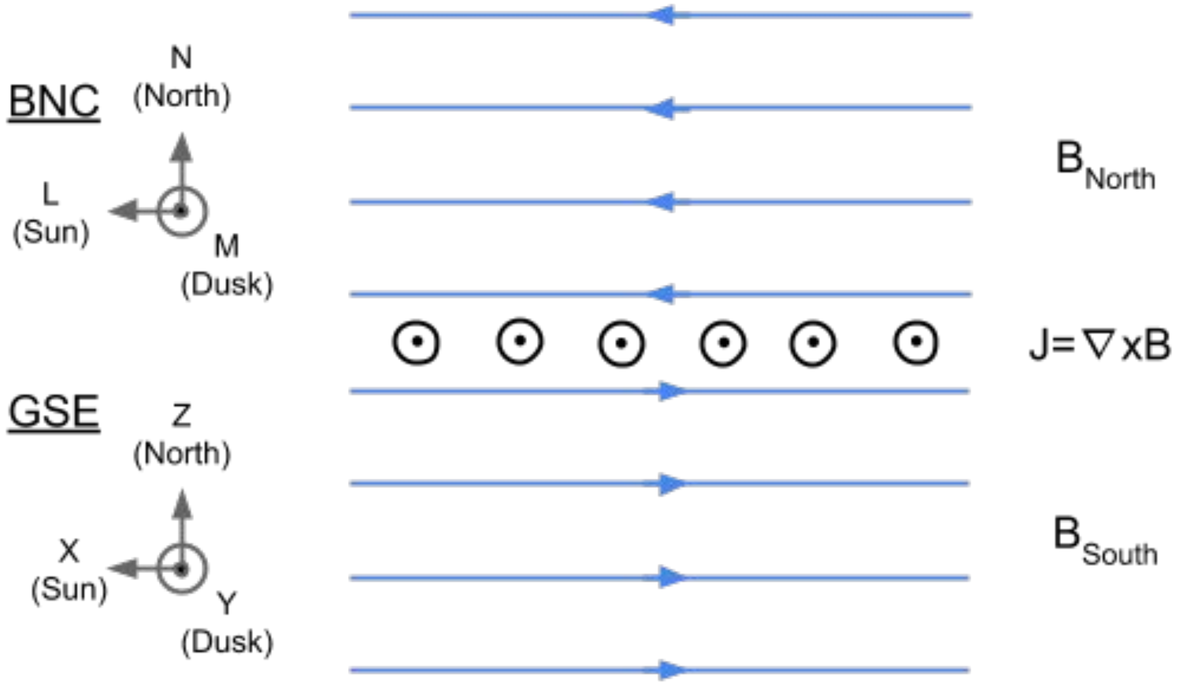
Summary

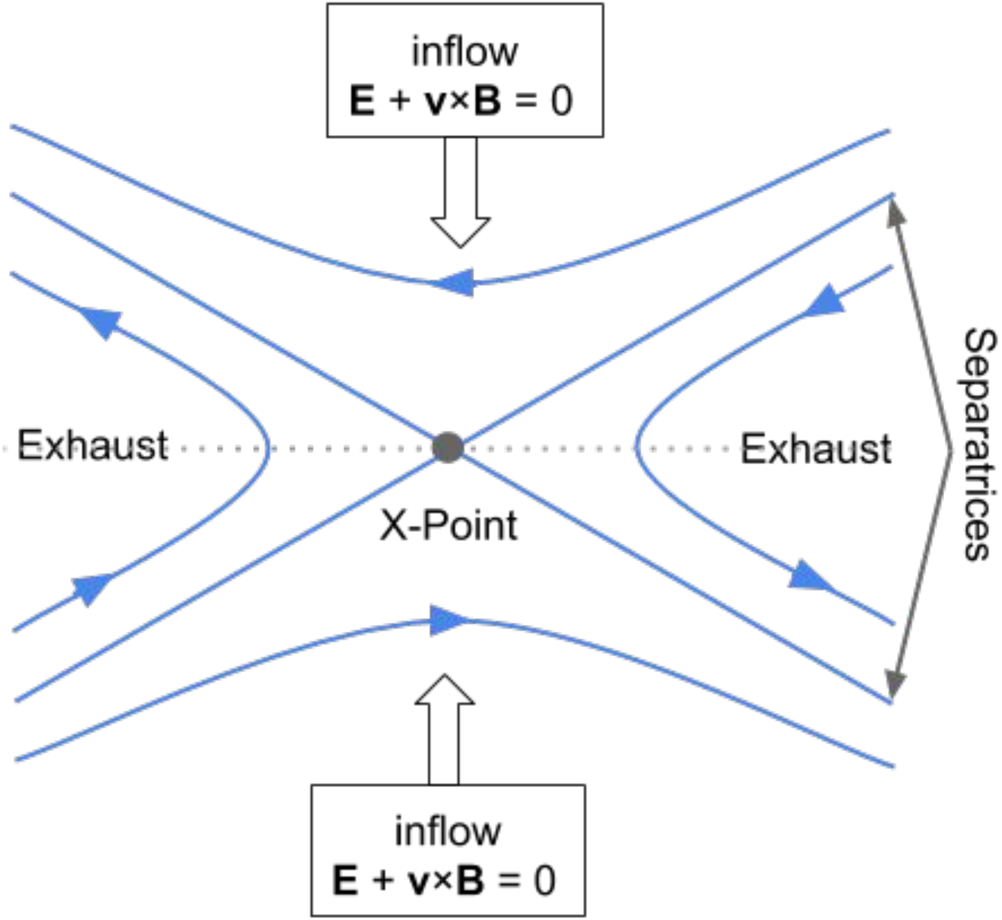
- Charge density profiles are consistent with the Hall B, E, and J signatures
- Net negative charge is embedded in regions of net positive charge
  - EDR within IDR
- ñ/N: Percent charge imbalance suggests plasma remains quasi-neutral
  - Tail: 1% Magnetic Peak: 0.25%
  - MP: 1×10^{-3}% Electron Hole: 4%
- ϱ is typically 1-2 orders of magnitude greater than the error threshold
- Propose $\nabla\cdot E / |\nabla\times E + \partial B/\partial t|$ as an error estimate
  - $\nabla\cdot E$ ($\nabla\times E$) is the sum (difference) of large (small) numbers
  - $\nabla\times E$ and $\partial B/\partial t$ are uncorrelated and on different scales
- $\partial B/\partial t \ll \nabla\cdot E$ would imply $E = -\nabla V$
  - Works better at the magnetopause

Thank you

Backups

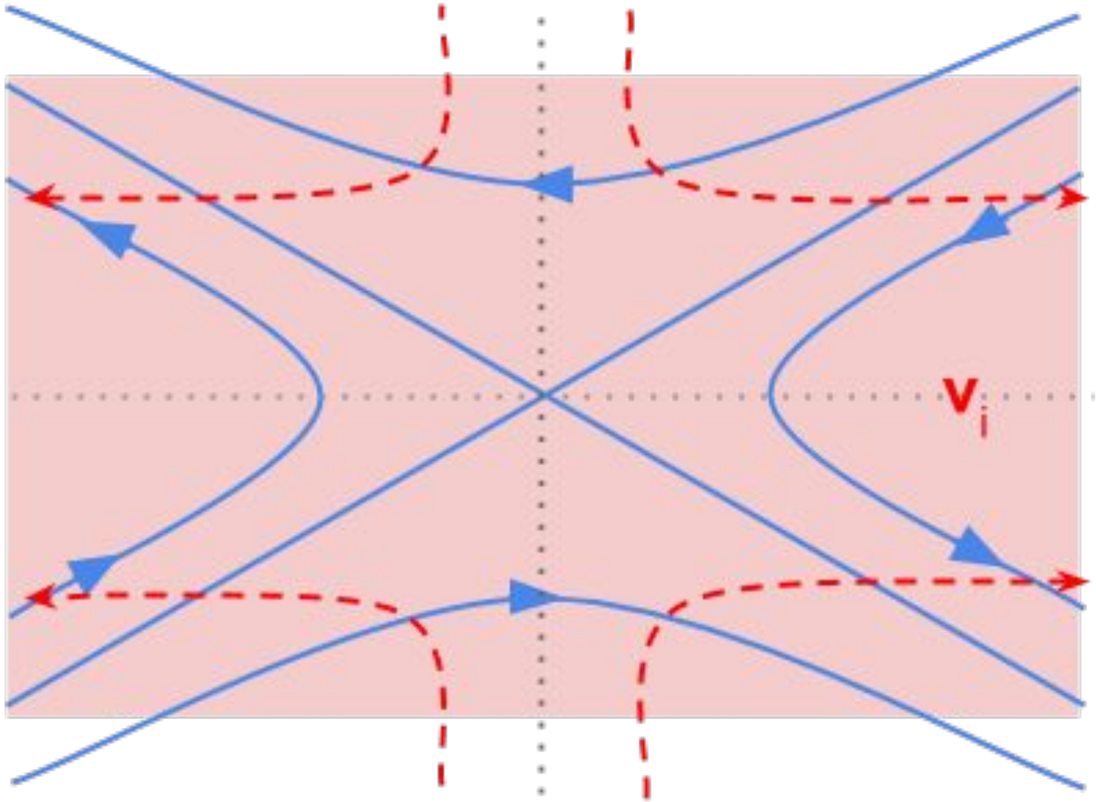
Hall System
(Symmetric Reconnection)


BNC
N
(North)
L
(Sun)
M
(Dusk)
GSE
Z
(North)
X
(Sun)
Y
(Dusk)
B North
J=∇xB
B South


inflow
E + v×B = 0
Exhaust
Exhaust
X-Point
Separatrices
inflow
E + v×B = 0

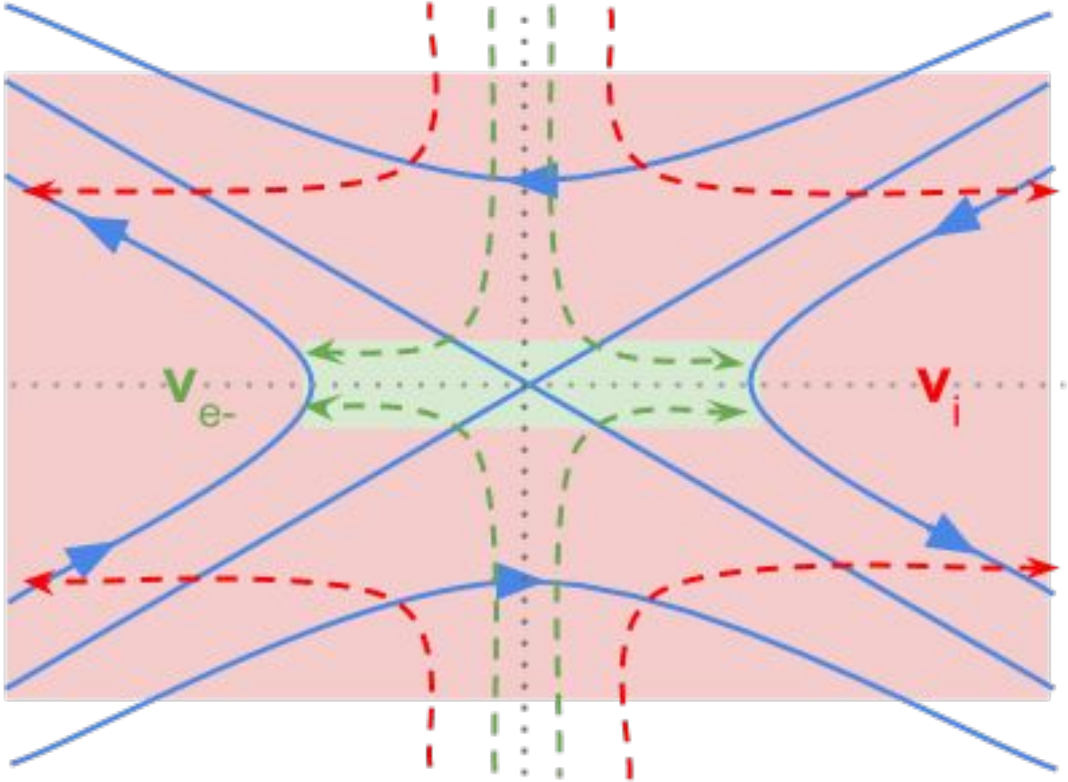
Ion Diffusion Region

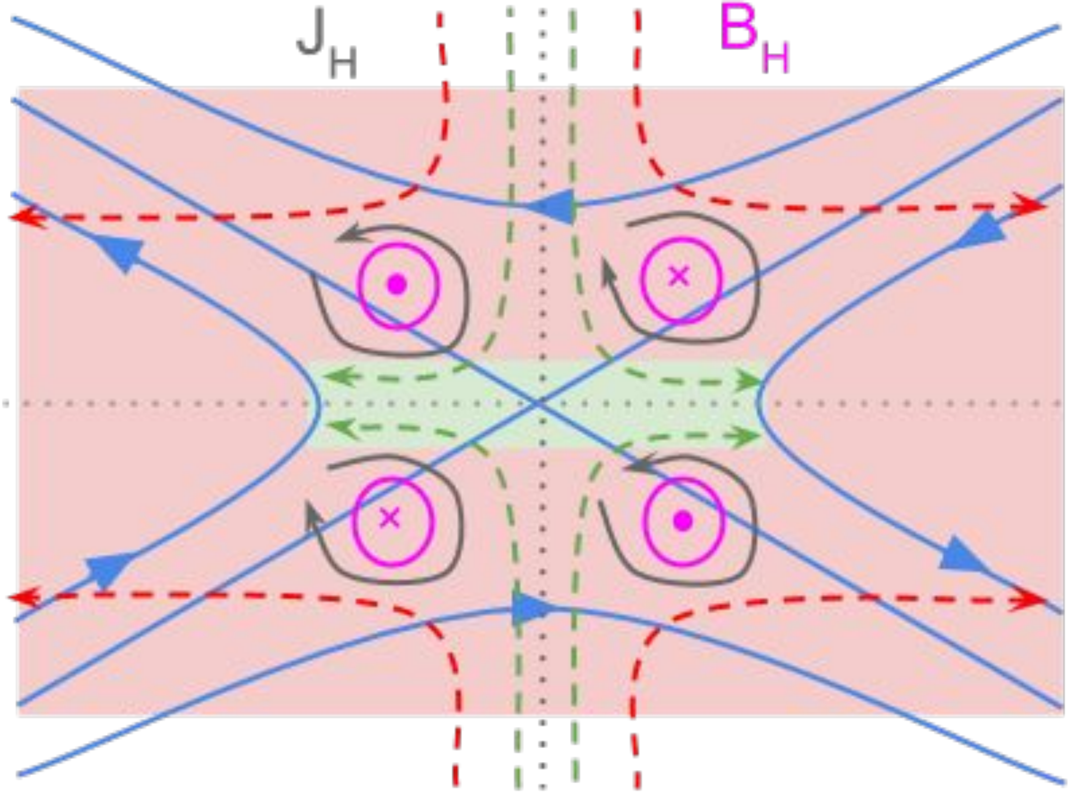
$\mathbf{E} + \mathbf{v}_i \times \mathbf{B} \neq 0$



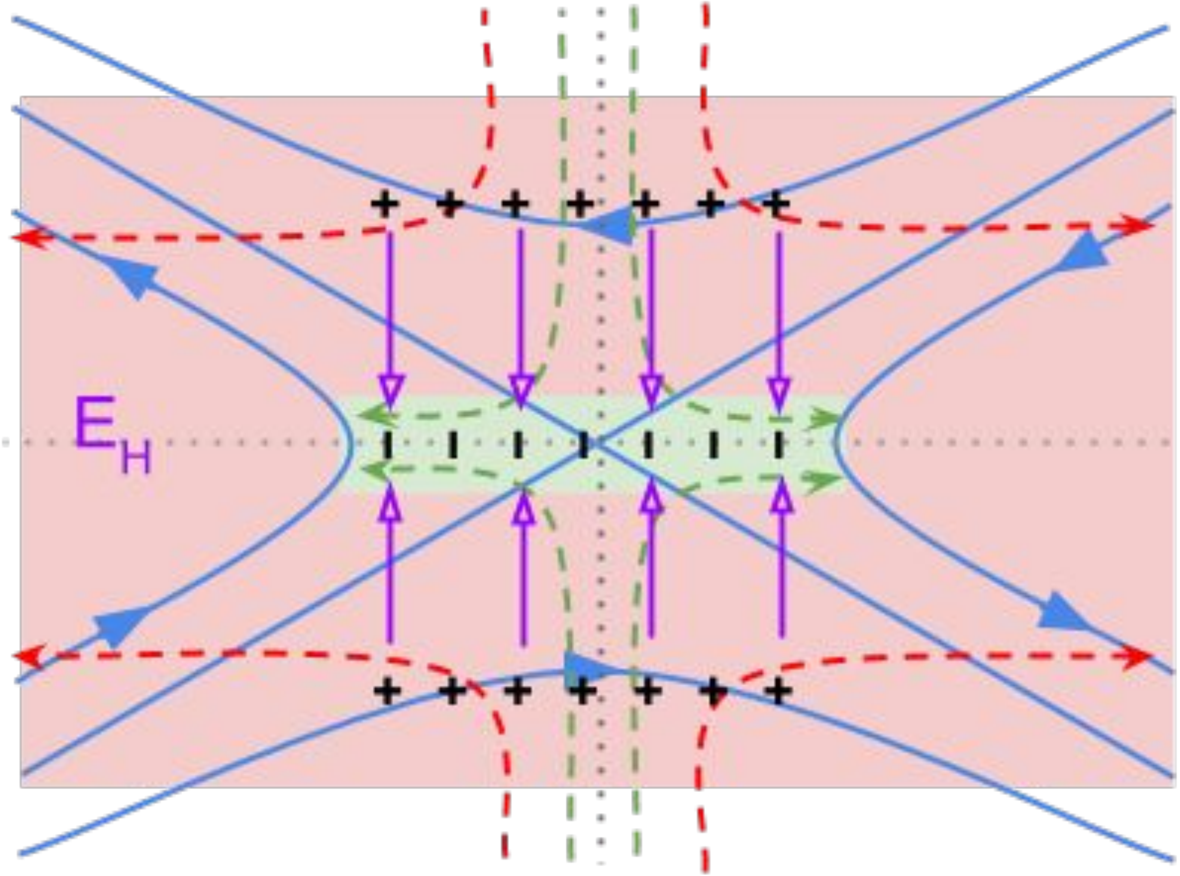
Electron Diffusion Region

$E + v_e \times B \neq 0$

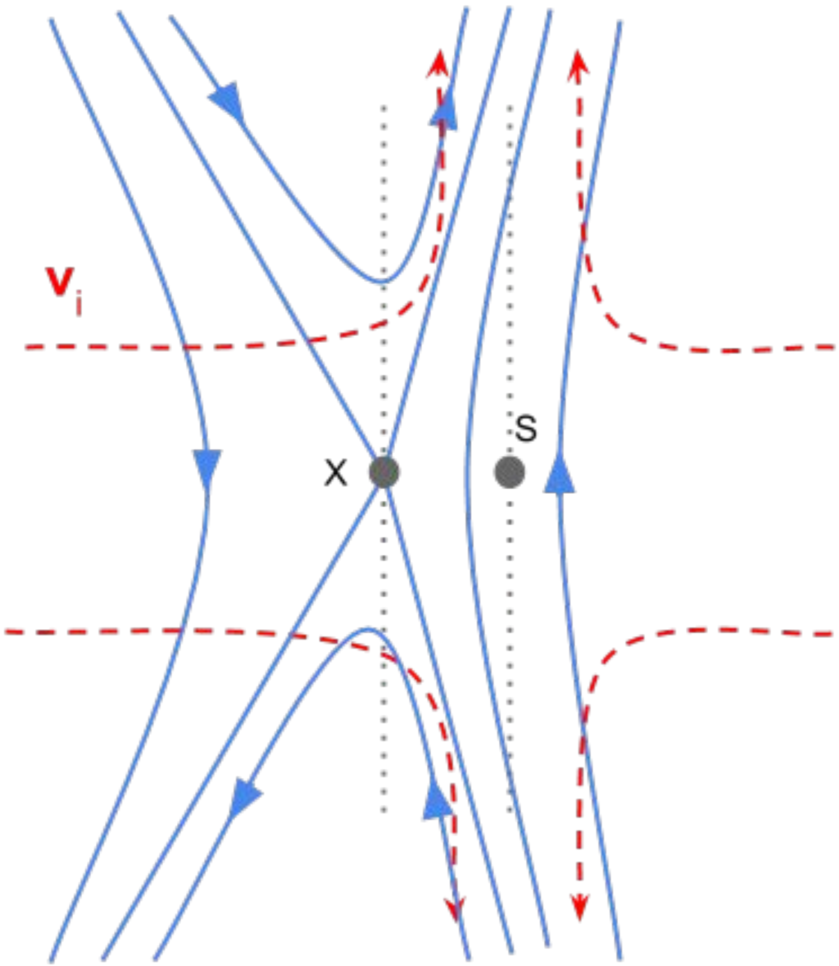


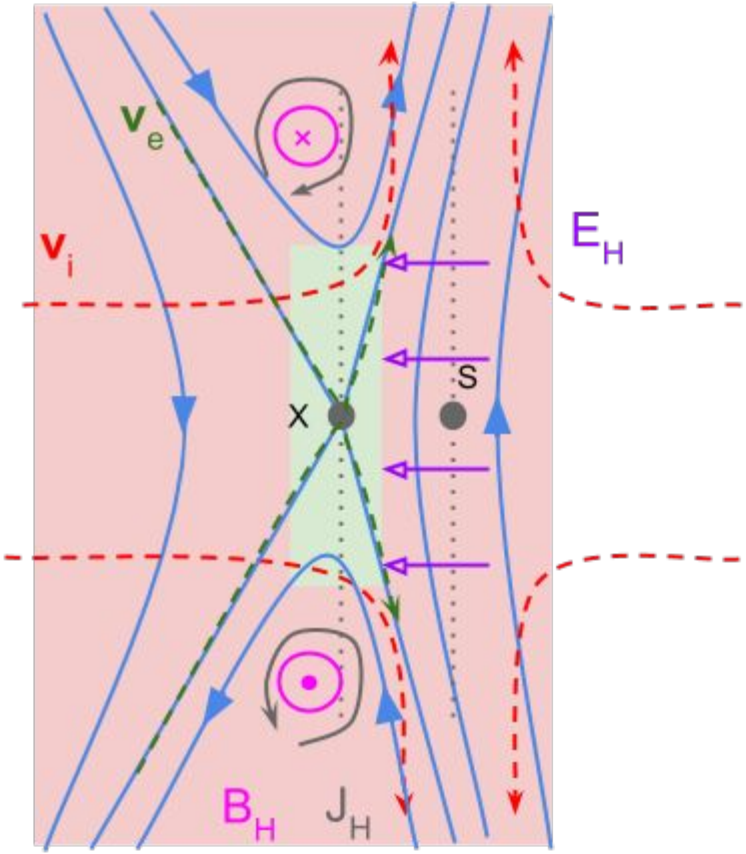


J_H
B_H


E_H

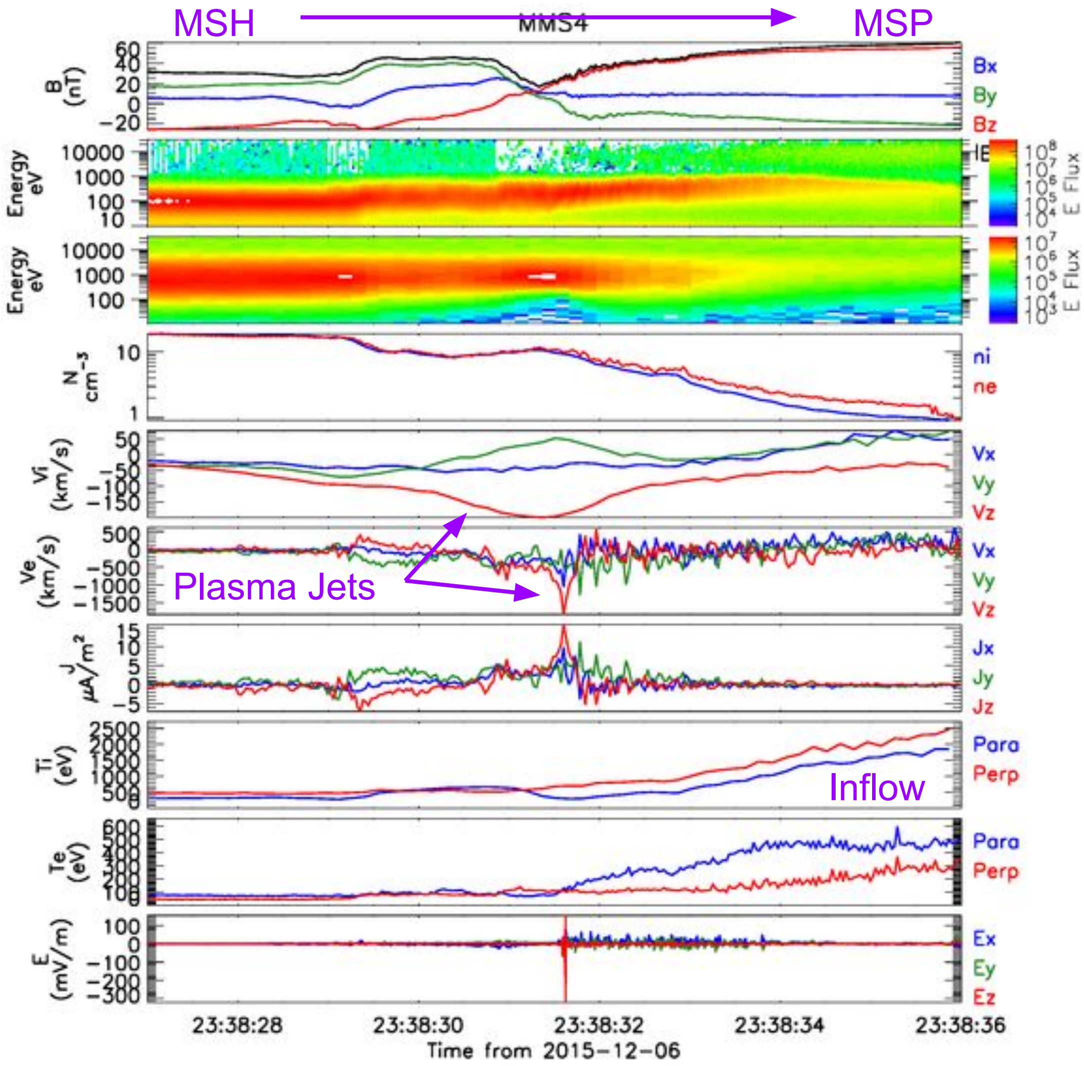
Asymmetric Reconnection


v_i
X
S

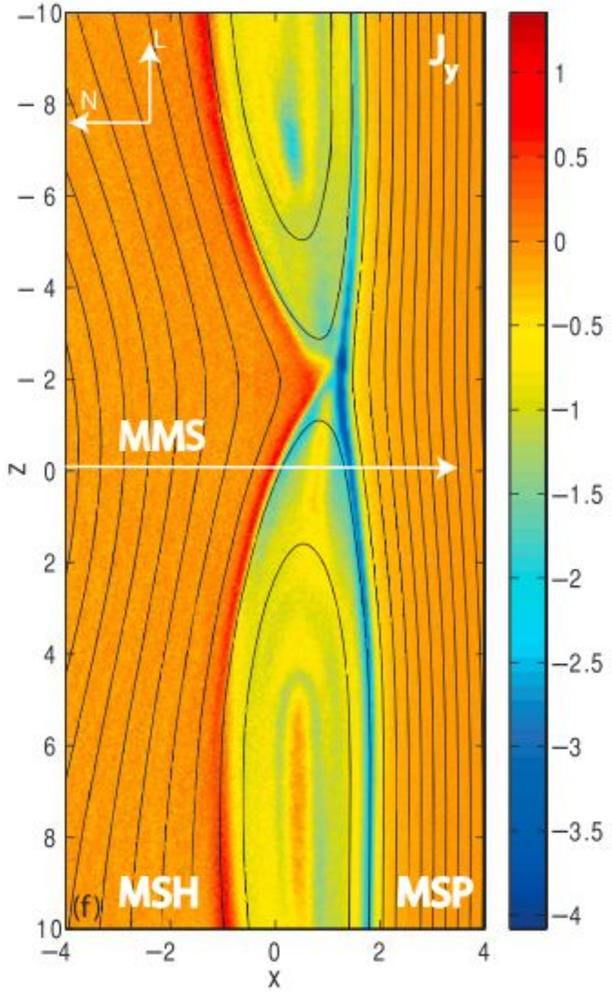

v_e
v_i
E_H
S
X
B_H
J_H

Event 2

Asymmetric Reconnection

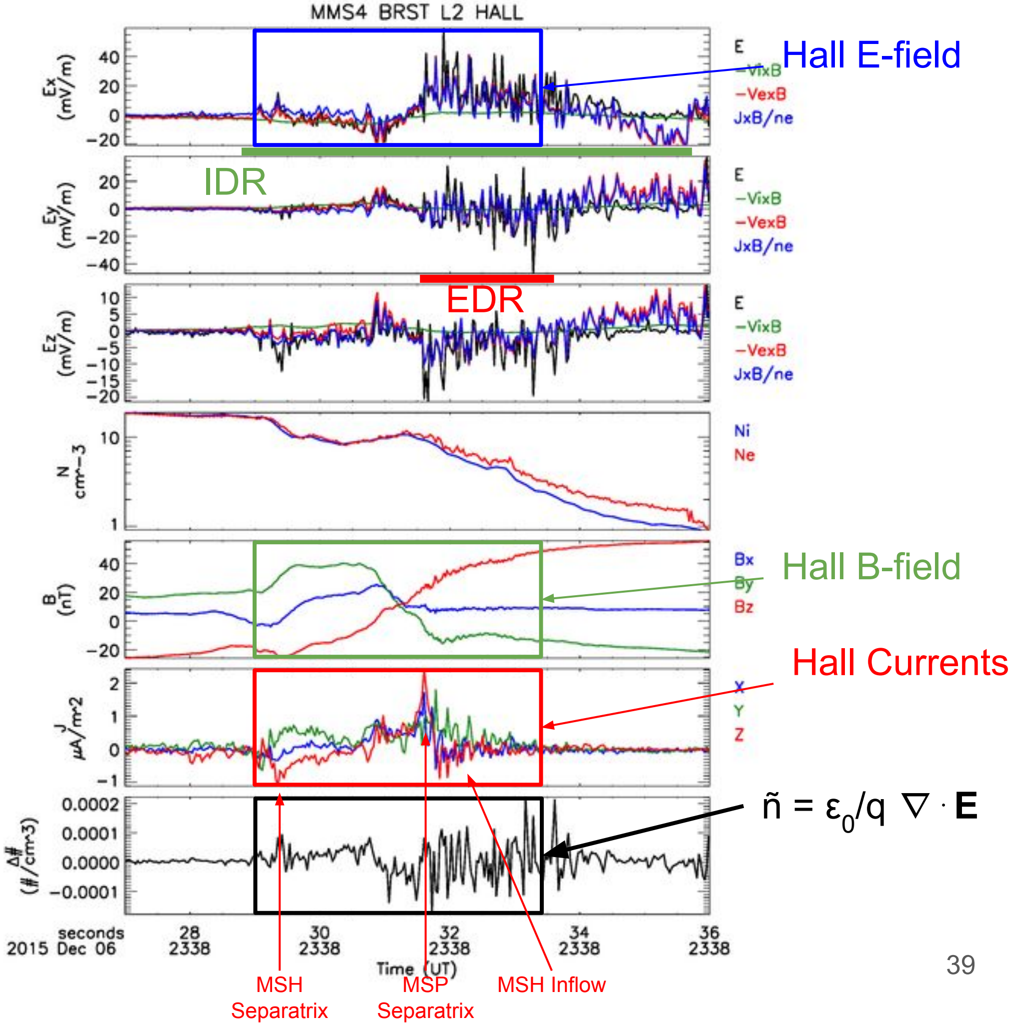


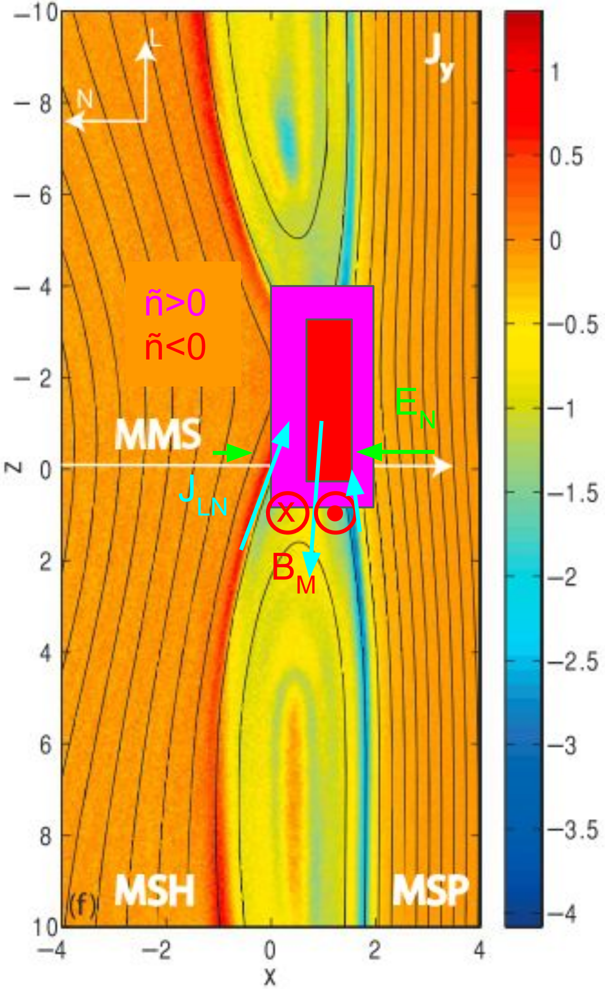
Khotyaintsev, et al., GRL, 2015



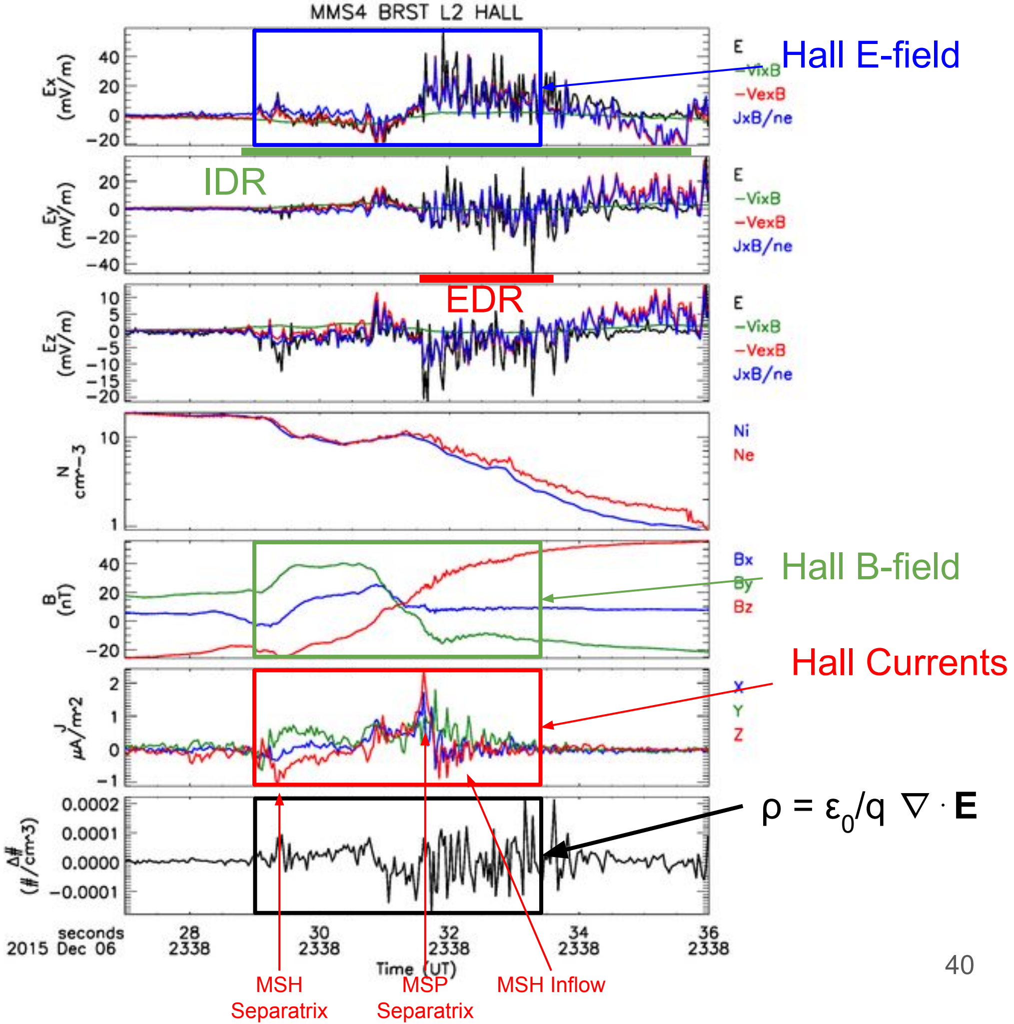
Hall System

- **E** balanced by **J**x**B**/ne
  - E_X strong throughout IDR
- **J** supports $+B_Y$
  - Electrons flow into (out from) X-line along MSH (MSP) separatrix
- ñ > 0 (ñ < 0) in outer (inner) diffusion region
- ~$1x10^{-4}$ excess electrons
  - $1x10^{-3}$ % of N_{MSH}





L
N
J_y
ñ>0
ñ<0
MMS
E_N
J_{LN}
B_M
MSH
MSP
(f)
Z
X



MMS4 BRST L2 HALL
Hall E-field
IDR
EDR
Hall B-field
Hall Currents
ρ = ε$_0$/q ∇ · **E**
MSH Separatrix
MSP Separatrix
MSH Inflow
2015 Dec 06
Time (UT)

MP Encounter

Region I

- **E** and **B** fields among spacecraft diverge -> enter IDR
- ρ > 0

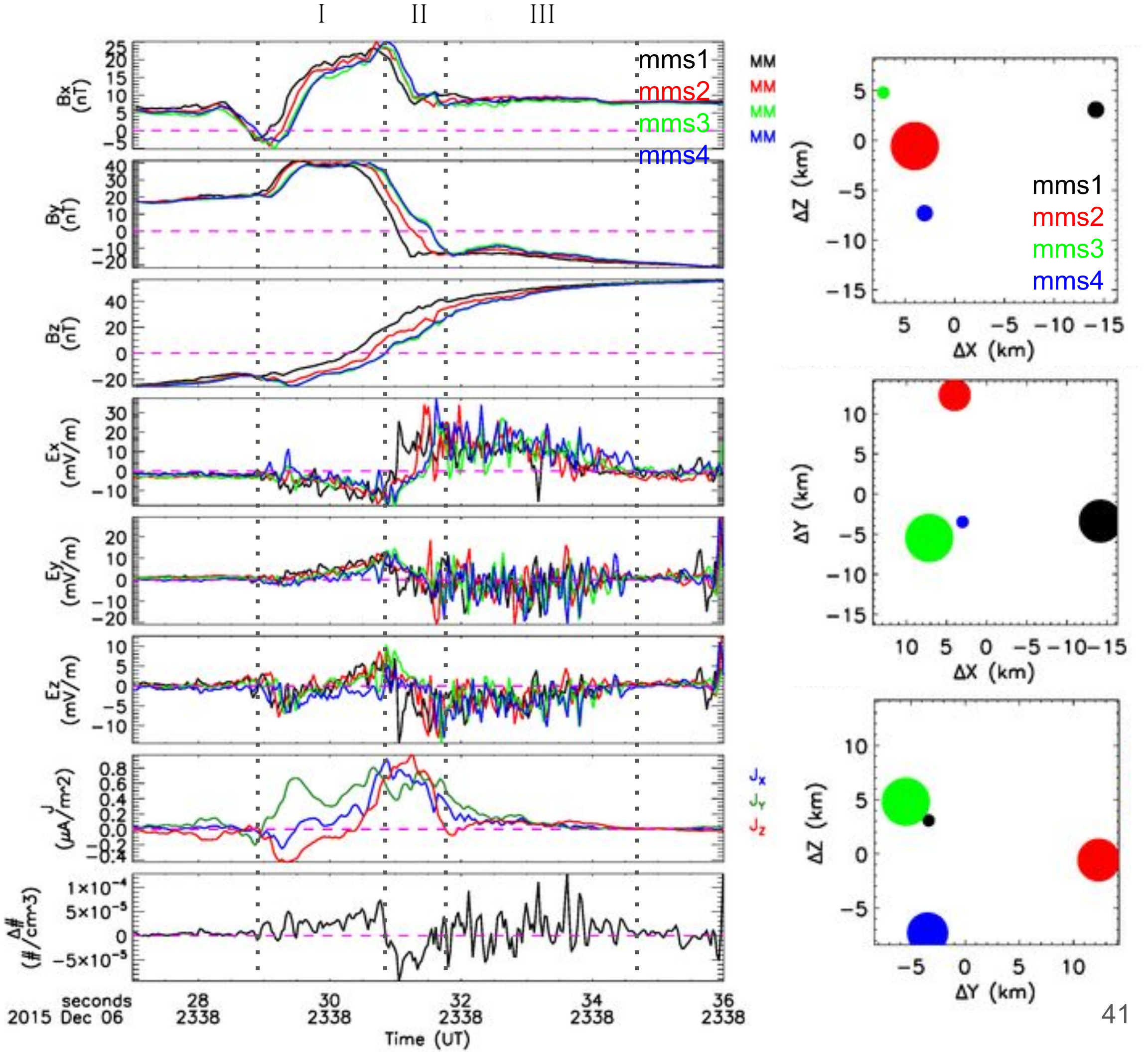
Region II

- Strong, demagnetized electron jet
- ρ changes sign

Region III

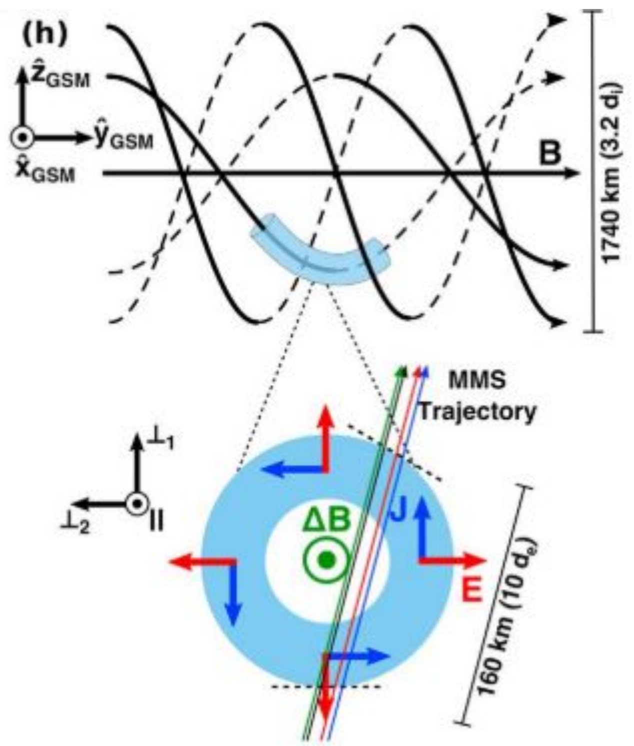
- **E** and **B** fields among spacecraft converge -> exit IDR
- ρ > 0 again

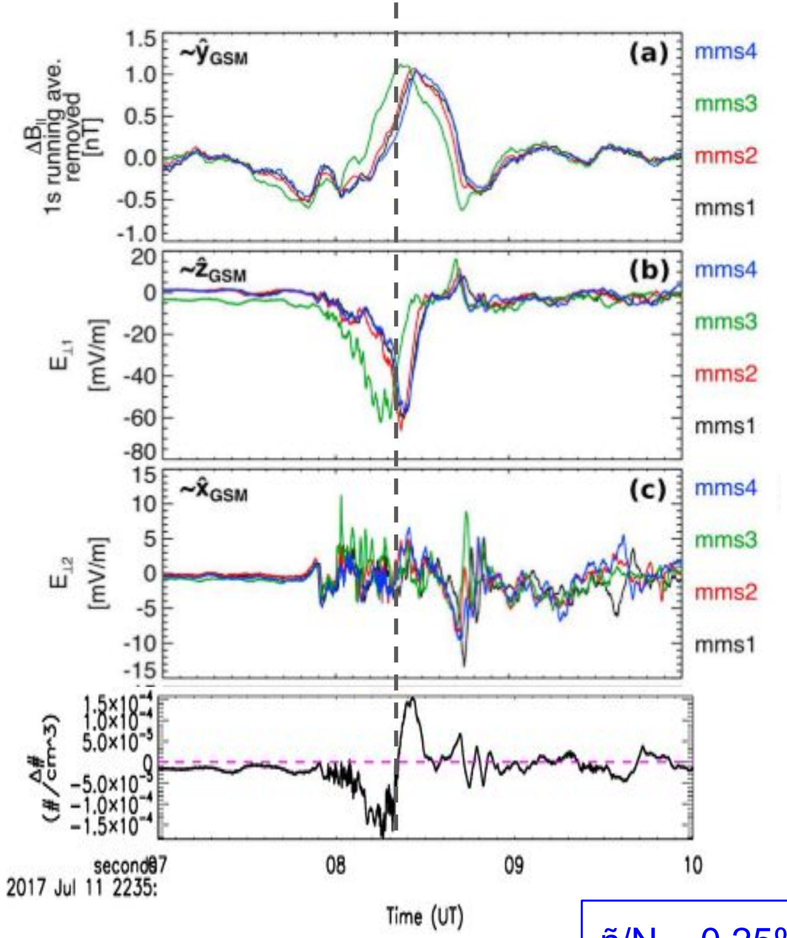
$\tilde{n}/N \sim 1\text{x}10^{-3}$ %



Event 3

Electron-Scale Magnetic Peak



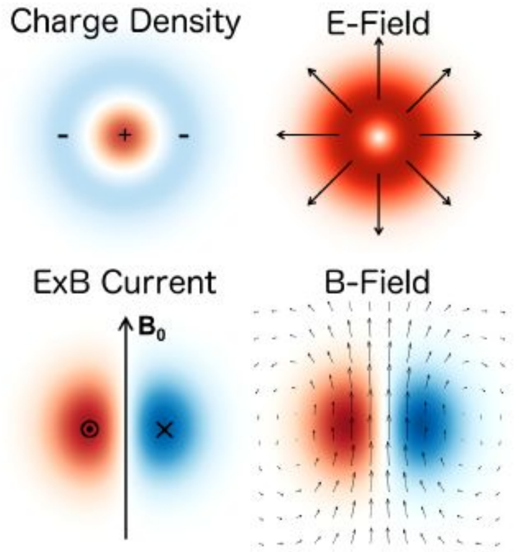


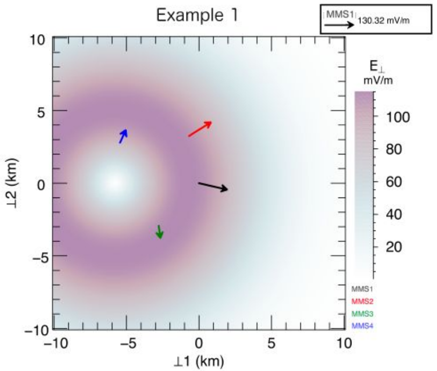
ñ/N ~ 0.25%

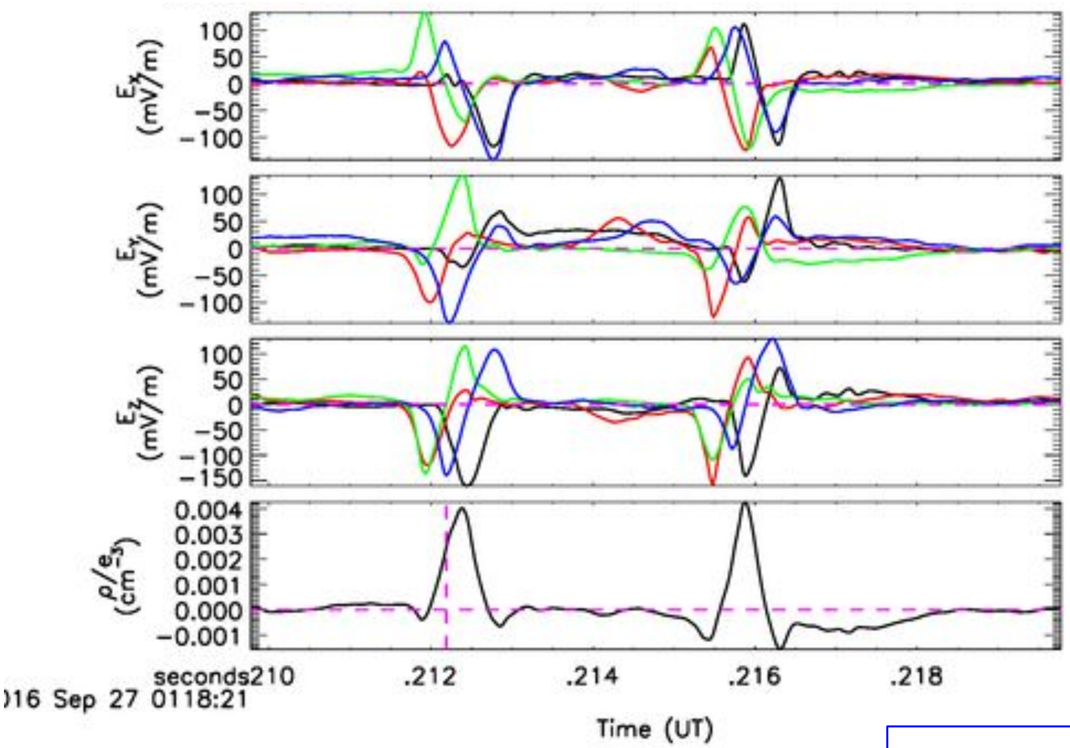
Stawarz, et al., GRL 2018

Event 4

Phase Space Hole



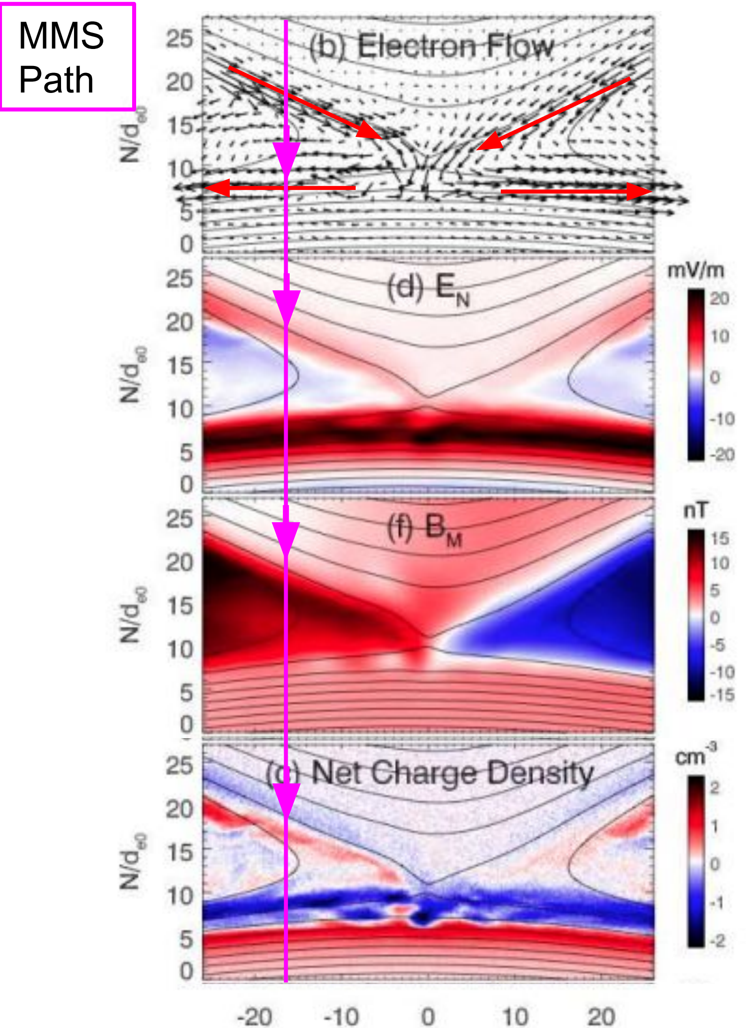




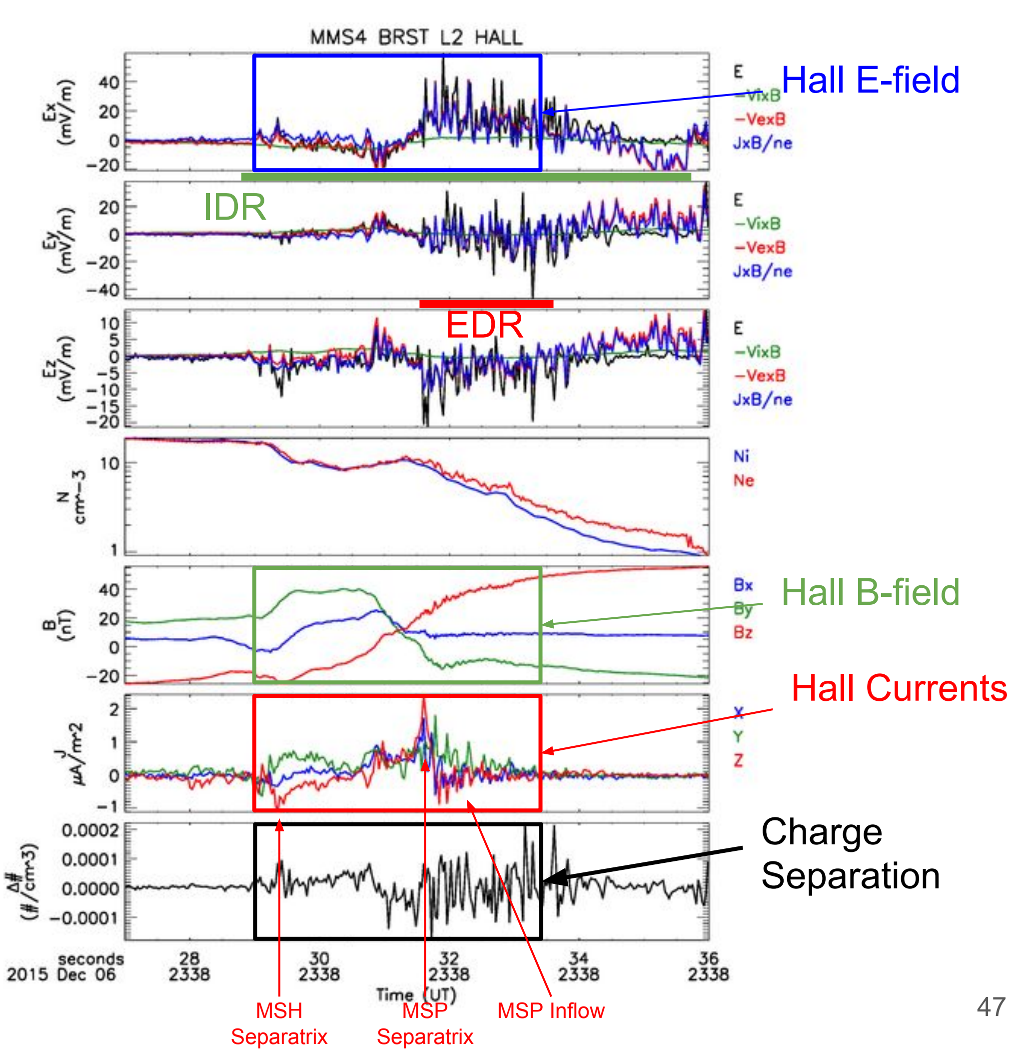
ñ/N ~ 4%

Holmes, et al., In Press 2018

Comparison to Simulations



Swisdak, et al.



Errors:

$$\rho/e = \varepsilon_0/e \ \nabla \cdot E = n_i - n_e$$

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: Gradient approximated as average of unique s/c-to-s/c differences

$$\sigma^2_{(\nabla\cdot E)} = \sum_{i=1}^{3}\left\{\left[\frac{\partial(\nabla\cdot E)}{\partial(\Delta E_{1i})}\sigma_{\Delta E_{1i}}\right]^2 + \left[\frac{\partial(\nabla\cdot E)}{\partial(\Delta E_{2i})}\sigma_{\Delta E_{2i}}\right]^2 + \left[\frac{\partial(\nabla\cdot E)}{\partial(\Delta E_{3i})}\sigma_{\Delta E_{3i}}\right]^2\right\}$$

$$\sigma^2_{(\nabla\cdot E)_1} = 2\frac{\sigma^2_E}{l^2_{sc}}$$

n_i - n_e

$$E \approx \sqrt{2}\frac{e}{\epsilon_0}\sigma_n l_{sc}$$
$$\approx \sqrt{2}\frac{e}{\epsilon_0}0.1\,cm^{-3}15\,km \approx 38386\,mV/m$$

In terms of charge neutrality: ñ = ρ/e = ε_0/e ∇•E = n_i - n_e

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

<< 1.0×10^{-4} cm^{-3}

Error & Quality Estimates:

$$\nabla \times E = -\partial B/\partial t$$

$$E = -\nabla V$$

General Error Formula

$$\sigma^2_{f(x_1,x_2,\ldots)} = \left(\frac{\partial f}{\partial x_1}\sigma_{x_1}\right)^2 + \left(\frac{\partial f}{\partial x_2}\sigma_{x2}\right)^2 + \ldots$$

Curl of E

$$\sigma^2_{(\nabla\times E)_1} = \sum_{i=1}^{3}\left\{\left[\frac{\partial(\nabla\times E)_1}{\partial(\Delta E_{2i})}\sigma_{\Delta E_{2i}}\right]^2 + \left[\frac{\partial(\nabla\times E)_1}{\partial(\Delta E_{3i})}\sigma_{\Delta E_{3i}}\right]^2\right\}$$

$$\sigma^2_{(\nabla\times E)_1} = \frac{4}{3}\frac{\sigma_E^2}{l_{sc}^2}$$

Typical Values

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

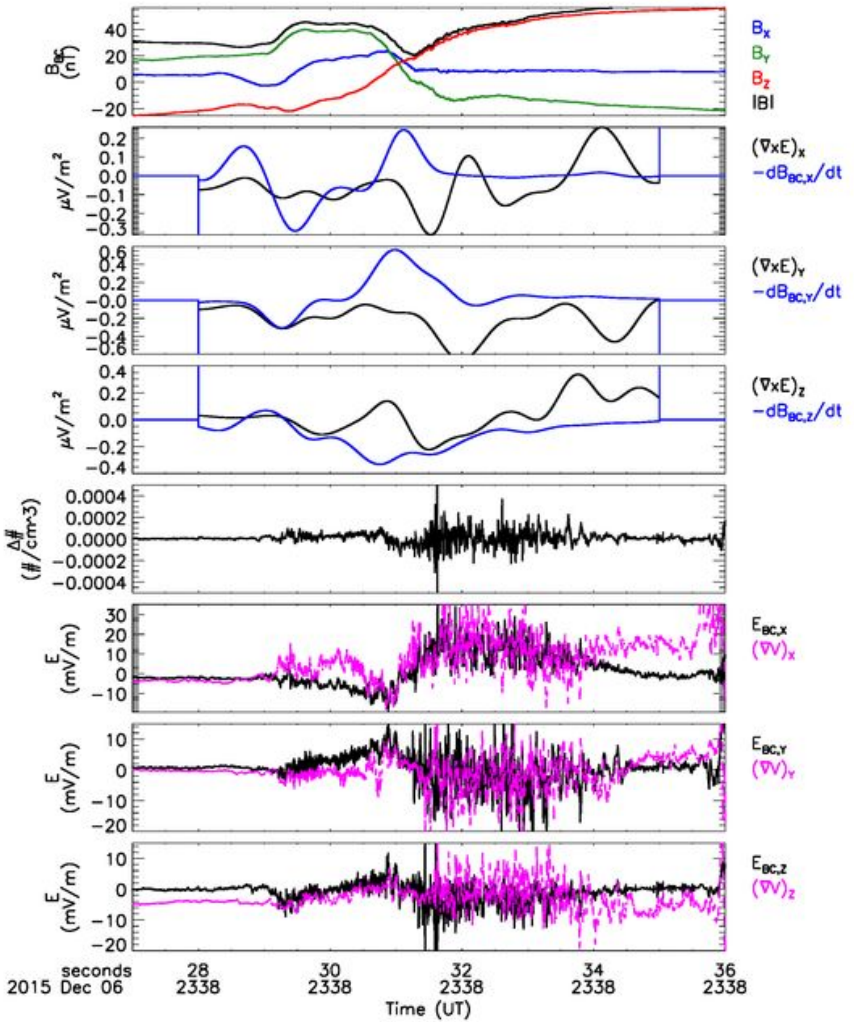
Similarly for dB/dt

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

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

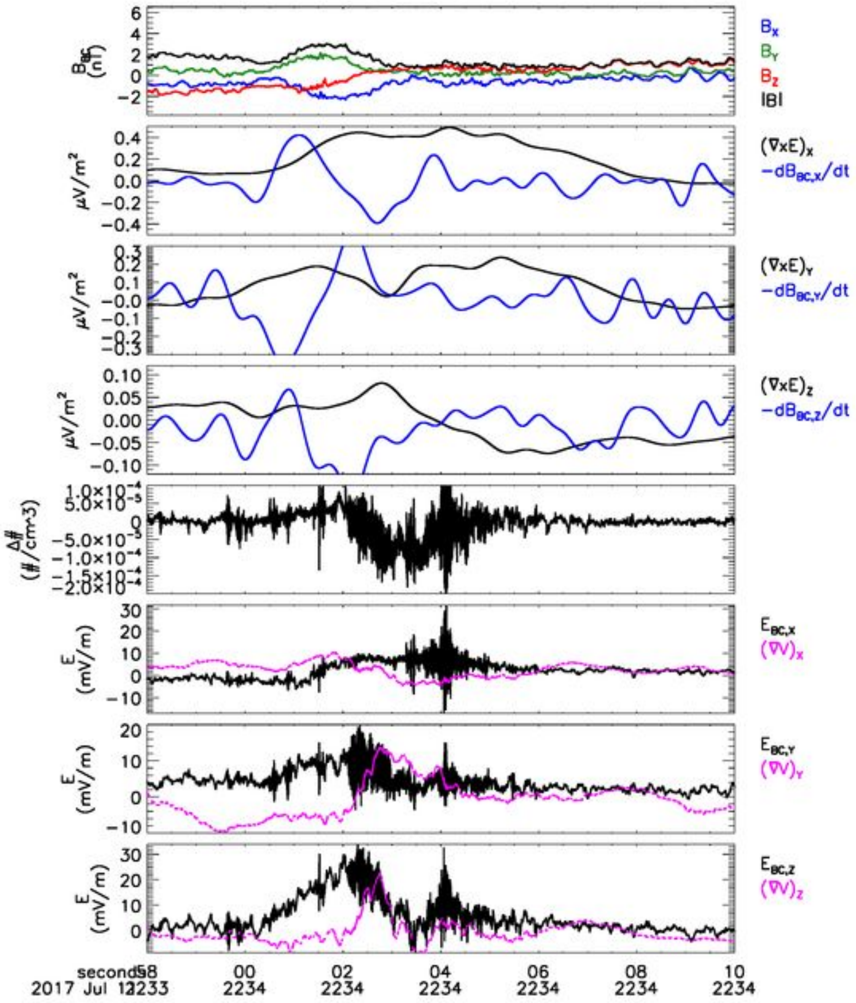
Quality Estimates

- As for **∇·B** = 0 with curlomter
- Two possible quality estimates:
  - $\mathbf{E}_{BC} = -\nabla V$
  - $\nabla \times \mathbf{E} = -\partial \mathbf{B}_{BC}/\partial t$
- $-\partial \mathbf{B}/\partial t$ is scaled by a factor of 10 for the (x,y,z)-components
  - Low-pass filtered f_c=1Hz
- $-\nabla V$ is scaled by factors of (500,260,142) for the (x,y,z)-components



Quality Estimates

- As for $\nabla \cdot \mathbf{B} = 0$ with curlomter
- Two possible quality estimates:
  - $\mathbf{E}_{BC} = -\nabla V$
  - $\nabla \times \mathbf{E} = -\partial \mathbf{B}_{BC}/\partial t$
- $-\partial \mathbf{B}/\partial t$ is scaled by factors of (200,200,100) for the (x,y,z)-components
  - Low-pass filtered f_c=1Hz
- $-\nabla V$ is scaled by a factor of 50 for the (x,y,z)-components
  - Noisier than 2015-12-06



Conclusions

- ñ is typically one order of magnitude greater than the error threshold
- Charge density profiles are consistent with the Hall B, E, and J signatures
- Net negative charge is embedded in regions of net positive charge
  - EDR within IDR
- ñ/N: Percent charge imbalance
  - MP: 1×10^{-3}% — Magnetic Peak: 0.25%
  - Tail: 1% — Electron Hole: 4%
- Positive charge observed within
  - Electron-scale magnetic peak
  - Electron phase space holes
- Quality Considerations
  - $\nabla\times E$ and $\partial B/\partial t$ are uncorrelated and on different scales
    - Despite errors being roughly equal
    - E could have smaller natural scale lengths
  - ∇V and E could be consistent