A STATISTICAL STUDY OF DIPOLARIZATION FRONTS OBSERVED BY MMS

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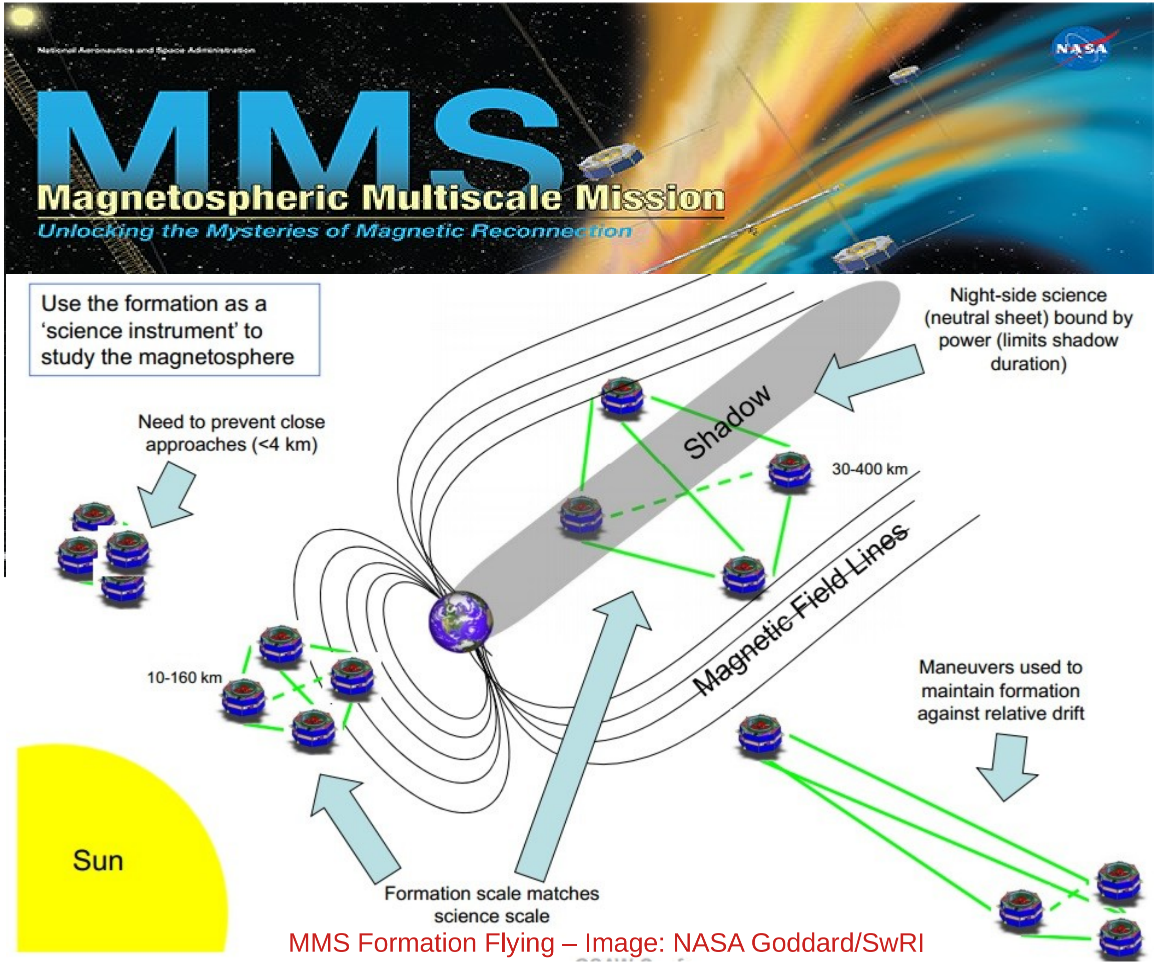
The Magnetospheric Multiscale Mission

MMS is constituted by four identical satellites evolving in a tetrahedron formation separated at electron scales.

Investigates:

- How the Sun's and Earth's magnetic fields connect and disconnect, explosively transferring energy?
- It targets the very small electron diffusion region.
- Unprecedented high spatial and time resolutions.
- The key to understanding reconnection regions near Earth, where the most energetic events originate.

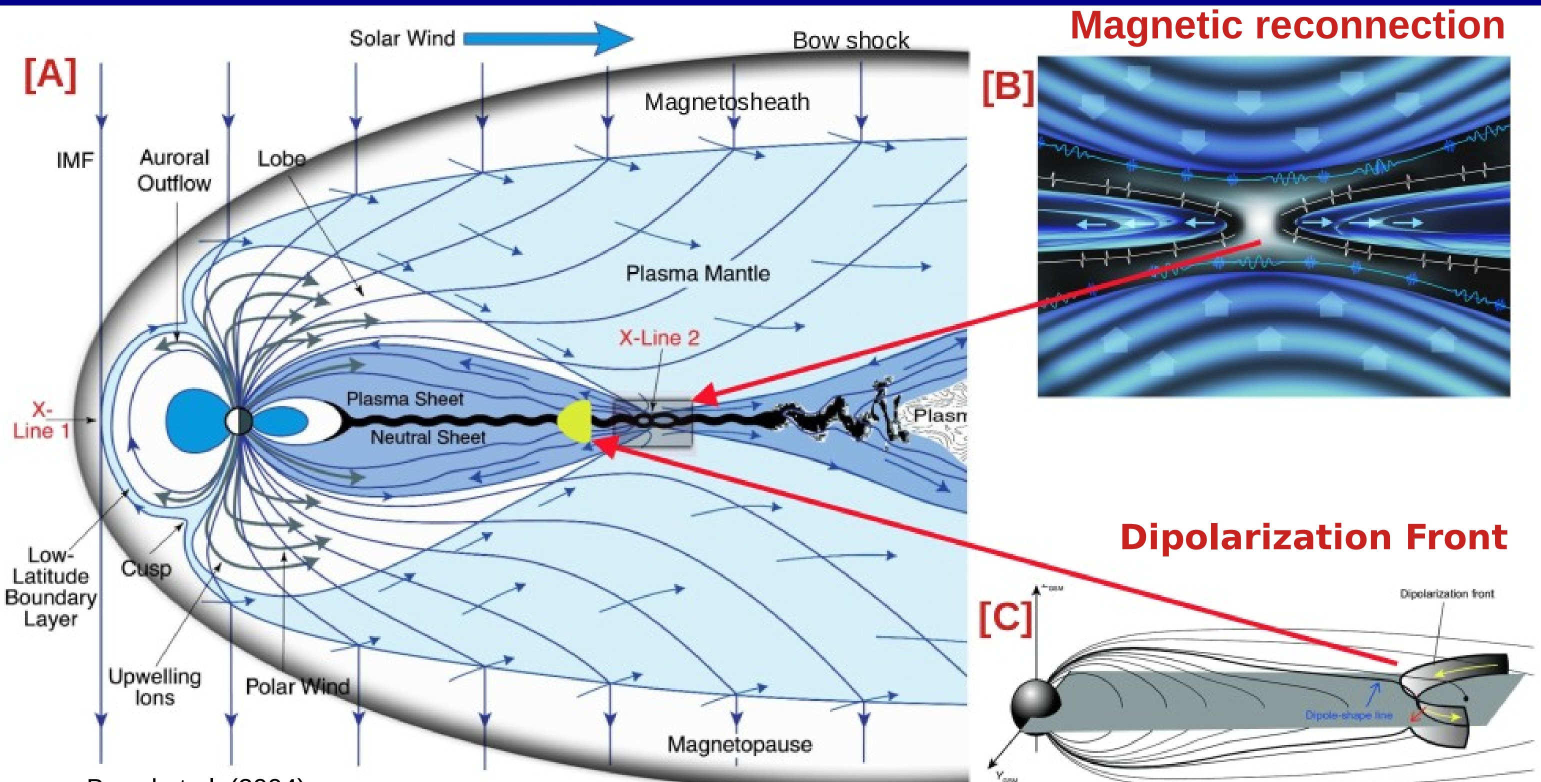


MMS Formation Flying – Image: NASA Goddard/SwRI

Questions?

What is a Dipolarization Front?

Why is studying DF interesting and important?



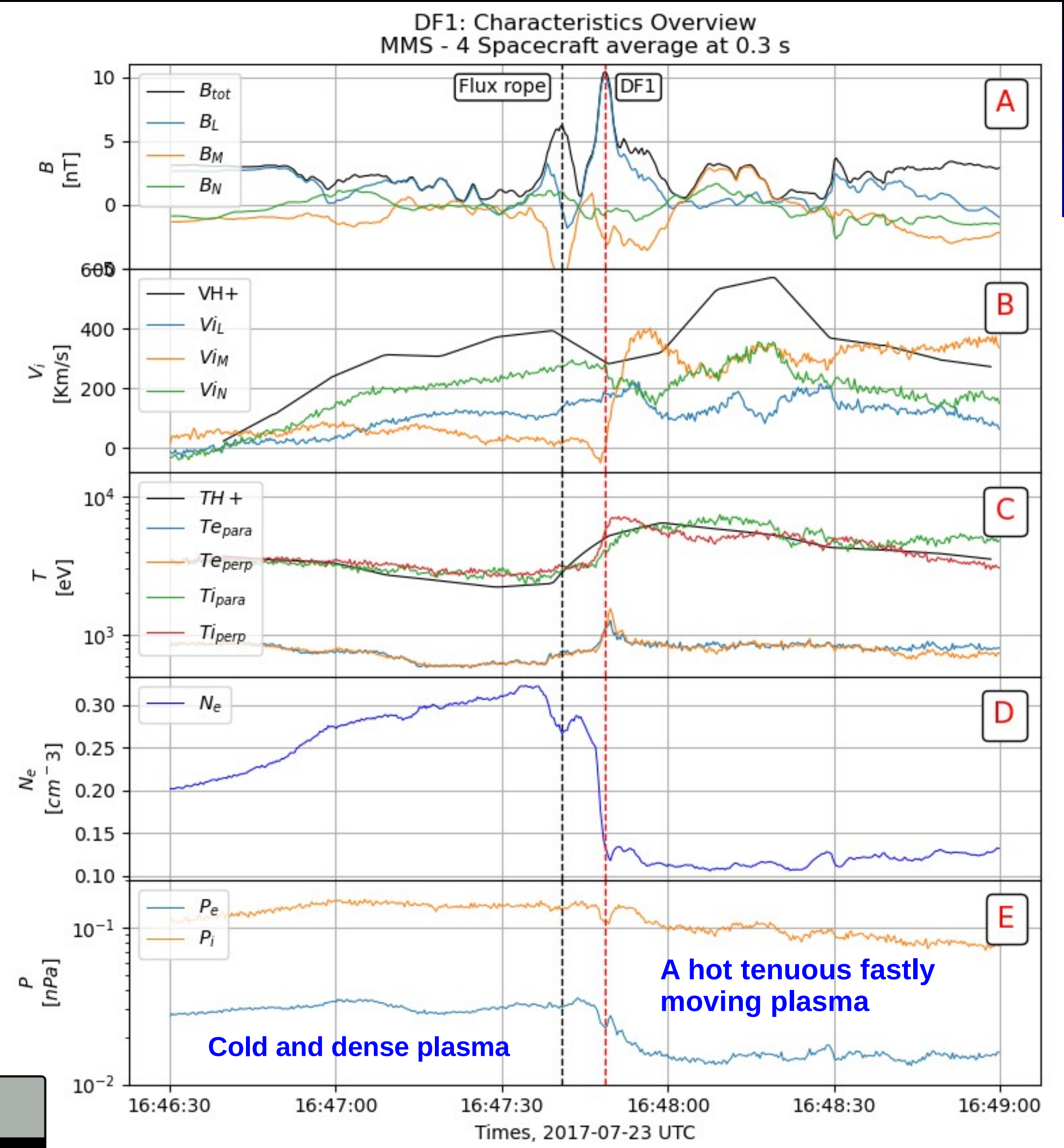
Board et al. (2004)

[e.g., (M. S. Nakamura et al., 2002; Fu, Khotyaintsev, Vaivads, Andre, & Huang, 2012; Runov et al., 2009; Angelopoulos et al., 1992; Baumjohann et al., 1990)].

One MMS DF example 16:46:30-16:49:00 UT

DF/fast flow properties [e.g. Runov et al., GRL 2009, Sergeev et al., GRL, 2009]

- Transition between cold dense plasma at rest to hot tenuous fastly moving plasma
- **MVA analysis** at (16:47:45/16:48:00): **LMN** frame of DF:
  L =(0.370 , 0.231, 0.899)
  M=(-0.485, 0.873,-0.025)
  N=(-0.791, -0.427,0.436)
- Increase of $\mathbf{B_L}$
- Increase of $\mathbf{Vi_N}$
- Increase of $\mathbf{T_{para,e}}$~$\mathbf{T_{perp,e}}$ ~1 keV
- Increase of $\mathbf{T_{para,i}}$~$\mathbf{T_{perp,i}}$~6 keV
- Decrease of $\mathbf{N_{e,i}}$

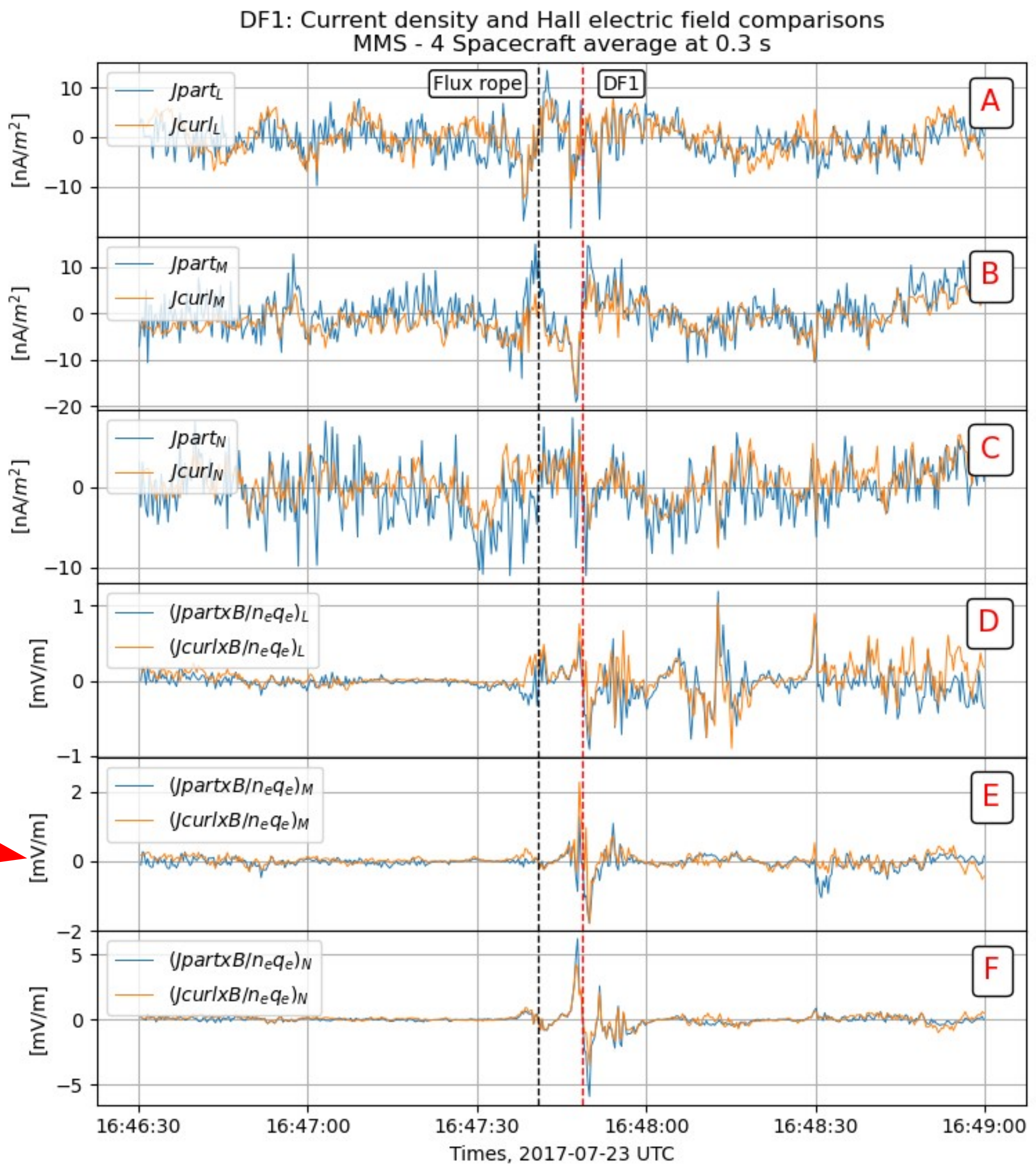


Current density comparisons

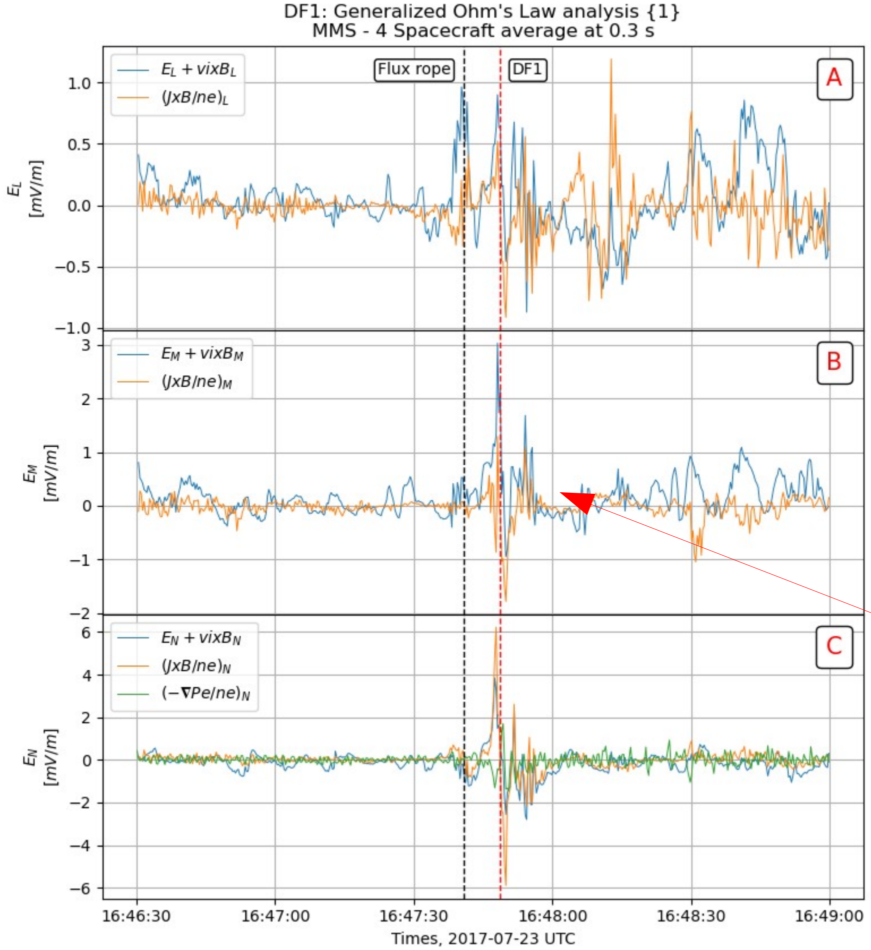
Current density comparison between
Jpart = en(**vi-ve**) & **Jcurl** = (**CurlB**/mu$_0$)
Jpart is calculated from particle (FPI) data and **Jcurl** from magnetic field (FGM) data, all data are time averaged at 0.3 s.

Small values but good agreement within <10nA/m2

Hall electric field comparison between
E_Hall = **Jpart**x**B**/(nqe) & (**Jcurl**x**B**/(nqe)
=> Good confidence in curl and particle moments calculations.
Good agreement within 1 mV/m



Ion Ohm's Law & electron Ohm's Law 1646:05-1649:00 UT

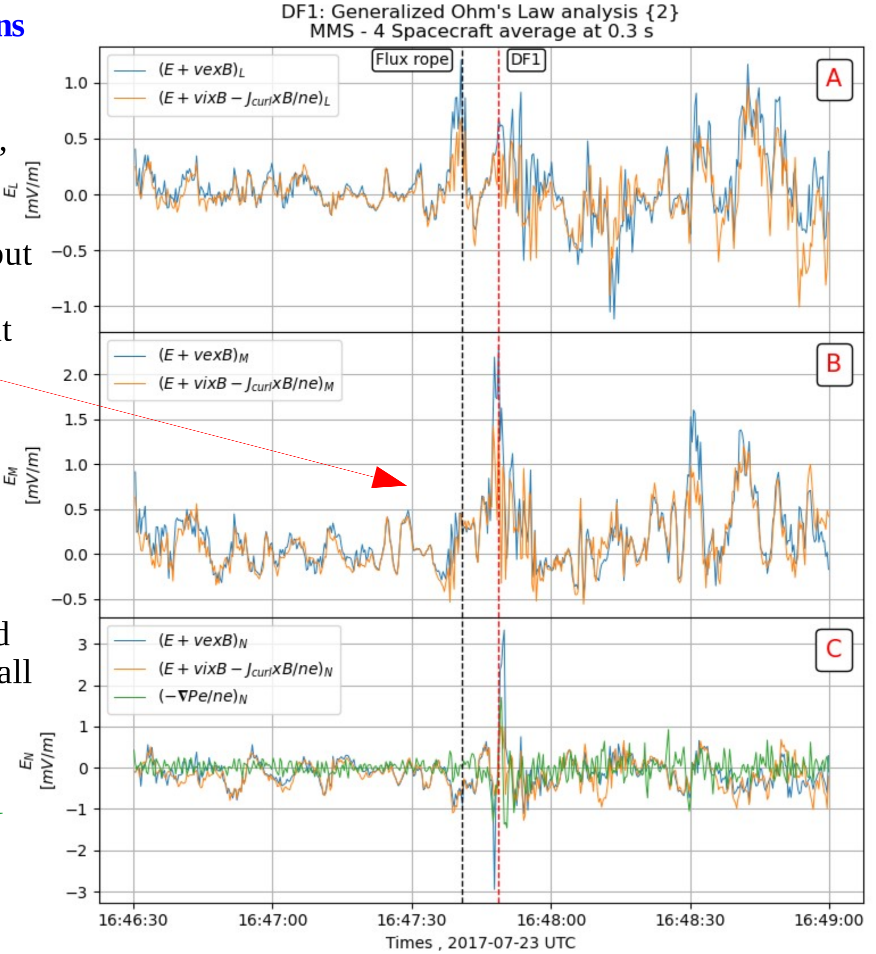


Ohm's law from electrons

- Good agreement **E+vexB** < +/- 1mV/m, except at the DF.
- Electrons most of the time are magnetized but can be decoupled by their pressure gradient term (green line in panel C).

Ohm's law from ions

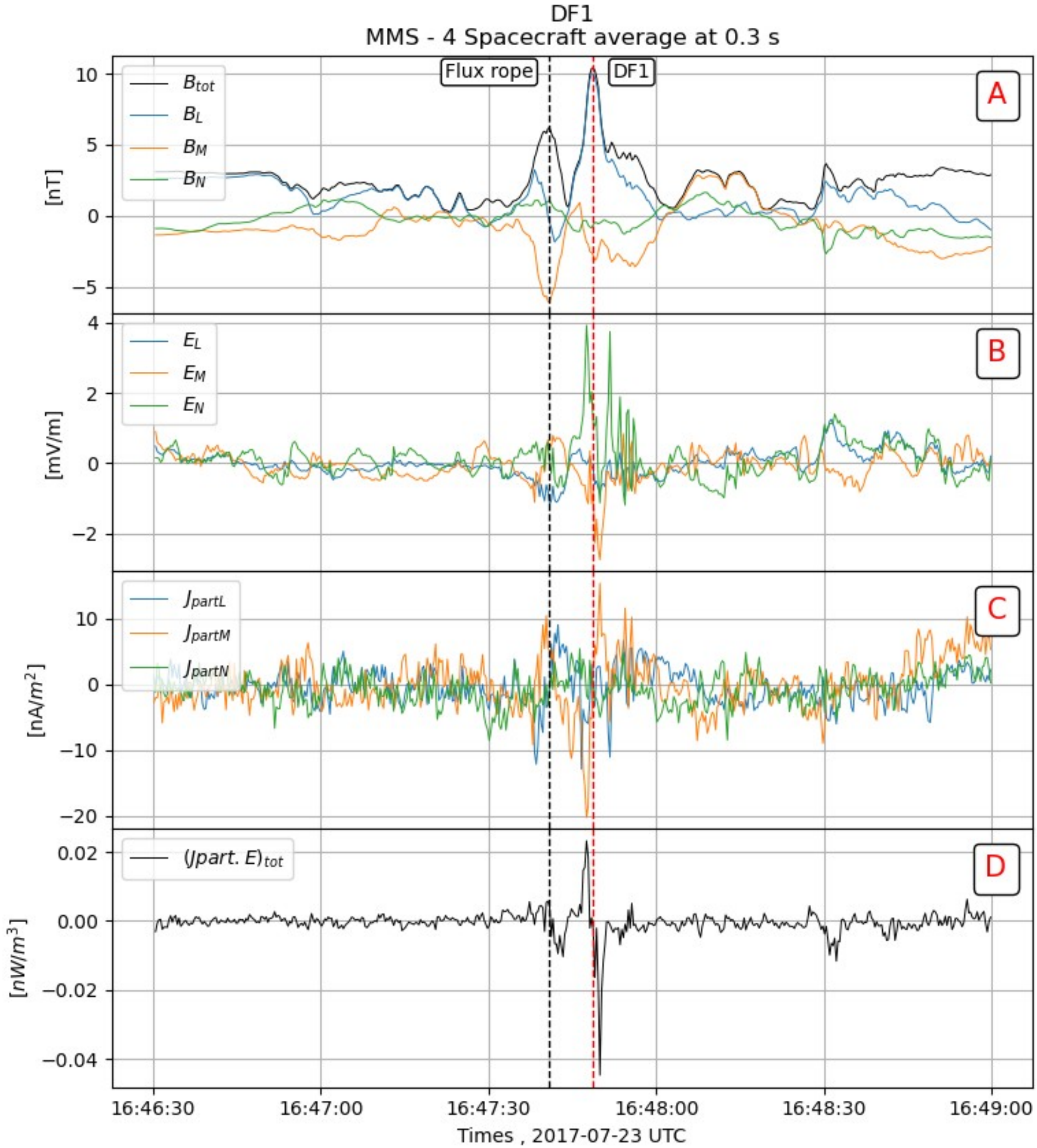
- Good agreement **E+vixB** and **JxB/ne**
- Ions can be decoupled from B due to large Hall fields at DF.
- Panel C also includes electron pressure gradient term along N (green line)



Energy conversion (I)

In (s/c frame):

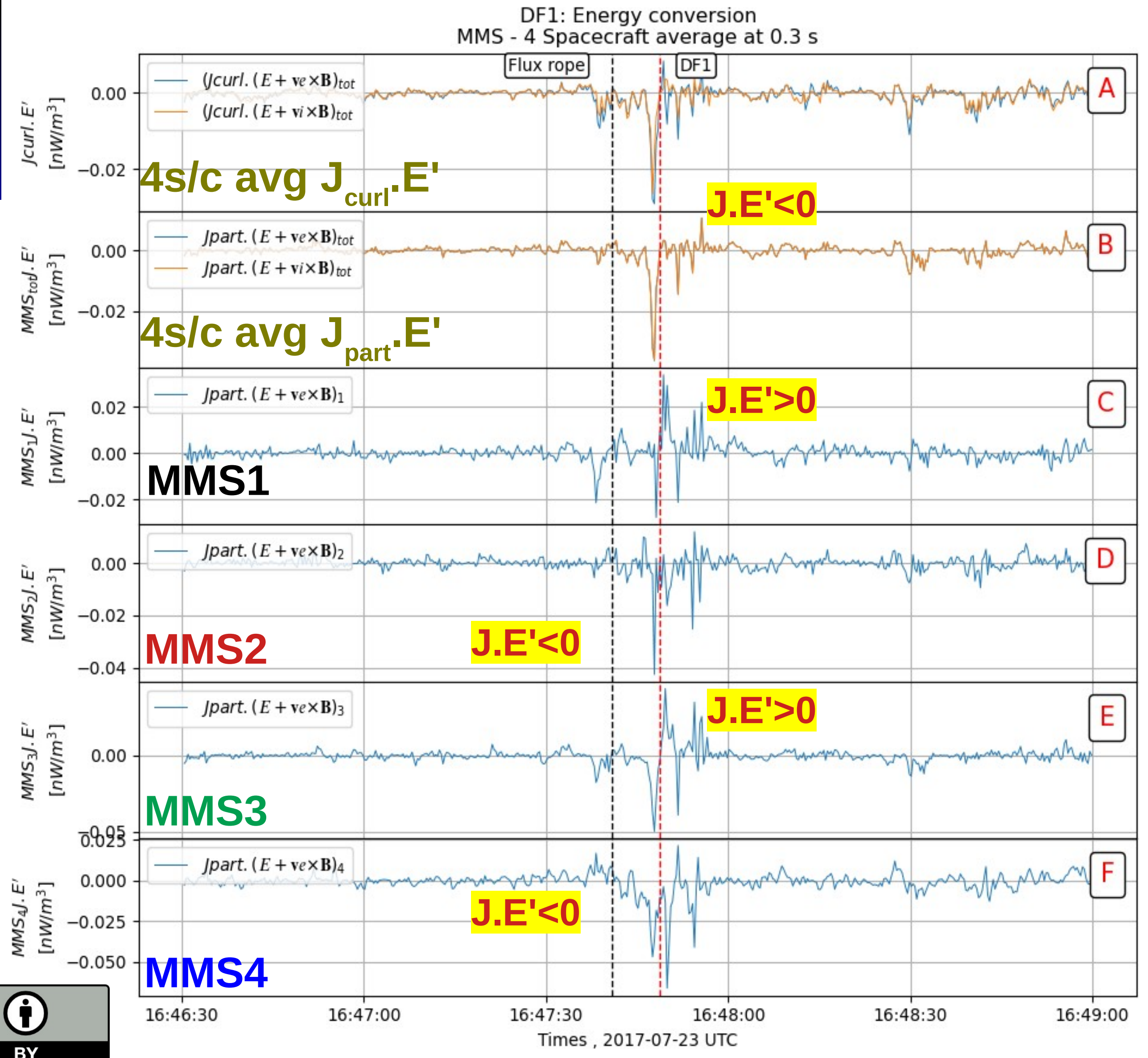
- Max of **$Jpart_M$**~ -20 nA/m2
- **E_M**~ -2.5 mV/m around 1647:45 UT at DF.
- **Ahead of the front**, (**J**.**E**>0) the energy is dissipated from the electromagnetic field to the particles.
- **Behind of the front**, (**J**.**E**<0) the energy is transferred from the particles to the electromagnetic field.
- Max of **J**.**E** +0.023 nW/m^3 at DF and **J**.**E** - 0.043 nW/m^3 after DF.
- Max of **J**.**E** - 0.01 nW/m^3 at Flux rope.



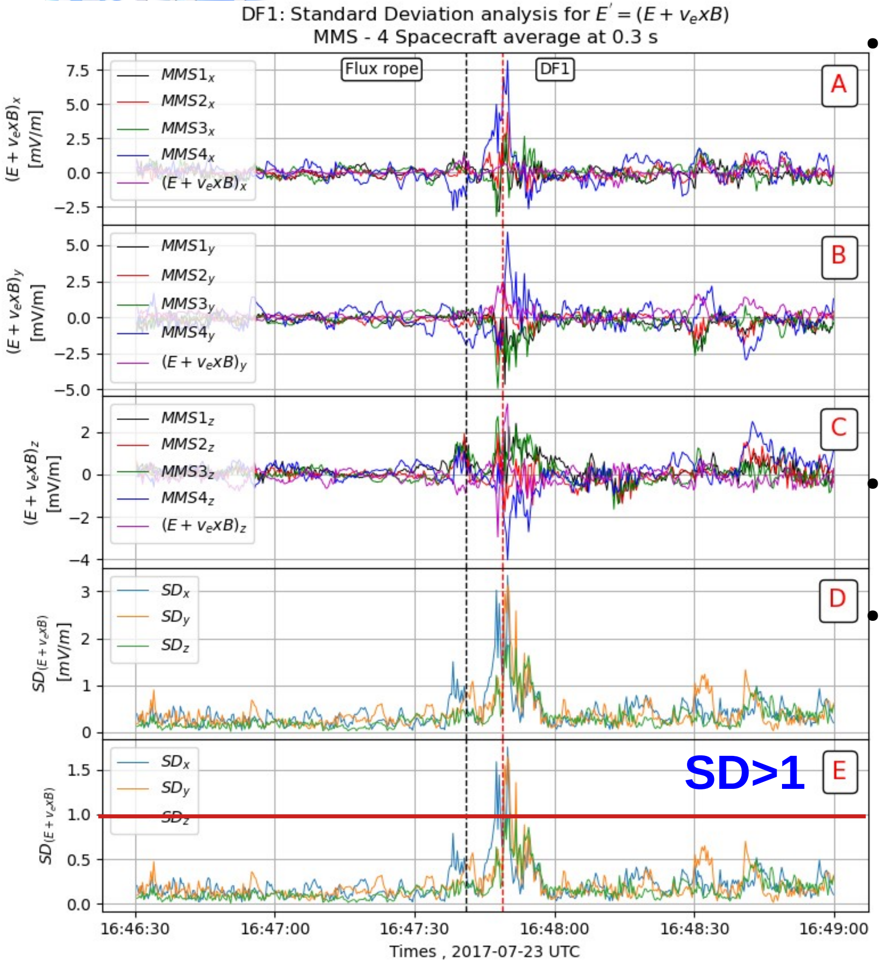
Energy conversion (II) 16:47:30-16:48:40 UT

In (Ion & electron frames):

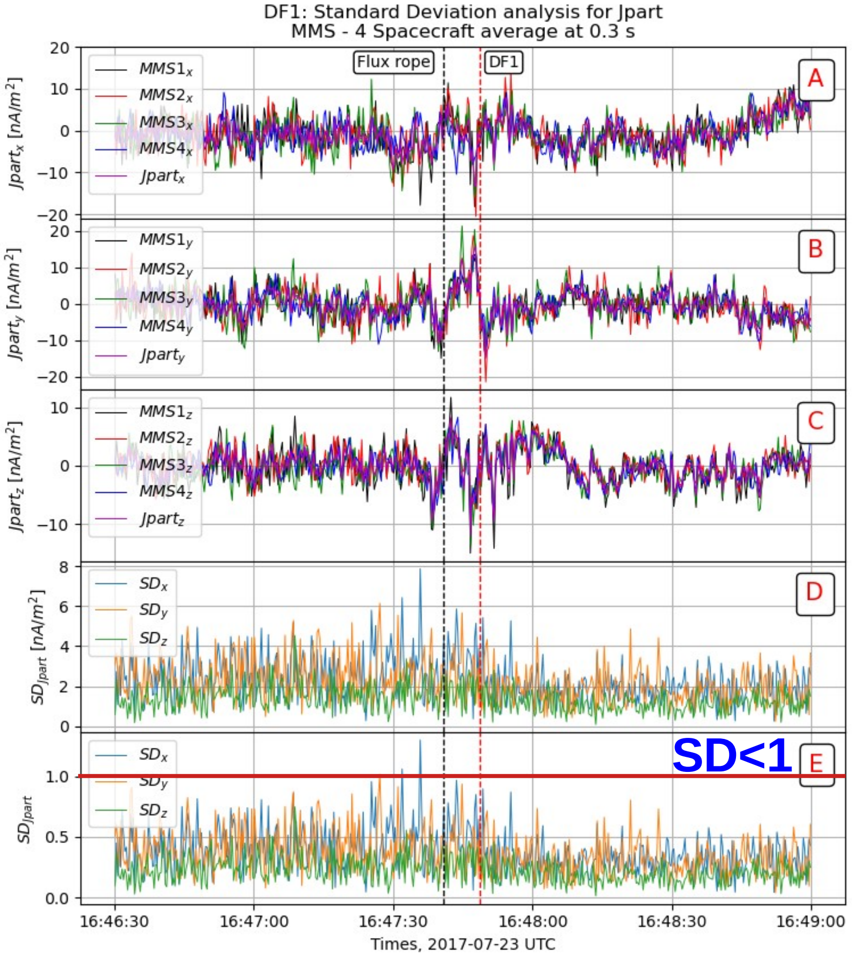
- We checked that **J**.(**E**+**ve**x**B**) = **J**.(**E**+**vi**x**B**) for each MMS as **J**.(**vi**x**B**-**ve**x**B**) = **J**.(**J**x**B**/ne)=0, [Yao et al., 2017, JGR]
- Using 4 s/c avg **J**.(**E**+**ve**x**B**) = **J**.(**E**+**vi**x**B**) also for both **Jpart** & **Jcurl** => Good confidence with all **J.E'** calculations.
- **J.E'**>0, Dissipation (energy goes from field to particles) ~ after the DF (from single s/c MSS1, 3)
- **J.E'**<0, Dynamo (energy goes from particles to field) ~ at DF (from 4 s/c and all singles s/c)
- These results are consistent with [Yao et al., 2017, JGR].
- **The energy conversion is not homogeneous at the scale of the tetrahedron (electron scales).**



Standard Deviation analysis for E’ & Jpart 16:47:30-16:48:40 UT



- Investigation of the homogeneity in the energy conversion by using the standard deviation (SD), and we normalized it by the error bars as ΔE’=~1.7 mV/m and
- ΔJ= e*(ΔNe)*(Vi-Ve) + e*Ne*(ΔVi + ΔVe) =~6.8 nA/m2.
- **Larger SD for Efield than for Jpart suggest that non homogeneity comes from the E field.**

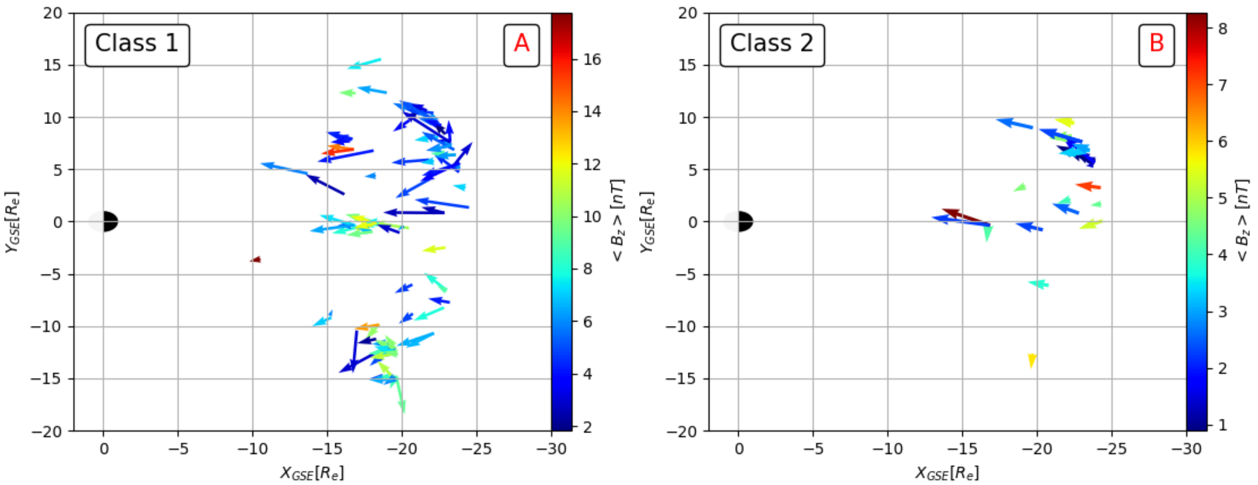


Summary (I)

- I have shown a DF event detected by MMS with classical signatures consistent with general properties of DF.
- I have found a good agreement between current densities calculated from particles and curl B.
- Ions can be decoupled mostly due to Hall field but also due to electron pressure gradient. Also electrons can be decoupled by electron pressure gradient.
- In Ion & electron frames the energy conversion given by (**J**.(**E**+**ve**x**B**)) or (**J**.(**E**+**vi**x**B**)) values indicates that 4 s/c average values are negative (energy transferred from plasma to fields) whereas individual s/c values can be positive or negative. It shows that energy conversion is not homogeneous at the electron scale (scale of the tetrahedron) mostly due to the E field fluctuations which are likely related to LHD waves. **[M. Hosner et al. 2022]**
- All these results have been confirmed with 5 other DF events occurring in the same period.
- **Alqeeq et al., PoP, MMS special issue, 2022.**

A statistical study of DFs

- The statistical study include the full magnetotail season of 2017 in order to compare with Zhong et al., 2019 study.
- We found 133 DF events near the Earth's magnetotail equator (|**Bx**|<5nT), using an AIDApy tool based on difference of max and min values computed with a 306 s sliding window, to request **Bz** and **Vi** increase and **Ne** decrease.
- This first automatic selection is then adjusted manually with the following criteria:
- Burst mode (partmoms) data are available at least 30s before and after the DF. The head of the DF denotes the time t0.
- **Bz** increase > 5 nT
- **Vi** > 150 km/s
- $\mathbf{N_{e,i}}$ decrease
- Both of ion and electron temperature increases.

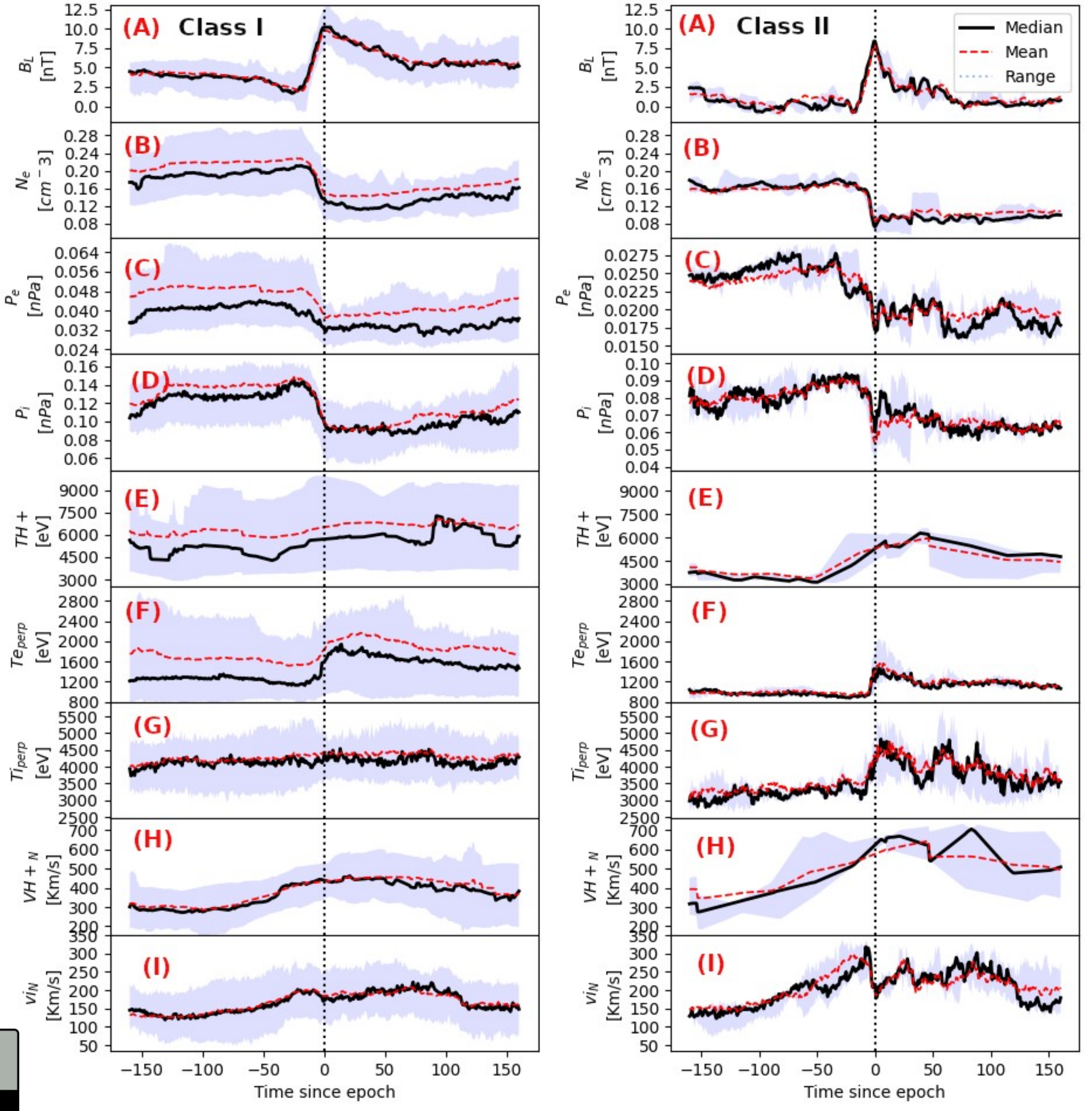


The colors represent the change in the northward magnetic field component during the DF, <**Bz**>, and the arrows represent the DF propagation direction perpendicular to the boundary (obtained by the timing method), projected onto the X/Y plane in GSM.

An overview of DFs

Characteristics overview of DFs

- **The Class 1** (74.4%) corresponds to a slow decrease of the magnetic field after the DF and is associated with smaller ion velocity and hotter plasma.
- **The Class 2** (25.6%) has the same time scale for the rising and the falling of the magnetic field (a bump) associated with a decrease of ion and electron pressures and faster velocity as shown in Alqeeq et al. 2021.
- In each panel the superposed epoch, the black line marks the superposed epoch median, the red dashed line marks the superposed epoch mean, and the blue fill marks the interquartile range.



Current density comparisons

MMS - 4 Spacecraft average at 0.3s

Current density comparison between:

$\mathbf{Jpart_M} = en(\mathbf{vi}\text{-}\mathbf{ve})$

$\mathbf{Jcurl_M} = (\mathbf{CurlB}/mu)$

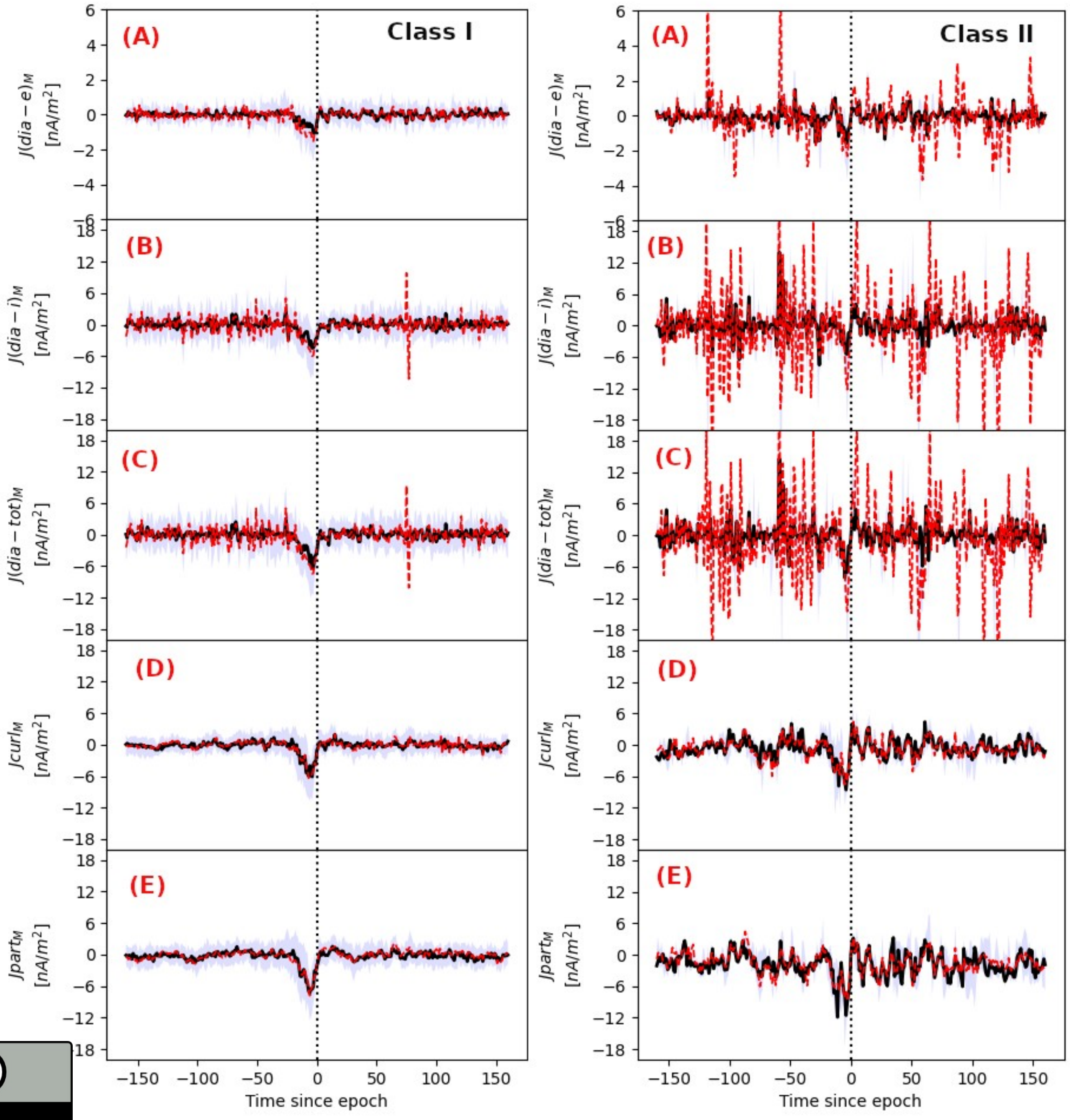
$\mathbf{Jdia_M} = \mathbf{B}L/\mathbf{B}^2\ \nabla n\ (Pi+Pe)$

$\mathbf{Jdia_{\{M,i\}}} > \mathbf{Jdia_{\{M,e\}}}$

Ion diamagnetic current is dominant (~72%).

Small values but good agreement within <10nA/m2

In Class 2 the reversal in $Jpart_M$ is due to the reversal of the diamagnetic current.



Energy conversion comparisons, MMS - 4 Spacecraft average at 0.3s

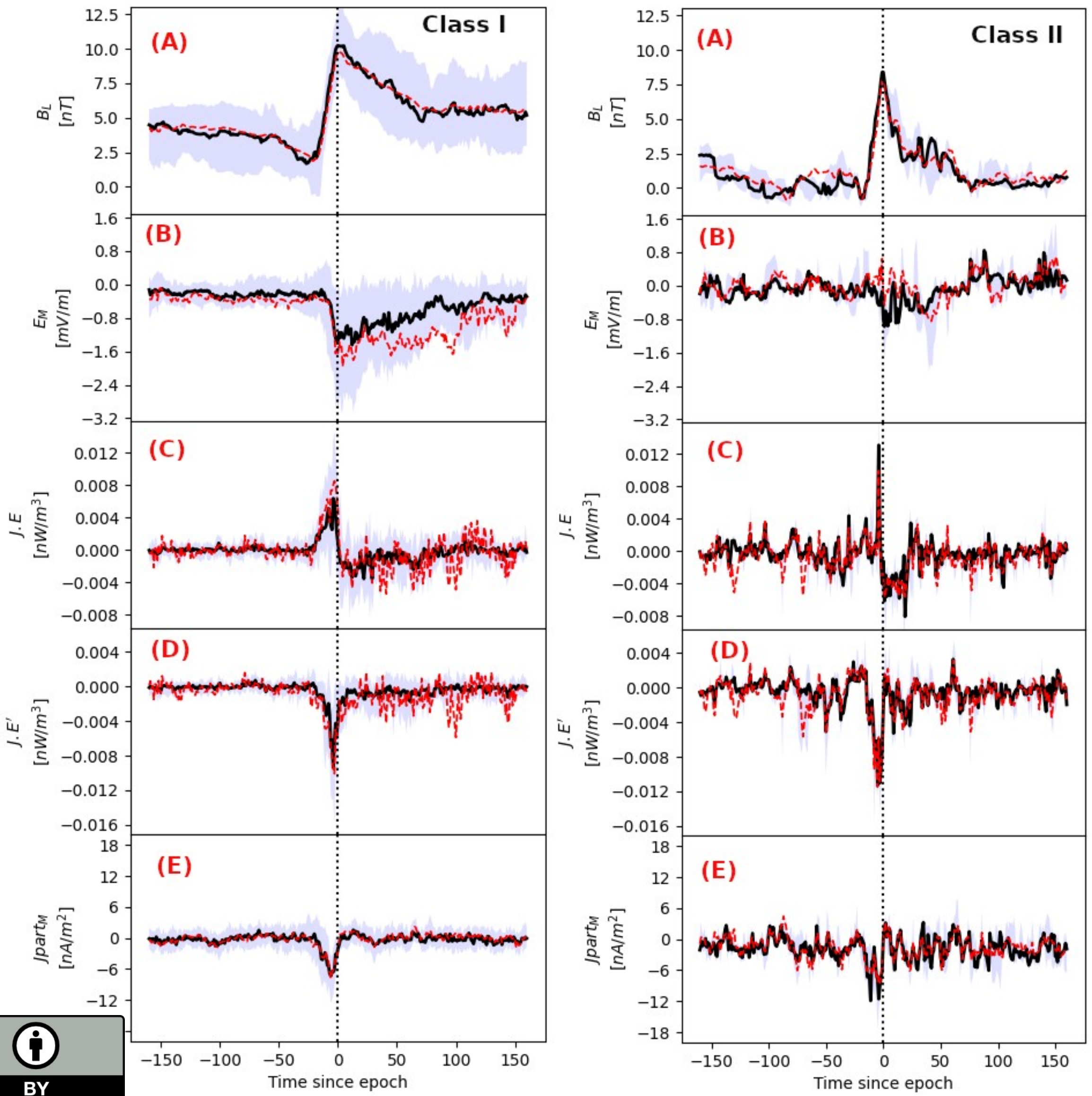
Class1:

- **In (s/c frame):**
  Ahead of DF, Jpart.E >0 The energy is dissipated from the electromagnetic field to the particles.
- **In (Ion & electron frames):**
  Ahead of DF, Jpart.E'<0 Dynamo (energy goes from particles to field)

Class2:

- **In (s/c frame):**
  Ahead of DF, Jpart.E >0 The energy is dissipated from the electromagnetic field to the particles.
  Behind of DF, **Jpart.E** <0 The energy is transferred from the particles to the electromagnetic field.
- **In (Ion & electron frames):**
  Ahead of DF, Jpart.E'>0 Dissipation (energy goes from field to particles)
  Behind of DF, **Jpart.E'**<0 Dynamo (energy goes from particles to field)

In Class 2 the reversal in (S/C & ion/electron frames) is due to the reversal of the diamagnetic current.



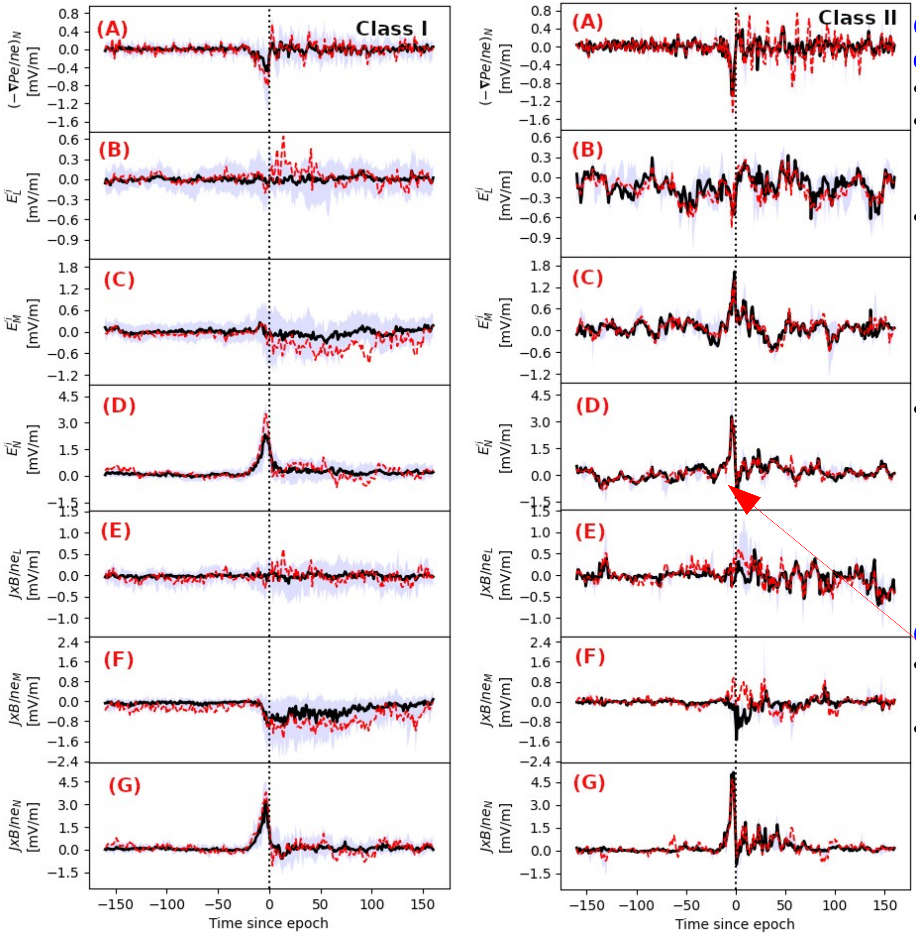
Summary (II)

For the full magnetotail season of 2017:

- Based on a superposed epoch analysis of DF basic properties (magnetic field, density, velocity, …) we distinguish two subcategories of events depending on the shape of the DF.
- The **Class 1** (74.4%) corresponds to a slow decrease of the magnetic field after the DF and is associated with smaller ion velocity and hotter plasma.
- The **Class 2** (25.6%) has the same time scale for the rising and the falling of the magnetic field (a bump) associated with a decrease of ion and electron pressures and faster velocity as shown in Alqeeq et al. 2021.
- For both categories we found a good agreement between current densities calculated from particles, Curl B and single S/C method ($Jdia_M$).
- For both categories we found that ions are mostly decoupled from the magnetic field by the Hall fields.
- The electron pressure gradient term is also contributing to the ion decoupling and likely responsible for an electron decoupling at DF. We also analyzed the energy conversion process.
- For the **Class 1** we found that the energy dissipation in the **S/C frame** is transferred from the electromagnetic field to the plasma ($\mathbf{J}\cdot\mathbf{E}>0$) ahead or at the DF.
- For the **Class 2**, we found the same behavior ahead or at the DF whereas it is the opposite ($\mathbf{J}\cdot\mathbf{E}<0$, Dynamo) behind the front.
- **In the fluid frame**, we found that the energy dynamo is mostly transferred from the plasma to the electromagnetic field ($\mathbf{J}\cdot\mathbf{E}'<0$) ahead or at the DF for both subcategories but energy dissipation ($\mathbf{J}\cdot\mathbf{E}'>0$) only occurs behind the front for the **Class 2**.

Thank you for your attention

Generalized Ohm's Law analysis {1}& {2}, MMS - 4 Spacecraft average at 0.3 s



Ohm's law from electrons

- Good agreement
- **E**+**ve**x**B** < +/- 1mV/m, except at the DF.
- Electrons are magnetized except at DF where they are demagnetized by the pressure gradient:
- E_N' =(E+vexB)_N = -(GradPe/en)N for both classes 1&2 and also probably along M for class2.

Ohm's law from ions

- Good agreement **E**+**vi**x**B** and **J**x**B**/ne
- Ions are demagnetized by Hall electric field. E'= E+vixB = (JxB)/en - (GradPe)en