A SUMMARY OF RESULTS FROM YEAR 1 OF THE MAGNETOSPHERIC MULTISCALE (MMS) MISSION

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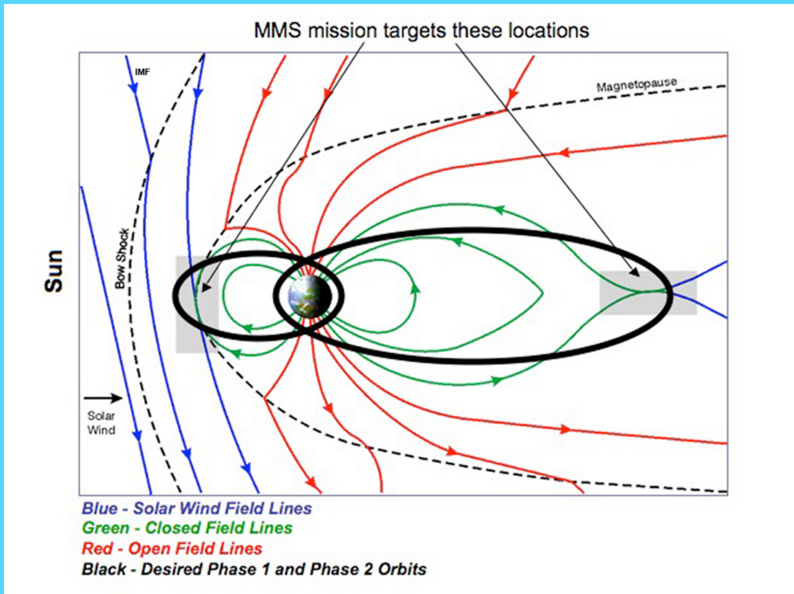
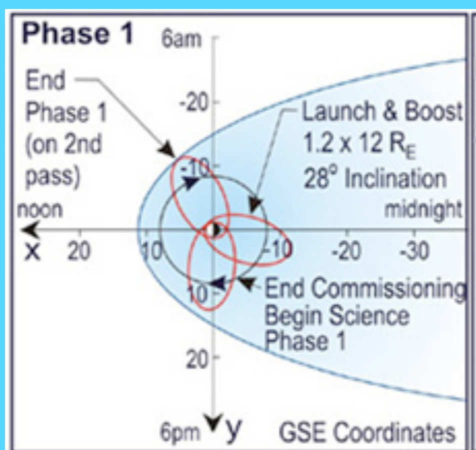
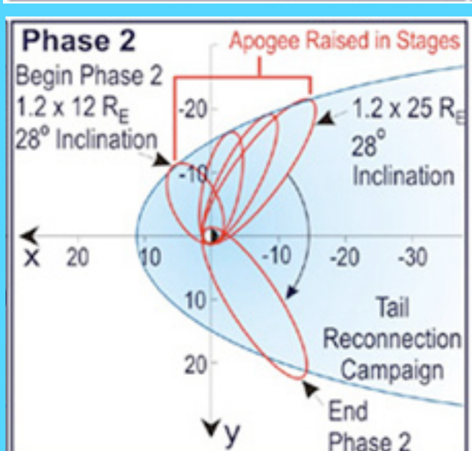
MMS

- A NASA Solar-Terrestrial Probe mission
- Mission is basic science using magnetosphere as a laboratory
    - Developed to study small scale physics of magnetic reconnection
- Four spacecraft in tetrahedral formation
    - Similar in flavor to Cluster
        - Smaller spacecraft separation
        - Higher time resolution
- In development since early 2000s
- Launched at KSC, March 12, 2015

REFERENCES -
BURCH ET AL., SPACE SCI. REV., 199, 5 (2016)
MOORE ET AL., JASTP, 99, 32 (2013)







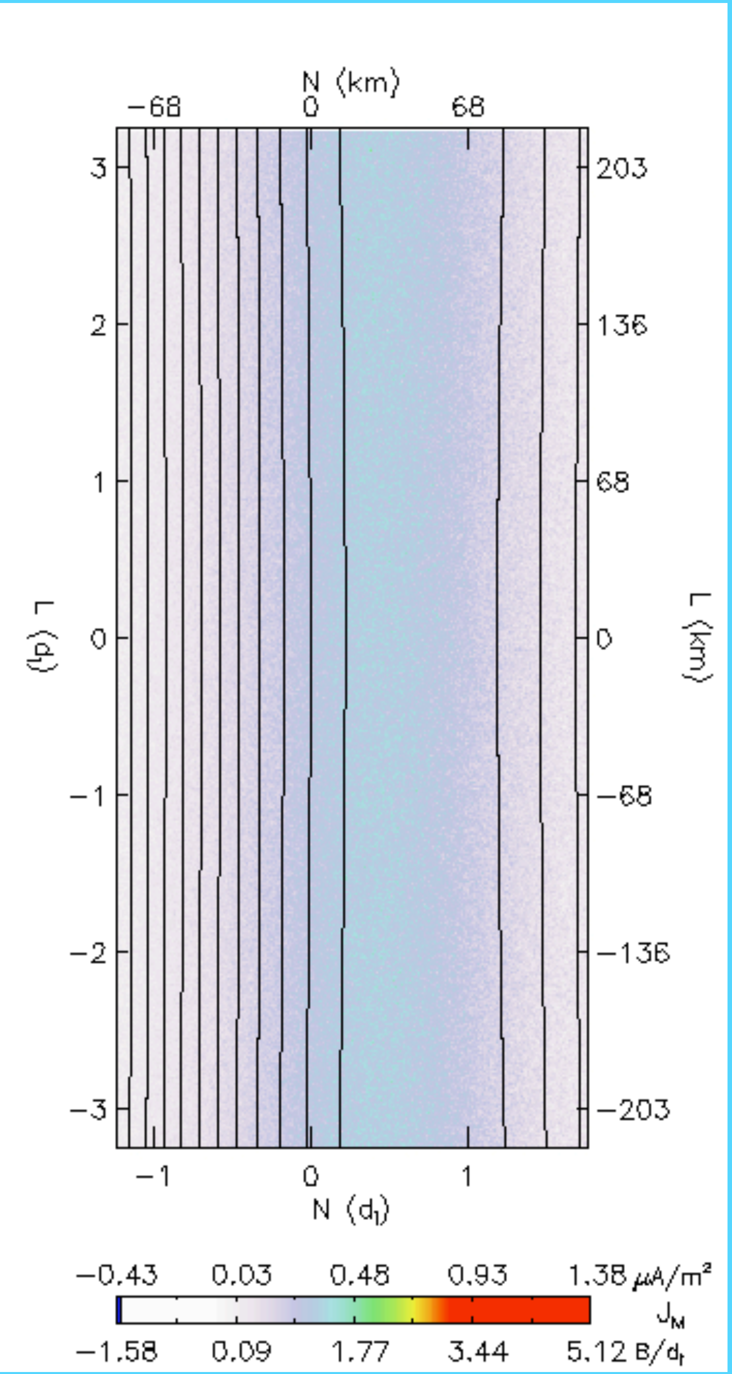
MISSION BASICS

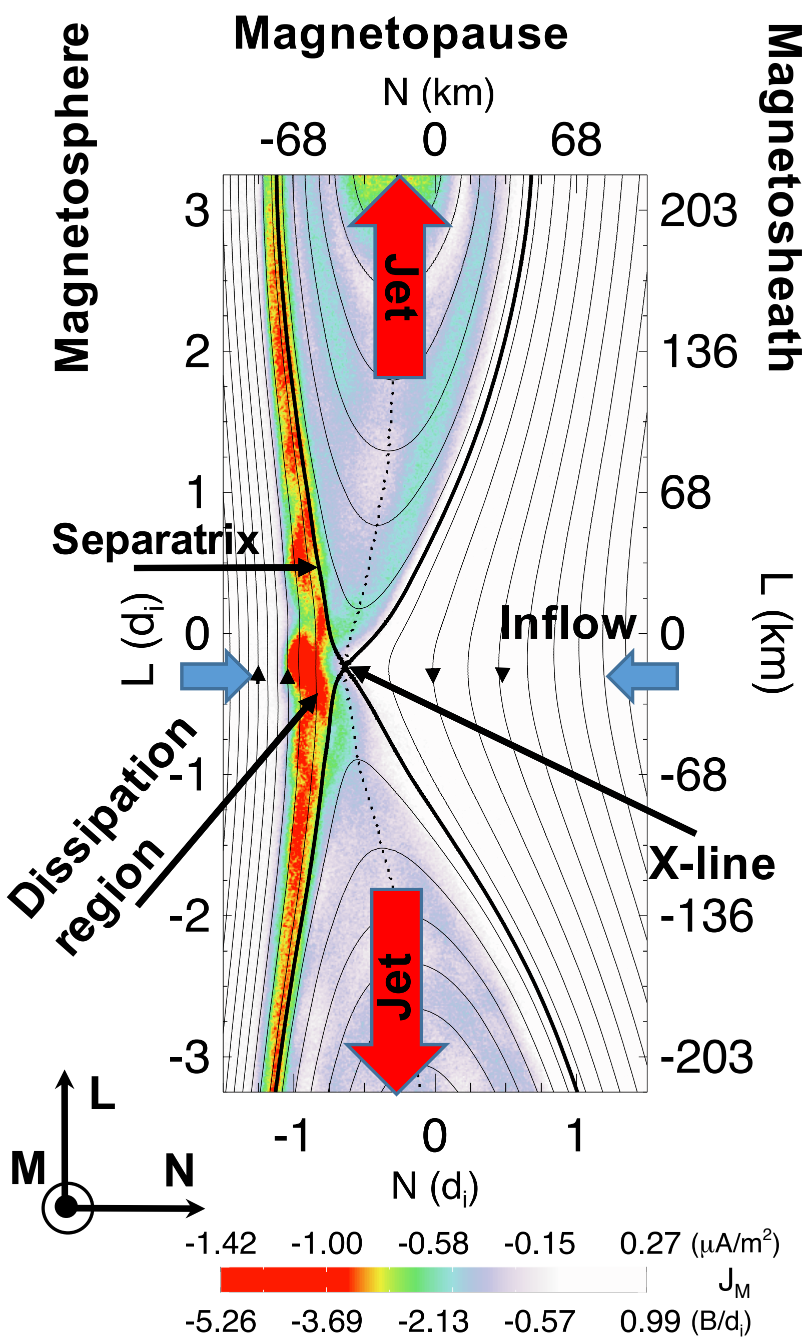
- Reconnection occurs both on the dayside and nightside; MMS will study both
  - Phase I — dayside
  - Phase II — magnetotail
- The orbit
  - Nearly ecliptic, highly elliptic, precessing
    - Phase I divided into 2 phases 1A and 1B, separated by 1X
      - Phase 1A is complete, Phase 1B starts 9/16
      - Phase 1X is “bonus” science that can be done between the two dayside phases
- Data analyzed on board and by Scientist-In-The-Loop
  - Only the most compelling data is downloaded

MAGNETIC RECONNECTION

- Magnetic field lines with oppositely directed component come together and effectively break
- Field line tension drives outflow, plasma jets go out at Alfvén speed
- New field lines brought in, process repeats
  - Crucial aspect of space weather both in solar atmosphere and magnetosphere
- Breaking of field lines requires dissipation, which occurs at small (electron) scales
  - Extremely difficult to probe, even in lab and simulations

REFERENCES -
CASSAK, SPACE WEATHER, 14, 186 (2016)
GONZALEZ AND PARKER, MAGNETIC RECONNECTION: CONCEPTS AND APPLICATIONS, SPRINGER (2016)





CHALLENGES I

- Resolving spatial scales
  - Dissipation occurs at electron gyroscales and below
    - Magnetopause — ~1 km
    - Magnetotail — ~10 km
  - Solution — tight formation
    - Spacecraft separation as low as 10 km
    - Uses GPS signals from below to coordinate
- Resolving time scales
  - Magnetopause motion ~100 km/s
    - Implies a need of ~0.01 s = ~10 ms resolution through magnetopause electron layer
  - Solution — higher cadence than ever before

MMS INSTRUMENTATION

Fields — 3D electric and magnetic field measurements at <1 ms time resolution (DC) and waves to 6 kHz (*B*) and 100 kHz (*E*)

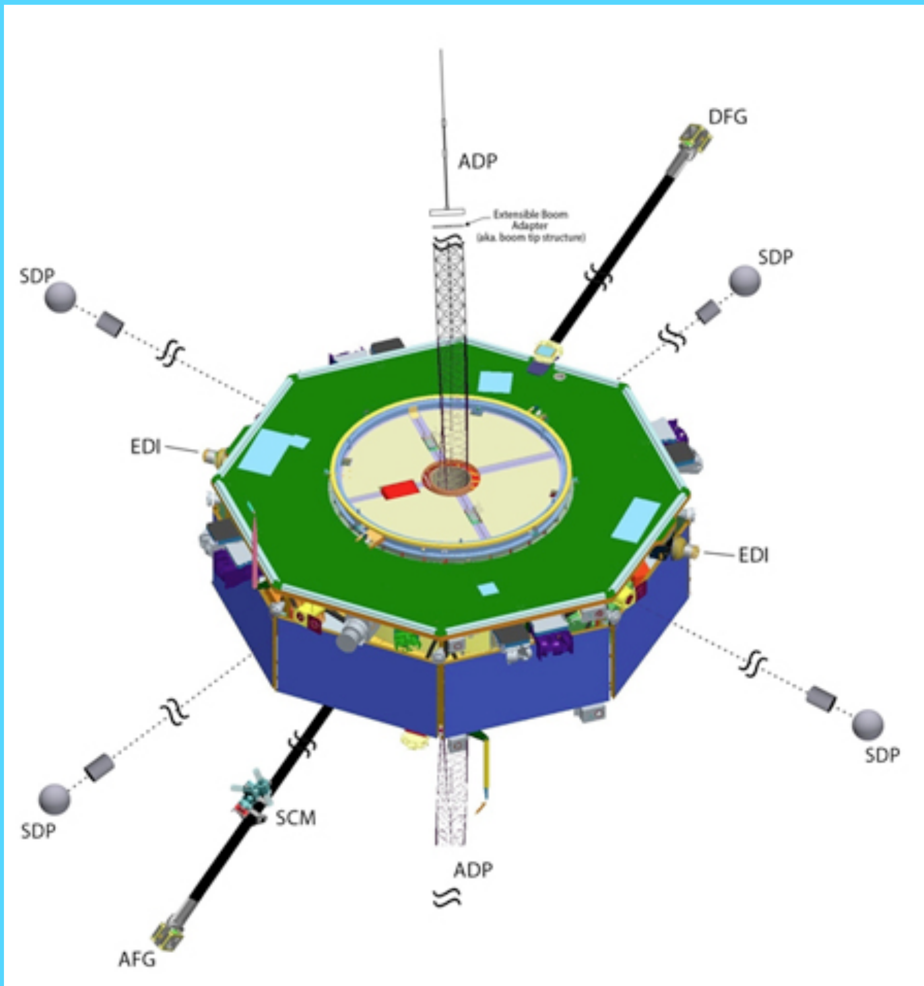
Fast plasma — Full sky viewing of plasma electrons and ions at 32 energies (10 eV to 30 keV): electrons in 30 ms, ions in 150 ms

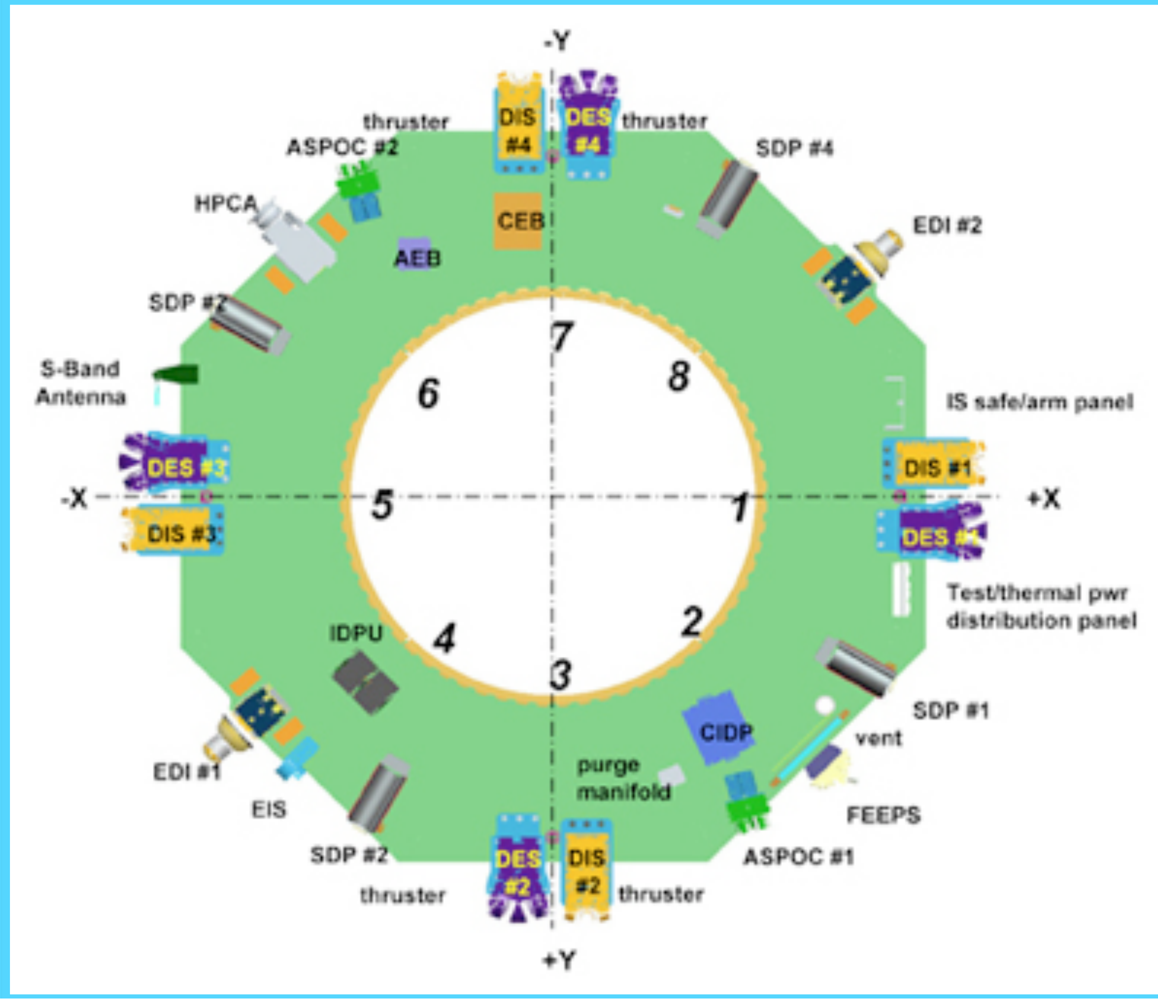
Energetic particles — Full-sky viewing of ion and electron energetic particles (20 – 500 keV) with composition

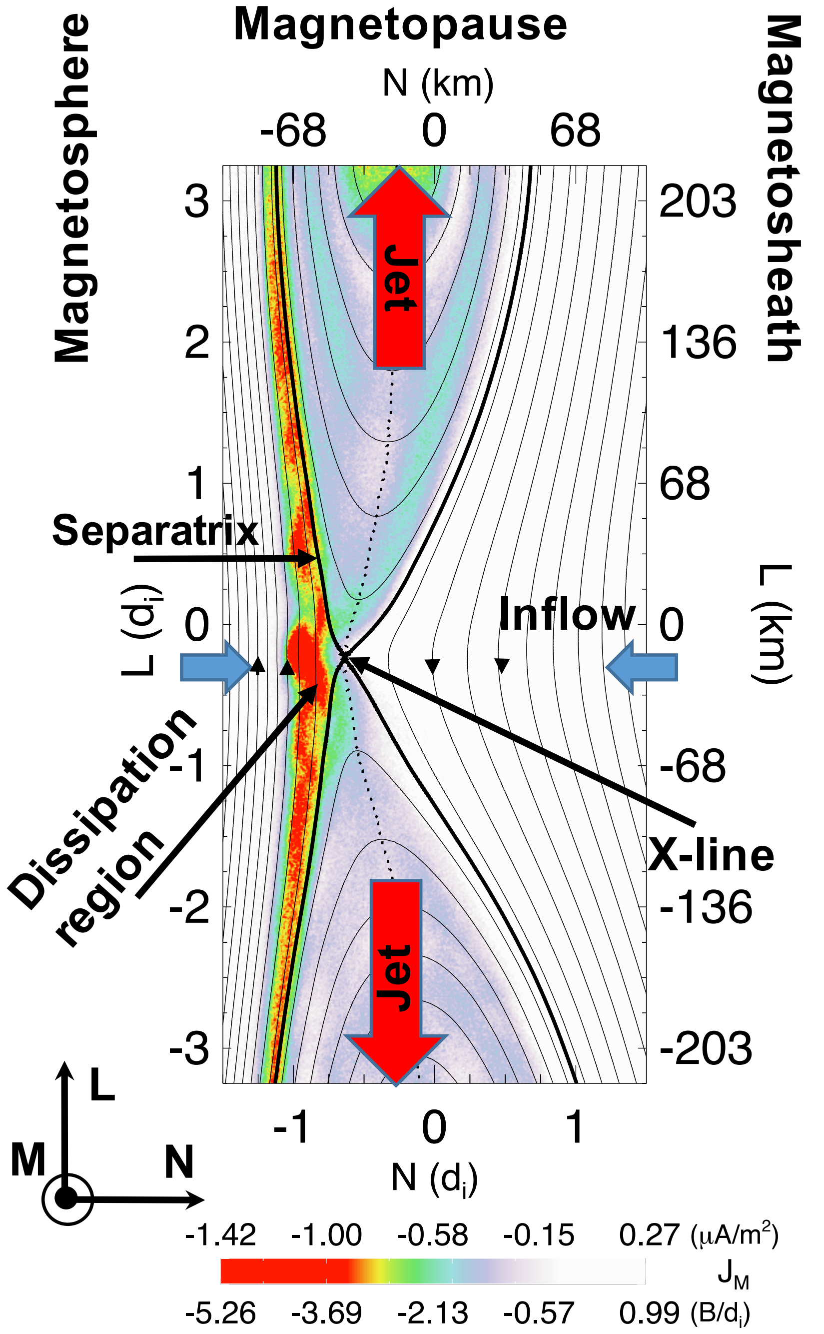
HPCA — Composition-resolved 3D ion distributions (1 eV - 40 keV) for H^+, He^{++}, He^+, and O^+; full sky at 10 s

ASPOC — Maintain S/C potential to ≤ 4 V using ion emitter

REFERENCES - 21 PAPERS IN SPACE SCI. REV., 199, 1-747 (2016)







CHALLENGES II

- Identifying the reconnection site in observations
    - In-plane field is zero (!) at X-line
    - Outflow flow is zero, inflow is too small to measure
        - Locations where field and flow are small are not unique to reconnection!
- Solution — need context; signatures from multiple plasma parameters, including field and particle data, and multiple spacecraft

POTENTIAL SIGNATURES

1) Magnetic field strength |B| goes to zero

2) Outflow jet reversal

3) Intense currents (electrons faster than ions)

4) Electron heating in region near where |B| goes to zero

5) Electron frozen-in breaks down

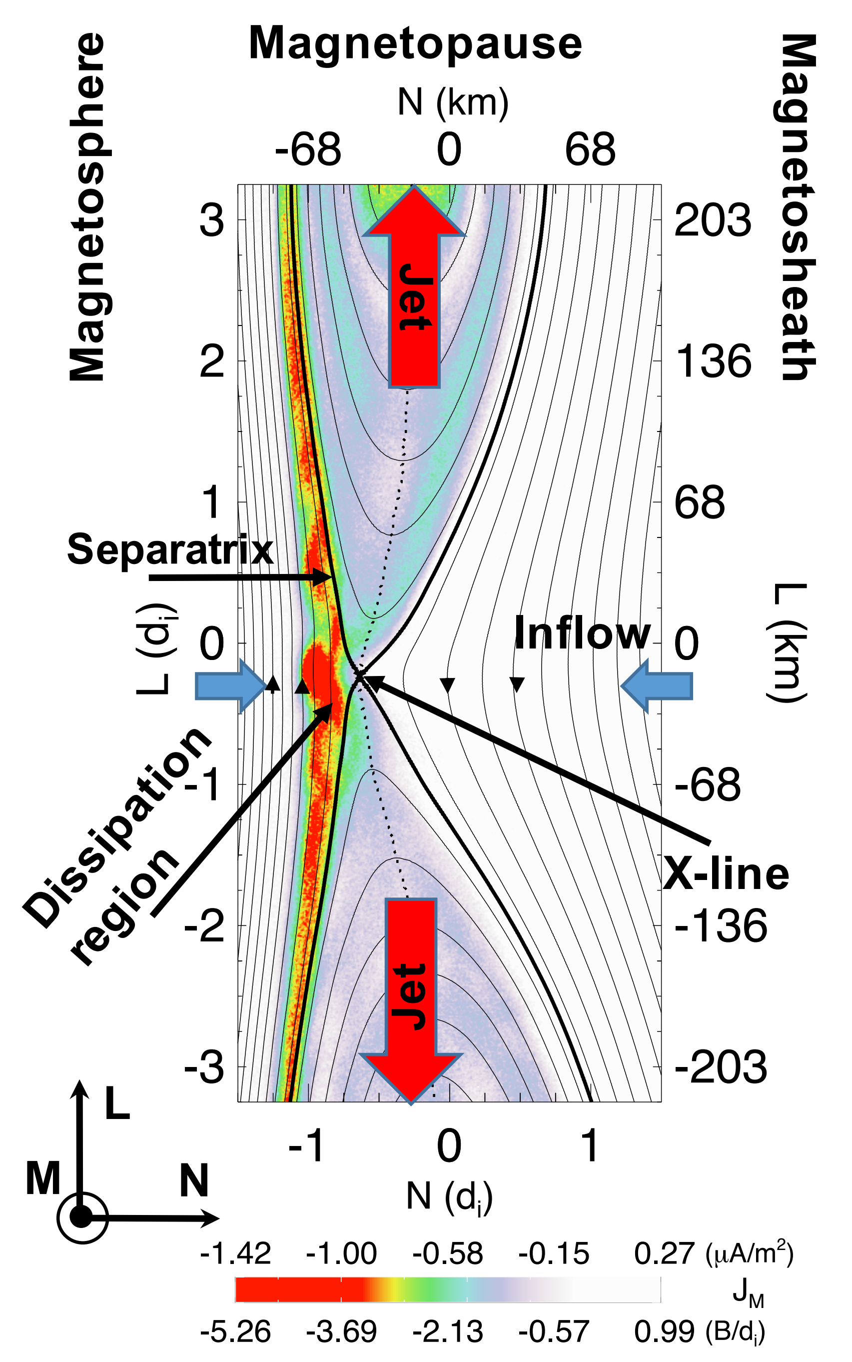
6) Increase in perpendicular energy flux where |B| = 0

7) Crescent-shaped distribution function on magnetospheric side, ring closer to where |B| = 0 (Hesse et al., GRL, 2014)

8) Crescent direction changes from perpendicular to B to parallel to B, consistent with magnetic field opening up

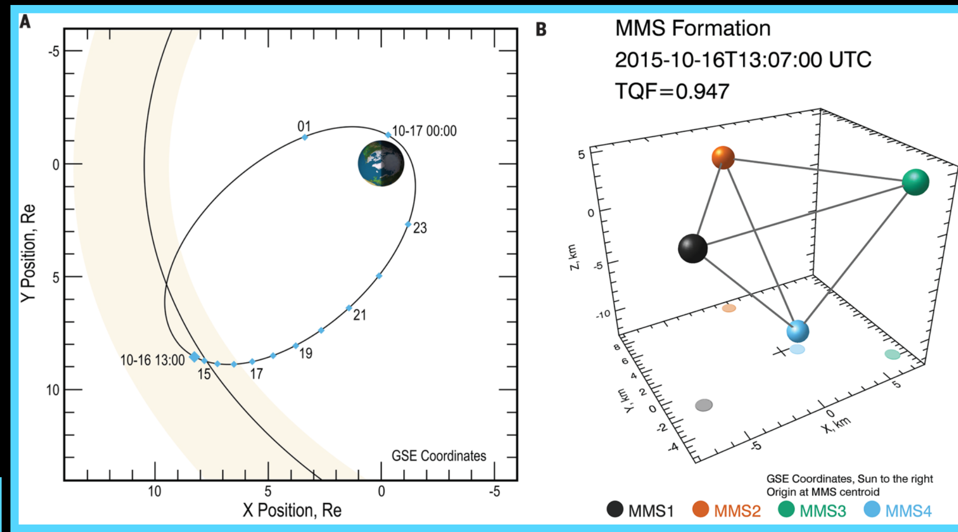
9) Energetic electrons appear at electron scales where |B| = 0

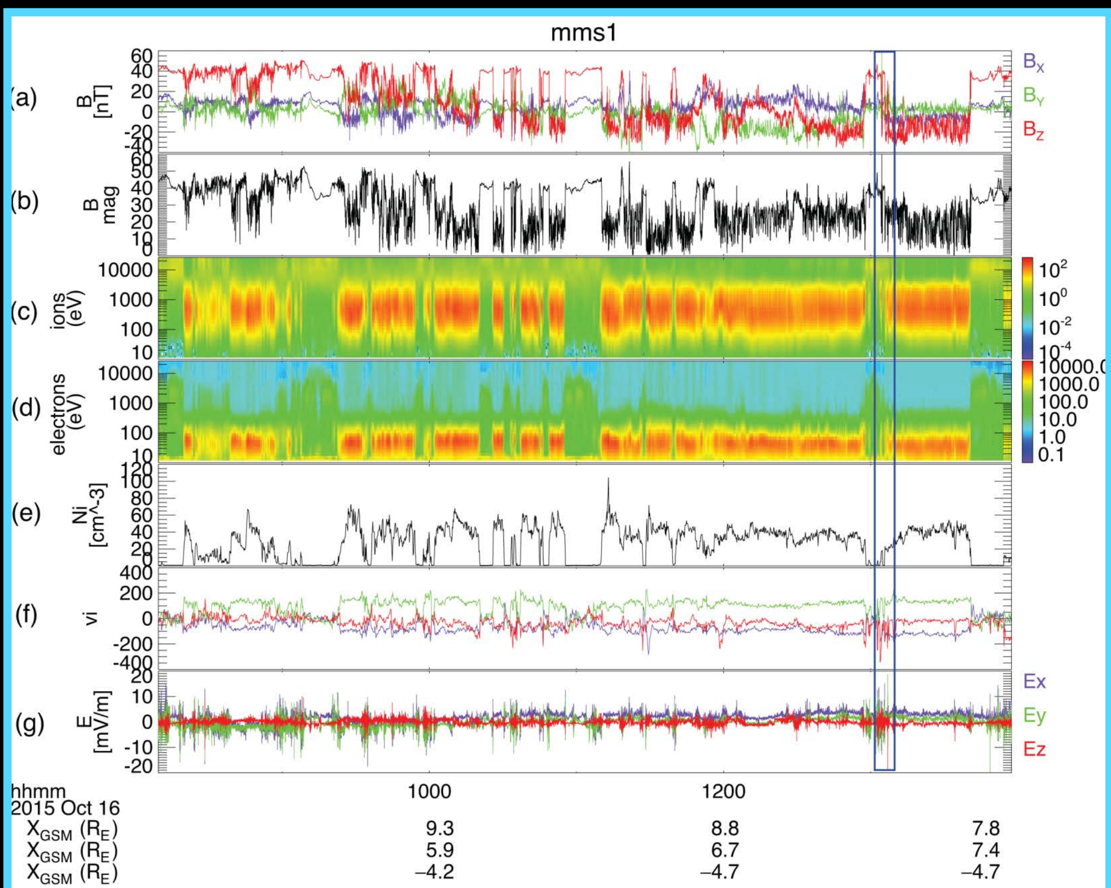
ALL OF THESE WERE SEEN IN MMS DATA FOR A SINGLE EVENT (BURCH ET AL., SCIENCE, 352, 1189, 2016)



OVERVIEW

- A — location of MMS on October 16-17, 2015
- Below — 6 hours of data: magnetic field (a) components and (b) magnitude, (c) ion and (d) electron energy spectrograms, (e) ion density, (f) ion bulk flow components, and (g) electric field components for this time period
- B — MMS formation at 13:07:00 UTC





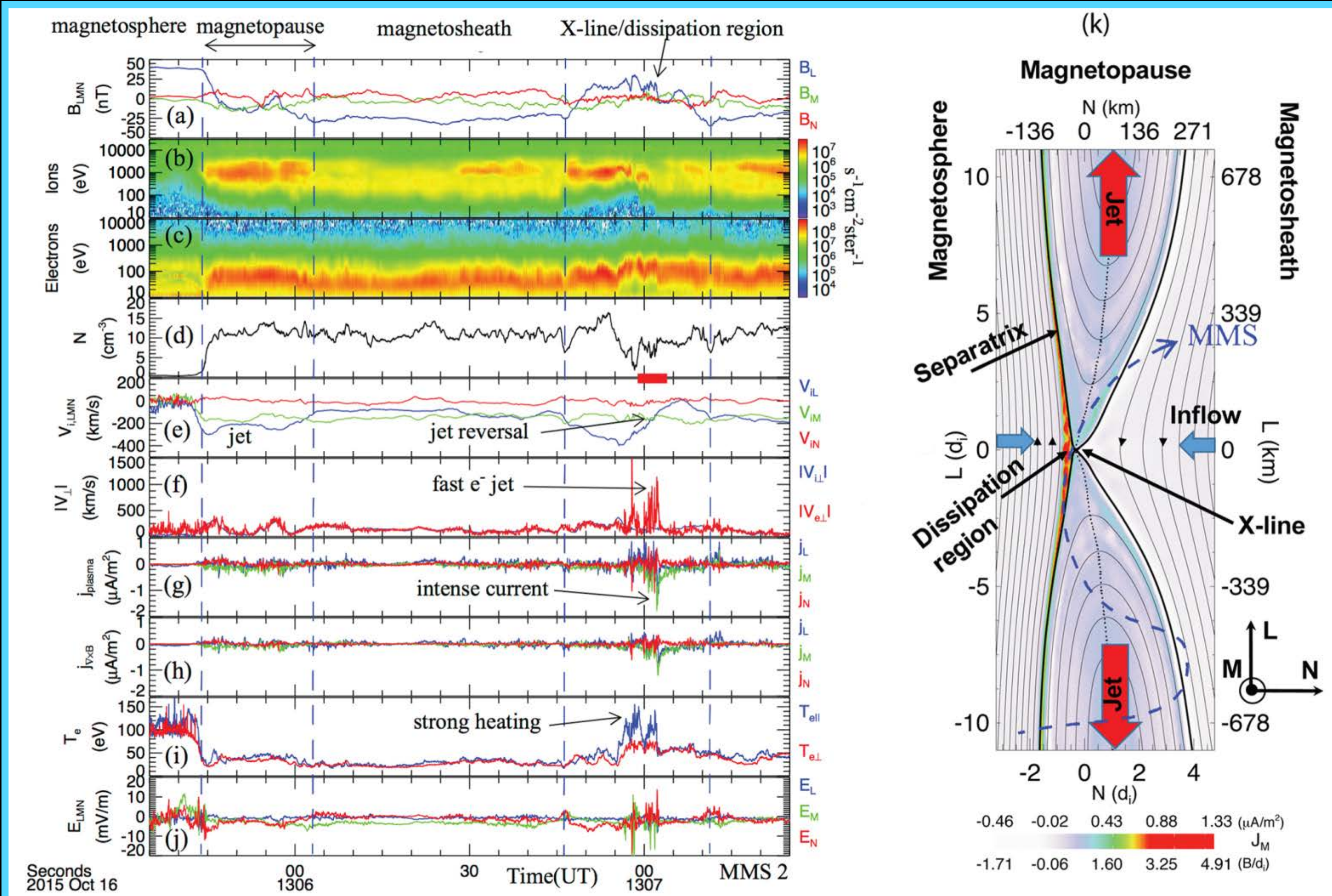
UPSHOT:
MANY MAGNETOPAUSE CROSSINGS
CROSSING AT 2015 OCT 16 IS PARTICULARLY INTERESTING

ZOOM IN NEAR 1307 UT

UPSHOT: EXCELLENT CONTEXT FOR A DIFFUSION REGION

1) |B| ~ 0
2) JET REVERSAL
3) INTENSE ELECTRON FLOW
3*) **J FROM ∇ X B AND ΣNEV NEARLY IDENTICAL**
4) ELECTRON HEATING WHERE |B| = 0

- 2 minutes of data from MMS2 near 2015 Oct 16, 1305 - 1307 UT
- At 1306, there is a crossing with a distinct southward ion jet
- At 1307, there is a crossing with a jet reversal



ZOOMED IN EVEN MORE!

- 3 seconds (!) of data from MMS2 near 2015 Oct 16 1307

UPSHOT: OVERWHELMING EVIDENCE

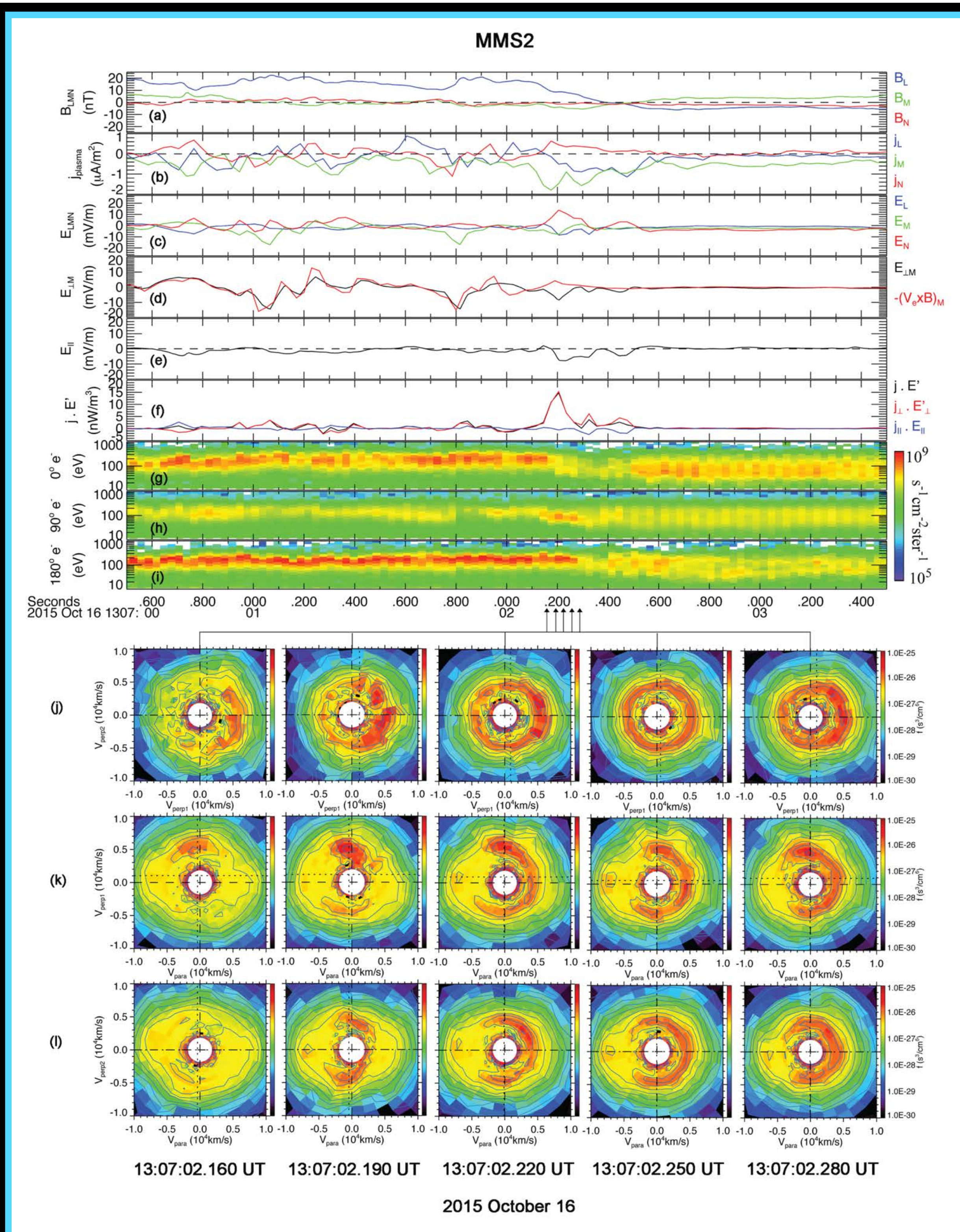
5) ELECTRON FROZEN-IN BREAKS DOWN

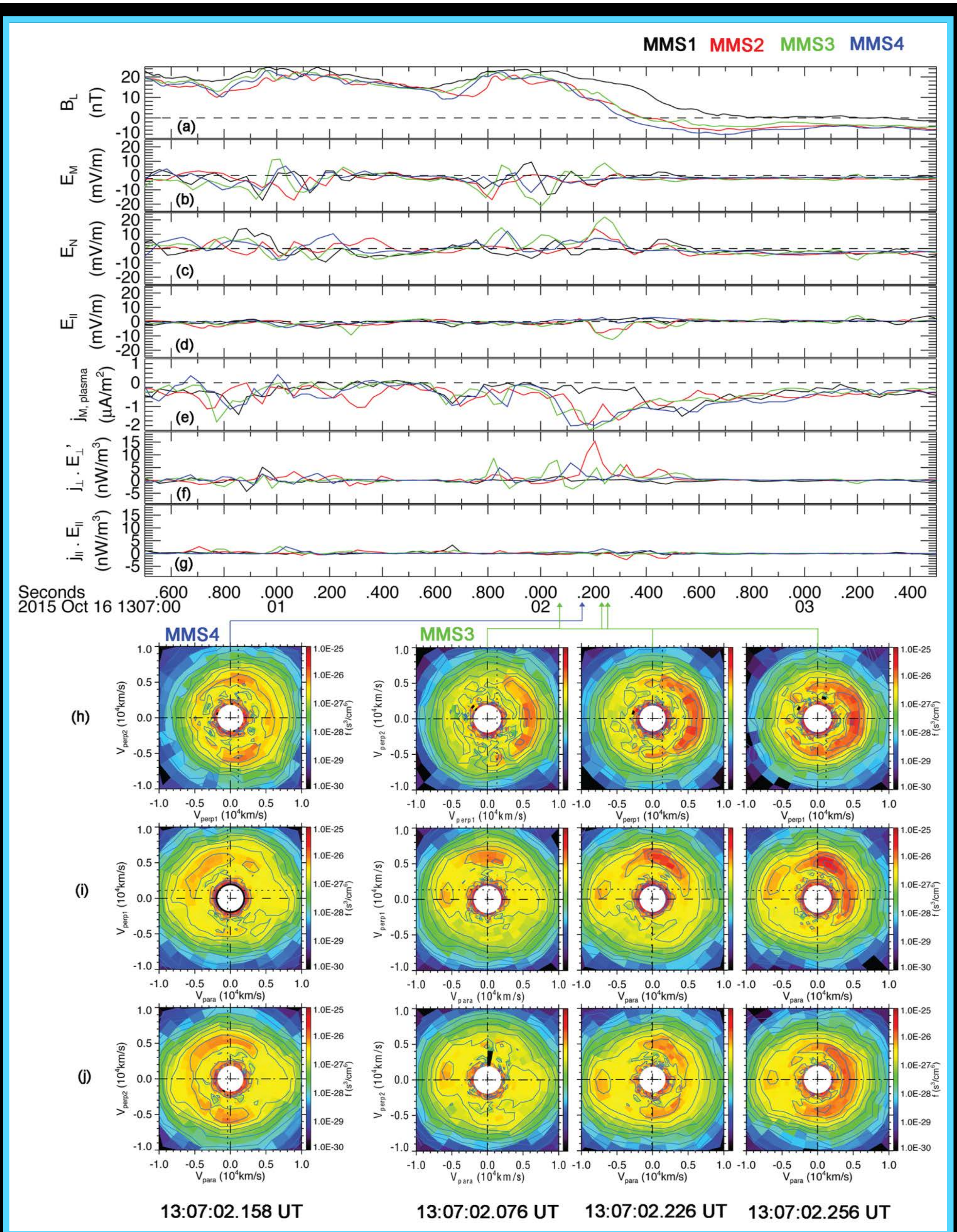
5*) **CALIBRATION SO GOOD THAT E AND $-V_E \times B$ USUALLY AGREE**

6) INCREASE IN PERPENDICULAR ENERGY FLUX WHERE |B| = 0

6*) **DIRECT MEASUREMENT OF J • E IN DIFFUSION REGION (~15 NW/M^3)**

7) CRESCENT-SHAPED DISTRIBUTION FUNCTION ON MAGNETOSPHERIC SIDE, RING CLOSER TO WHERE |B| = 0





SPACECRAFT COMPARISON

- Same 3 seconds of data from all four MMS spacecraft

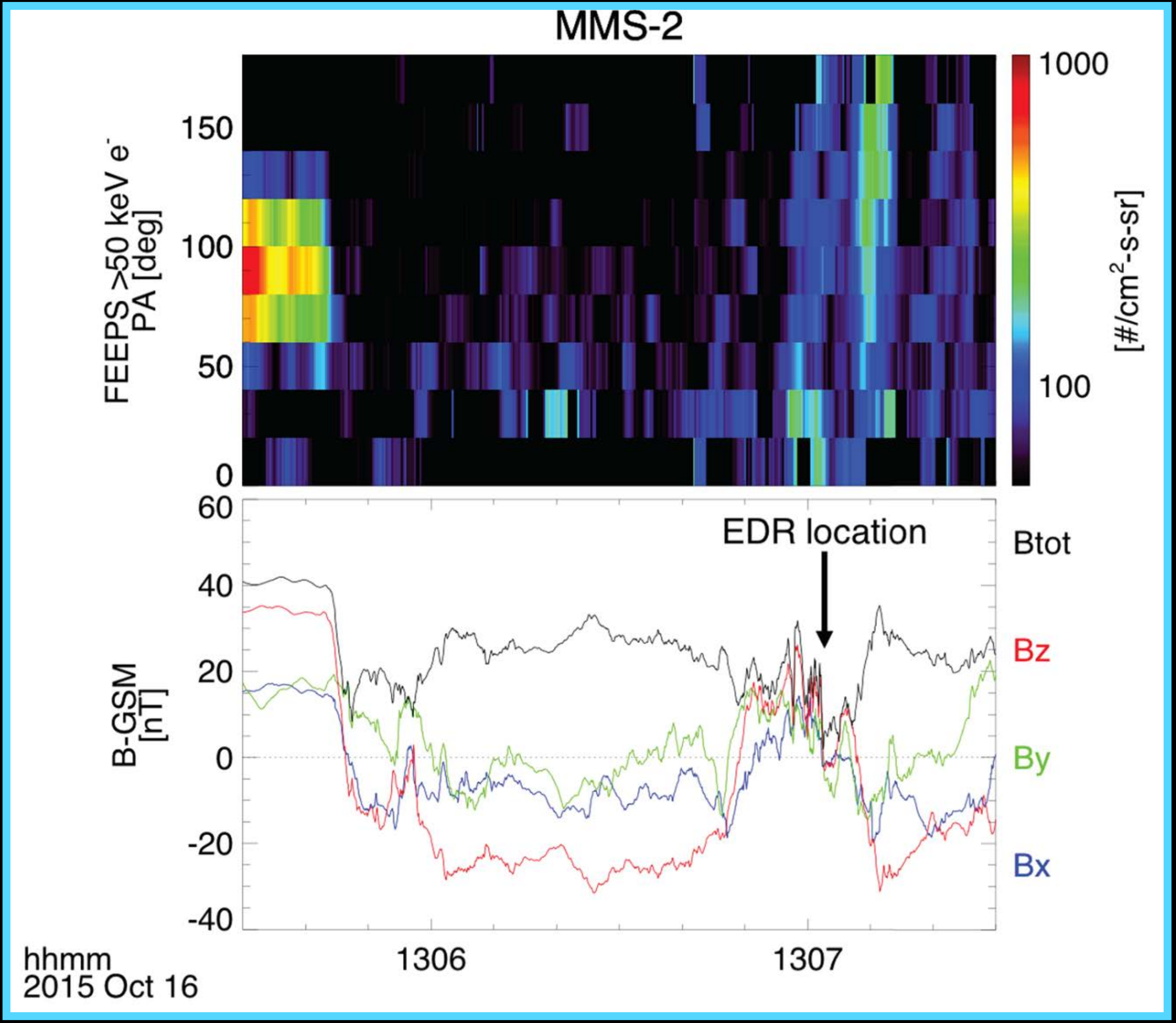
UPSHOT: OVERWHELMING EVIDENCE

8) CRESCENT DIRECTION CHANGES FROM PERPENDICULAR TO B TO PARALLEL TO B, CONSISTENT WITH MAGNETIC FIELD OPENING UP

ENERGETIC ELECTRONS

UPSHOT: ENERGETIC ELECTRONS OBSERVED

9) ENERGETIC ELECTRONS APPEAR AT ELECTRON SCALES WHERE |B| = 0



Conclusion - MMS got very close to an electron diffusion region

OTHER MMS STUDIES

- Special issue of GRL
  - Submission deadline was April 15
  - 65 (!) papers
- A few papers in other journals
  - 3 PRL, 3 JGR, some under review

- Sample results (32 of them!)
  - Measurement of terms in generalized Ohm's law (Torbert GRL)
  - Diffusion region on flanks with guide field 4 (Eriksson PRL); near subsolar region with guide field 1 (Phan/Burch GRL)
  - Mirroring electrons in exhaust (Lavraud GRL)
  - Strong parallel electric field (Ergun PRL/GRL, Goodrich GRL), wave emission and nonlinear structures (Mozer PRL, Le Contel GRL, Zhou GRL, Gershman GRL, Wilder GRL), current filaments in exhaust (Phan GRL, Graham GRL)
  - Reconnection during Kelvin-Helmholtz on flanks (Eriksson GRL, Li GRL)
  - FTEs (Eastwood GRL, Farrugia GRL, Hasegawa GRL)
  - Location of reconnection (Trattner GRL, Kitamura GRL, Petrinec GRL)
  - Electron escape from magnetosphere (Mauk GRL), electron acceleration (Chen GRL, Jaynes GRL, Baker GRL), ion acceleration (Wang GRL)
  - Ionospheric context (Anderson GRL), microinjections (Fennell GRL)
  - Theory - crescent distributions (Bessho GRL, Shay GRL, Price GRL)

CONCLUSIONS

- MMS studying electron scale physics during reconnection
- Successful identification of a crossing very near to a dayside reconnection X-line
  - Measuring reconnection rate and electron pressure gradient is still a challenge
- On the horizon:
  Phase 1X, "bonus" science during near-tail pass
  Phase 1B, second pass at the dayside, coming up
  Phase 2, focusing on the nightside, is next year
- Data publicly available at
  https://lasp.colorado.edu/mms/sdc/public/

AMAZING FEATURES OF MMS

30 MS ELECTRON CADENCE, 150 MS FOR IONS

E AND $-V_E$ X B MEASURED INDEPENDENTLY

J MEASURED THROUGH ∇ X B AND ∑NEV

DIRECT MEASUREMENT OF J • E

Magnetospheric Multiscale Mission Science Working Team Meeting – SwRI, San Antonio, TX – Nov 3-5, 2015