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EGU General Assembly
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4th May 2020

Science and Technology Facilities Council

Natural Environment Research Council

Electron trapping in magnetic mirror structures at the edge of magnetopause flux ropes

Sadie Robertson[1], Jonathan Eastwood[1], Julia Stawarz[1], Heli Hietala[1], Tai Phan[2], Benoit Lavraud[3], James Burch[4], Barbara Giles[5], Daniel Gershman[5], Roy Torbert[6], Per Arne Lindqvist[7], Robert Ergun[8], Christopher Russell[9], Robert Strangeway[9]

1. Space and Atmospheric Physics Group, Blackett Laboratory, Imperial College London
2. Space Sciences Laboratory, University of California, Berkeley
3. Institut de Recherche en Astrophysique et Planétologie, CNRS, UPS, CNES, Université de Toulouse
4. Southwest Research Institute, San Antonio, Texas
5. NASA, Goddard Space Flight Center, Greenbelt
6. University of New Hampshire, Durham, New Hampshire
7. KTH Royal Institute of Technology, Stockholm, Sweden
8. LASP/Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder
9. Institute of Geophysics, Earth, Planetary, and Space Sciences, University of California, Los Angeles

sadie.robertson14@imperial.ac.uk

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Study outline

- We investigate magnetopause flux ropes using data from the Magnetospheric Multiscale (MMS) mission
- We present two case studies of ion-scale flux ropes, on the edge of which we observe electron trapping in magnetic mirror structures
  - In particular, we focus on the particle pitch angle distributions, and how they can indicate particle trapping
- We discuss the possible formation mechanisms of the magnetic mirror structures, as well as how the structures could evolve and produce particle acceleration

Presentation Structure

sadie.robertson14@imperial.ac.uk

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1. Introduction

Flux ropes and particle acceleration

- Flux ropes are helical magnetic field structures formed during magnetic reconnection
  - Observed on the magnetopause and in the magnetotail (e.g. Russell & Elphic, 1978; Fear et al., 2008)

- They are a proposed site for electron acceleration
  - Fermi acceleration as island contracts (Drake et al., 2006)
  - Energetic electron fluxes observed to peak at sites of compressed density inside magnetic islands (Chen et al., 2007)
  - Particle acceleration and reflection in flux pile up region surrounding flux rope (Zhu et al., 2019)

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2. Electron trapping case study 1

2nd January 2017

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2^{nd} January 2017 magnetopause crossing

- MMS was moving outbound from the magnetosphere into the magnetosheath
- Data presented in LMN coordinates based on MVA on full magnetopause crossing at 03:07UT
- During a partial crossing of the magnetopause, a flux rope was observed at 03:18UT, just prior to the spacecraft exit from a reconnection exhaust into the magnetosheath

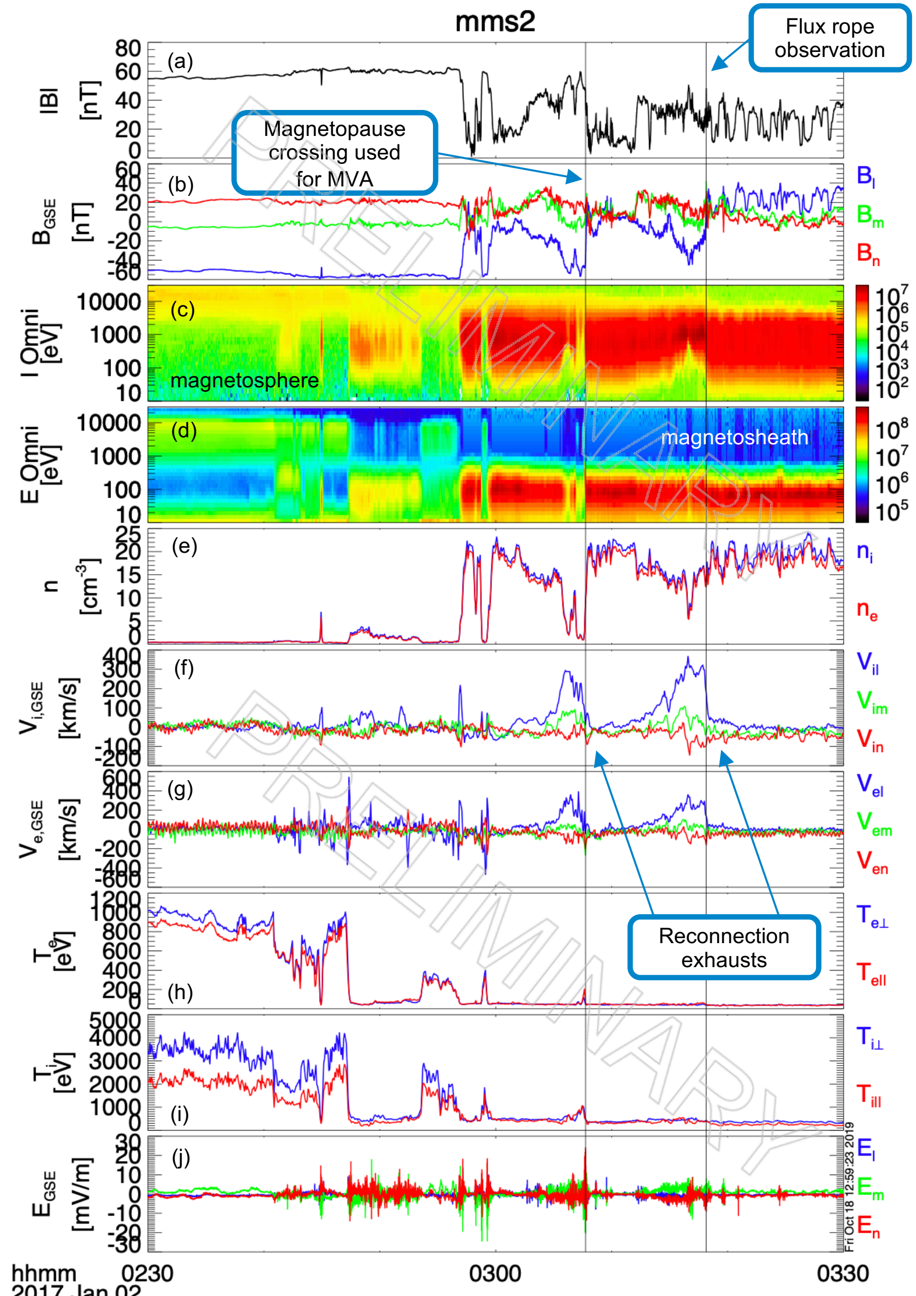

Figure 1: 2hr interval of MMS2 data during an outbound magnetopause crossing

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Ion-scale flux rope with unexpected electron trapping

- Electron pitch angles go from 90° to 60° and 120° and back (i-n)
  - Particularly for 50-200eV electrons (j & k)
- Corresponding dip in the magnetic field strength of ~10nT (a)
- Suggests electrons trapped by magnetic mirror

$$\frac{\sin^2 \alpha}{B} = \frac{\sin^2 \alpha_0}{B_0}$$

$\alpha(B)$ for α_0= 90° (corresponding to mirror points; where particles are reflected) and B_0 = 20nT, 30nT, 40nT are added to the particle patch angle distribution plots (i-n)

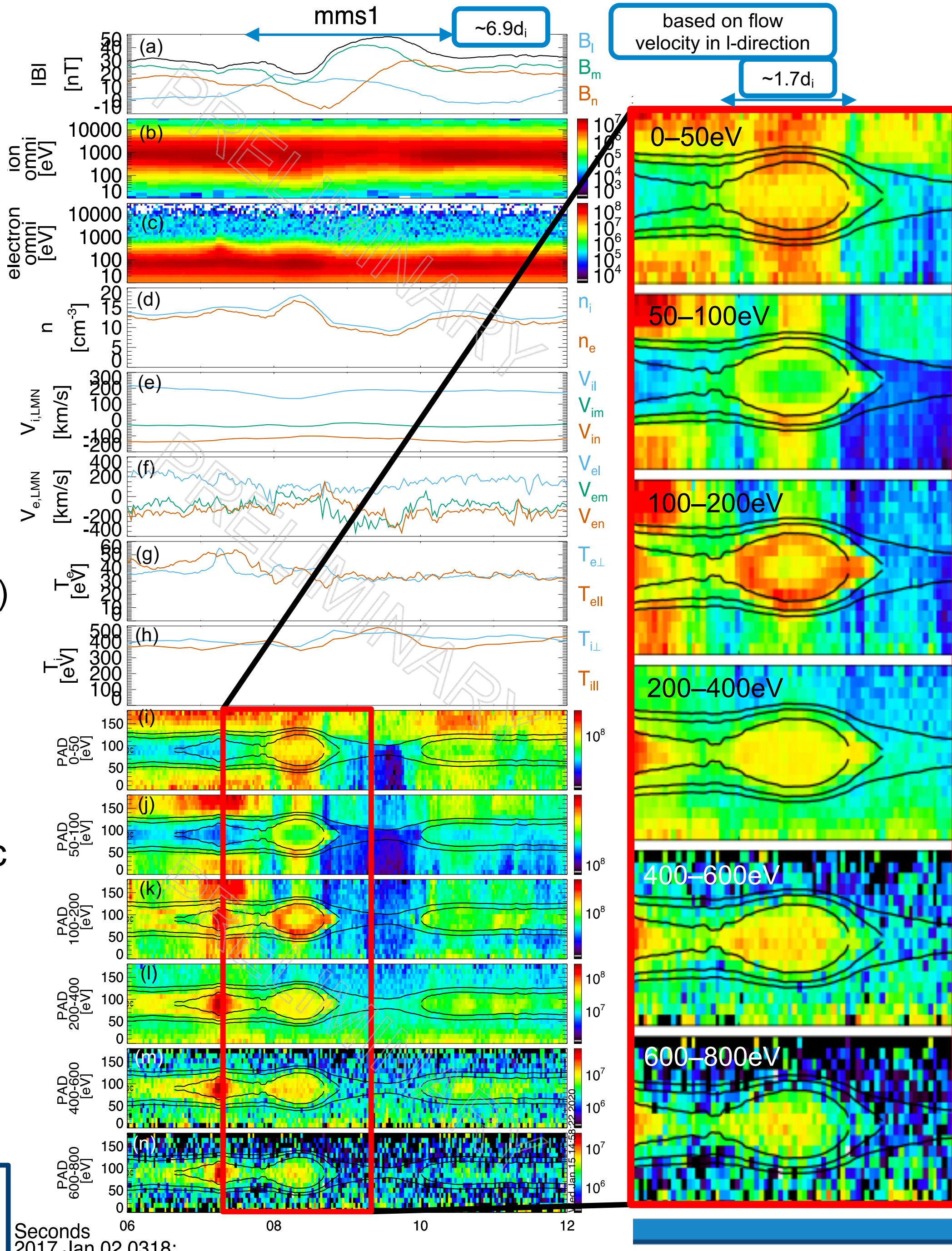

Figure 2: 6s plot of MMS1 data showing flux rope observation.

[Jump to plot for case study 2]

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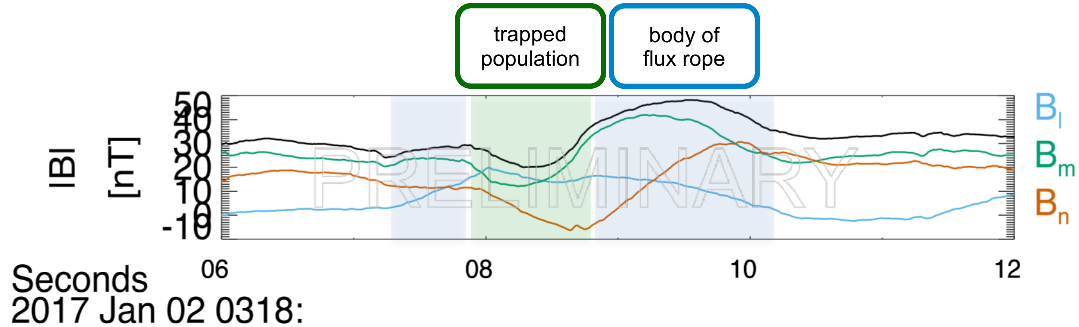
3D structure

- B_M guide field of ~20nT observed throughout flux rope observation
  - Flux rope and trapped population have extended 3D structure

- Dip in B_M component of magnetic field through trapped population provides majority of |B| decrease which leads to electron trapping
  - 'Steepening' of field lines through trapped population produces trapping – see diagram
  - $B_M \simeq B_L$ through trapped population, allowing us to set minimum m-extent of ~$1.7d_i$ for the trapped population



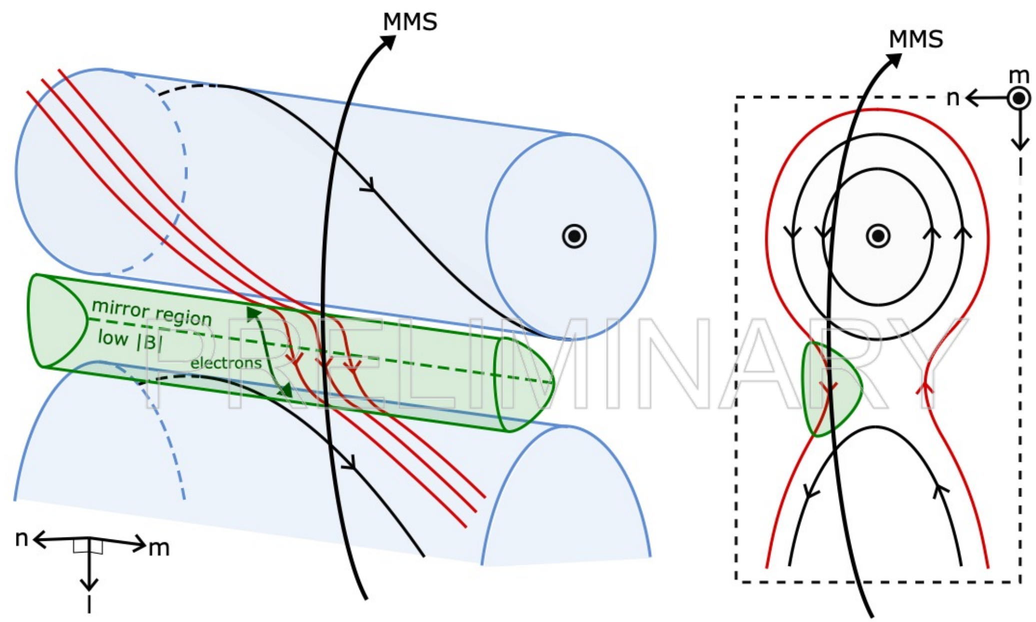


Figure 3: 3D diagram of flux rope observation

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Formation and evolution

- Consistent with magnetic hole observations (e.g. Yao et al. 2018)
  - Single isolated structure, rather than a train of holes
- Magnetic mirror instability
  - Growth of instability explains donut-shaped pitch angle distributions – see Southwood and Kivelson 1993
  - Mirror instability requires high plasma beta and a temperature anisotropy – we observe an increase in plasma beta (e) and temperature isotropies of ~1.5 (d) on the edges of the trapped populations
- Small increase (~0.2nPa) in total pressure through trapped population (f)
  - Increase in ion and electron pressures (~0.3nPa and ~0.1nPa, respectively) approximately balances decrease in magnetic pressure (~0.2nPa)

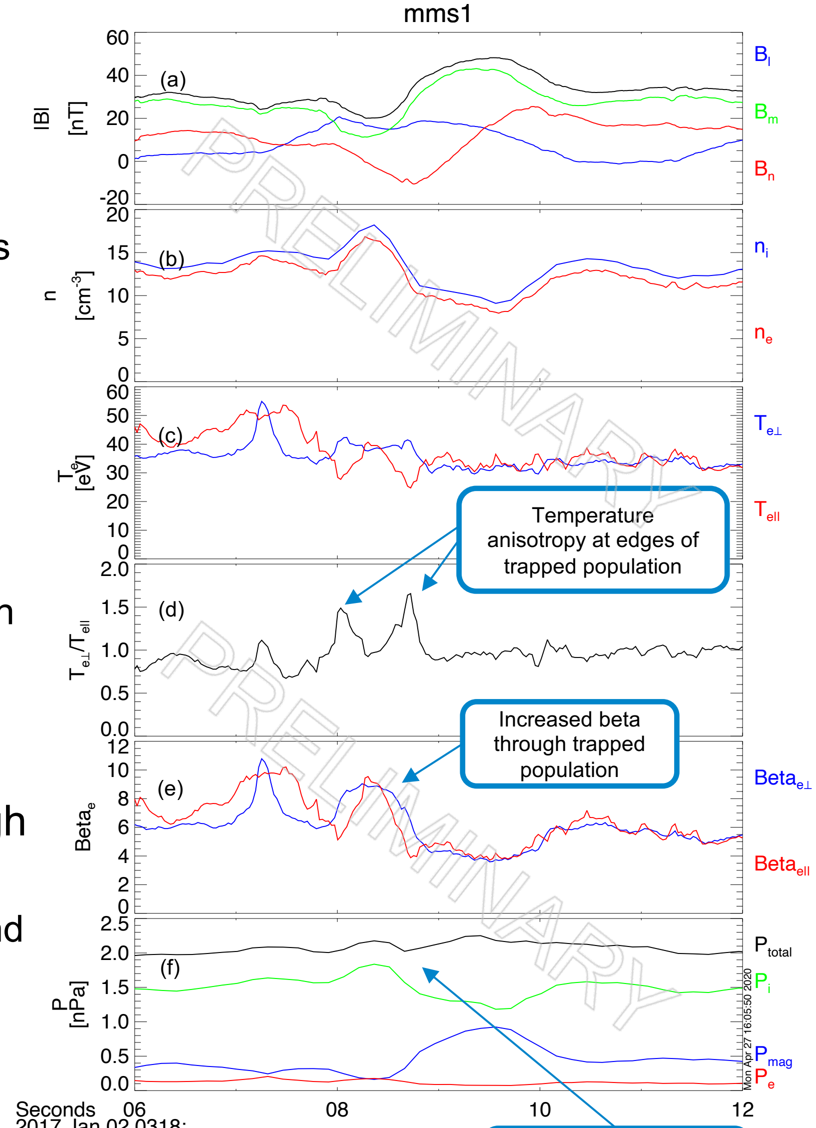

Figure 4: 6s plot showing temperature anisotropy and pressure throughout flux rope observation
Jump to plot for case study 2

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Second trapped population

- Shorter duration trapped population
  - Focused at 90 degrees, with no donut-shaped structure (i-n)
  - Corresponding $T_{e\perp}$ increase of ~20eV (g)

- Consistent with kinetic scale magnetic hole observations (e.g. Huang et al. 2016)

- If one structure evolved into the other, how much betatron heating would we observe?
  - 10eV of heating calculated from change in |**B**|
  - 15eV of heating observed

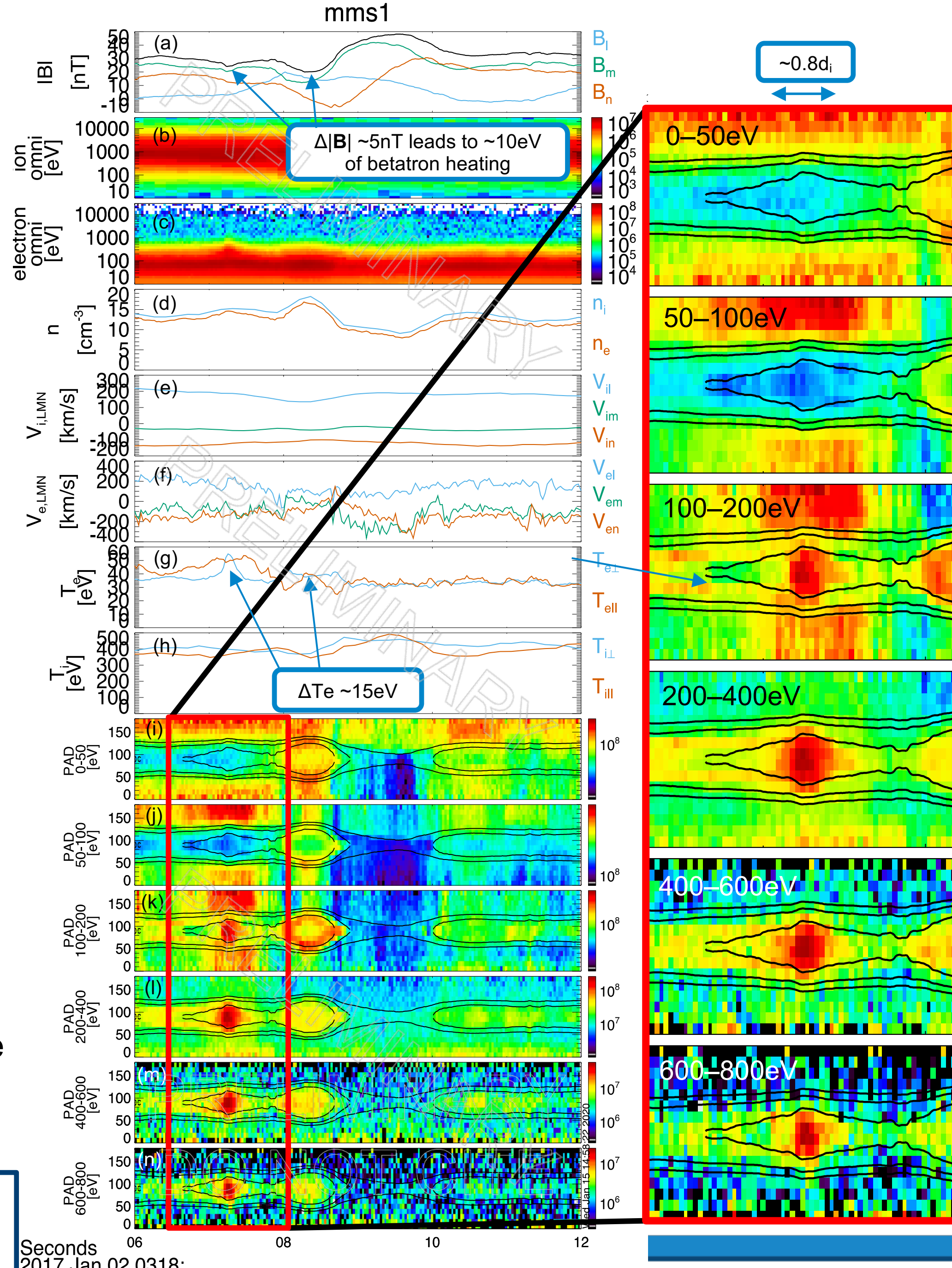

Figure 5: 6s plot of MMS1 data showing flux rope observation
Jump to plot for case study 2

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3. Electron trapping case study 2

9^{th} December 2015

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Second case study

9th December 2015

- Ion-scale flux rope observed during an outbound magnetopause crossing
- Electron magnetic mirror trapping in magnetic hole, as in case study 1
  - Dip in magnetic field strength of ~10nT on magnetosheath edge of flux rope (a)
  - Pitch angle distributions (i-n) exhibit similar donut features
- Field line configuration consistent with Figure 3
- Here we observe a corresponding parallel population of electrons in the pitch angle distributions (i-n)
  - The field lines on which electrons are trapped have a different topology to case study 1

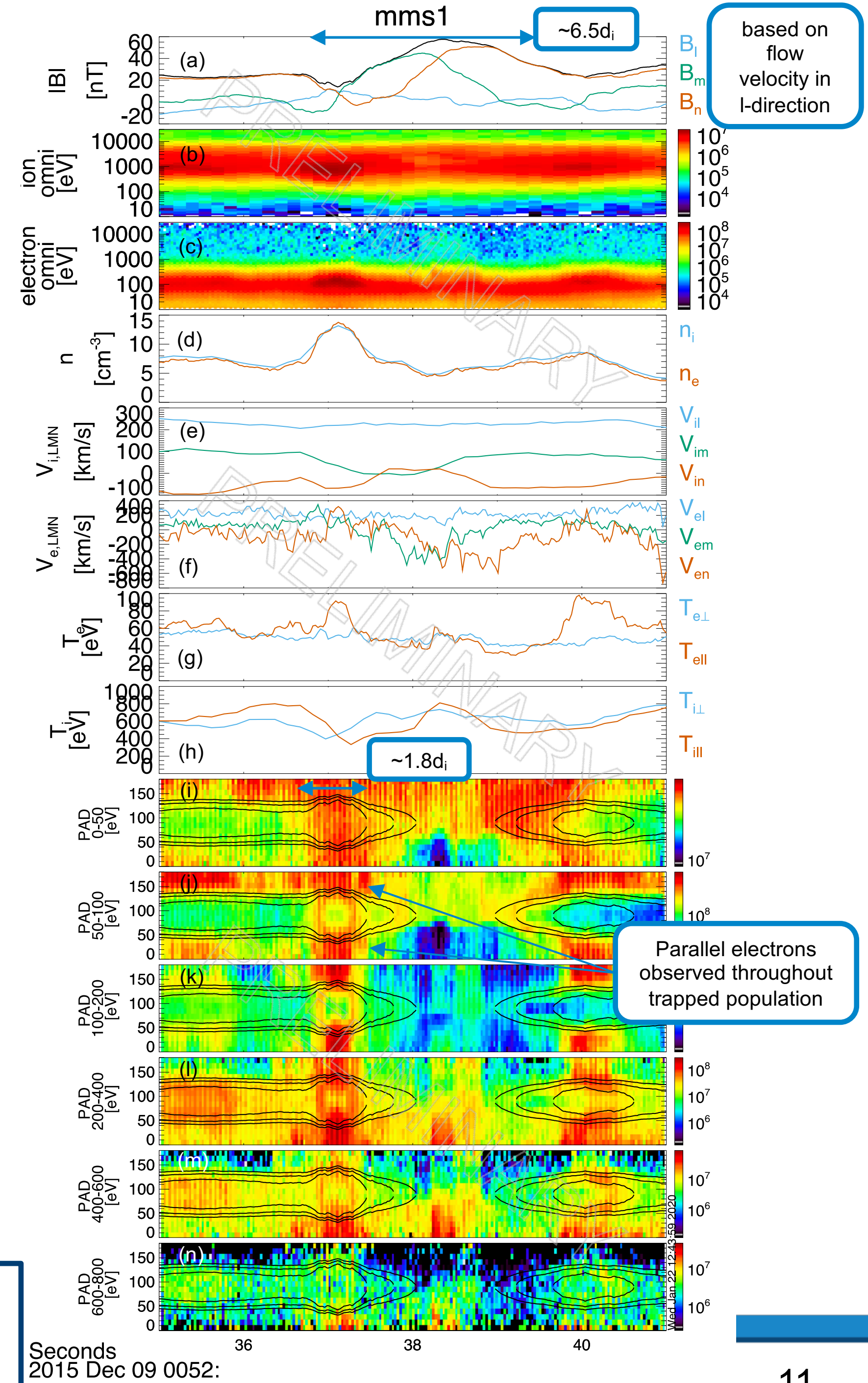

Figure 6: 6s plot of MMS1 data showing flux rope observation
Jump to plot for case study 1

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Second case study – *formation and evolution*

- We again observe a temperature anisotropy (d) and increase in plasma beta (e) through trapped population
  - Approximately uniform temperature anisotropy of ~0.5 throughout trapped population
  - Larger increase in parallel electron plasma beta than in perpendicular electron plasma beta

- Greater increase in total pressure (~0.4nPa) through trapped population (f)
  - Increase in electron pressure (~0.2nPa) balances decrease in magnetic pressure (~0.2nPa)
  - Increase in ion pressure (~0.4nPa) results in overall pressure enhancement

- Different pressure balance and temperature anisotropy profiles suggest the two case studies could be different evolutionary states of the same phenomena

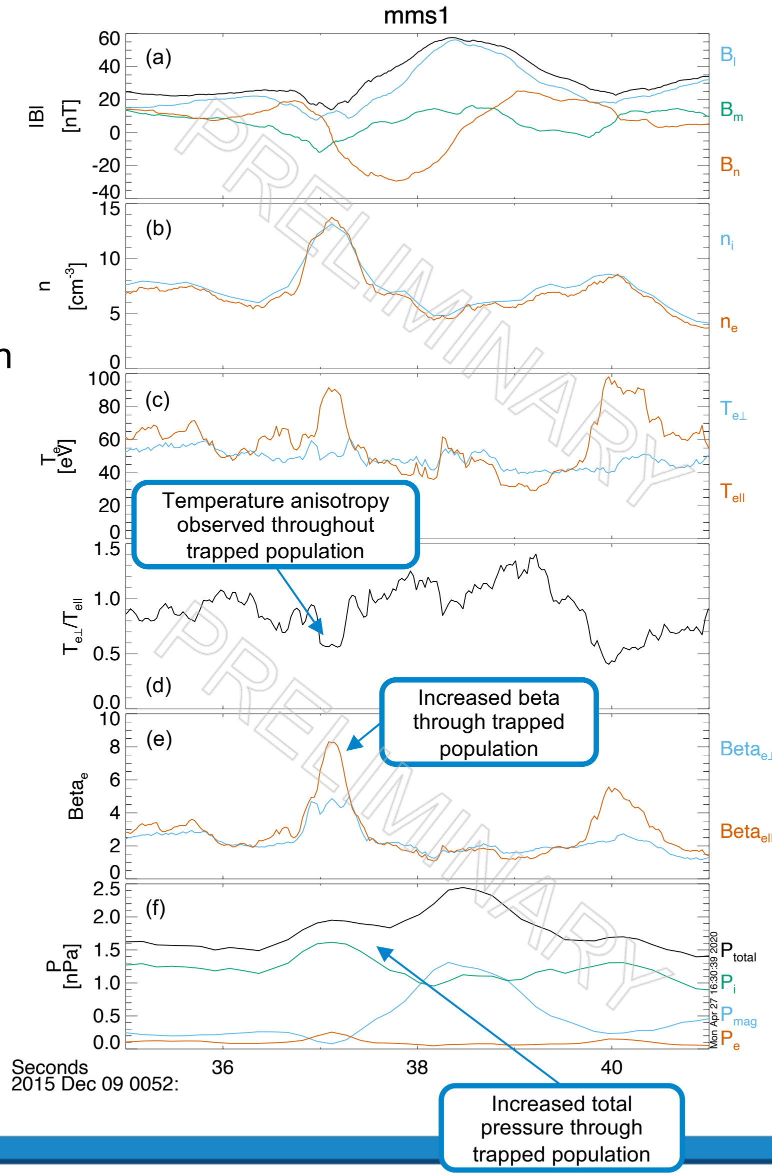

Figure 7: 6s plot showing temperature anisotropy and pressure throughout flux rope observation

[Jump to plot for case study 1]

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Second case study – *force analysis*

- Data is present for all 4 spacecraft throughout this event (some MMS3 data was missing for case study 1), meaning we are able to conduct multi-spacecraft analysis
  - The curlometer technique is used to investigate gradients and therefore forces on the plasma throughout the event
  - Analysis is in GSE, where X,Y,Z ≃ L,M,N

- Forces over trapped population could provide insight into dynamics of structure
  - Ion and electron measurements have different time resolution - we interpolate the sum of the forces onto both domains, noting that caution must be taken when interpolating ion data to higher electron resolution

- Potential bipolar signatures observed through trapped populations, however more analysis is required

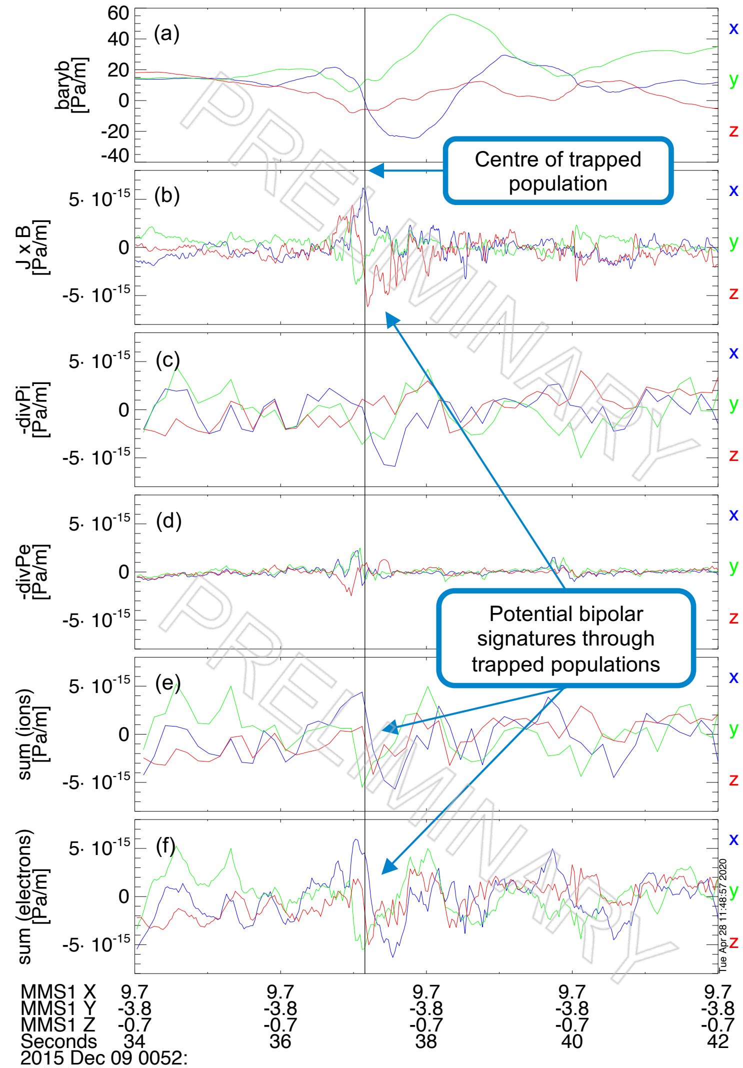

Figure 8: 8s plot showing force analysis throughout flux rope observation

sadie.robertson14@imperial.ac.uk

4. Conclusions

- Provided evidence of electron trapping in the field depression at the edge of a flux rope
  - Consistent with magnetic hole observations
- Shown that both the flux rope and the trapped populations have extended 3D structure
- Two case studies show different temperature anisotropy and pressure balance signatures, suggesting they could be different evolutionary states of the same phenomena
  - Scope to investigate this further using multi-spacecraft techniques and force analysis
- In one case study we also observe a second trapping event, consistent with kinetic scale magnetic hole observations
- The evolution and relationship between such structures over various scales could be important for particle acceleration in magnetic reconnection

sadie.robertson14@imperial.ac.uk

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sadie.robertson14@imperial.ac.uk