Reconnection & Thin Current Sheets at the Bow Shock

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Reconnection at the Bow Shock – The State of Play

Instabilities of waves in the shock foot and turbulence in the extended transition region can generate **reconnecting current sheets** and **magnetic islands**.

Observational Evidence:

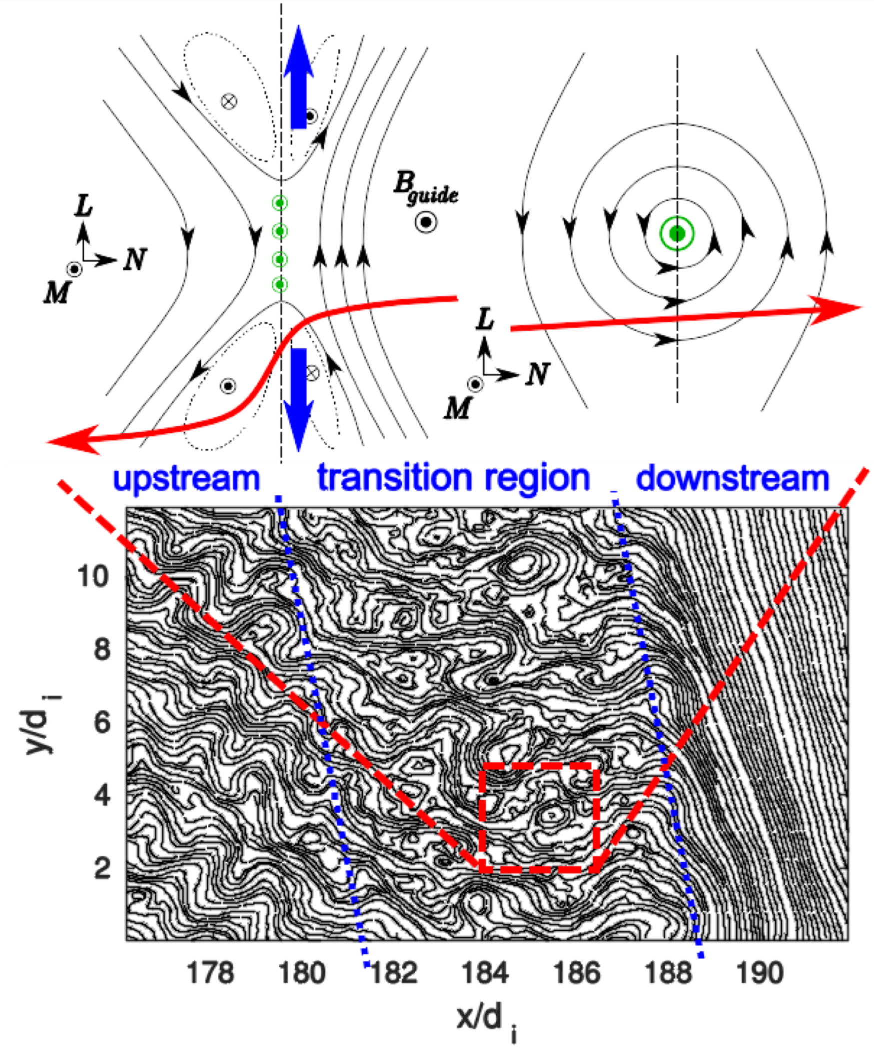
Gingell et al. 2019 – Case Study
Wang et al. 2019 – Case Study
Gingell et al. 2020 – Survey

Simulation of Mechanisms:

Matsumoto et al. 2015
Gingell et al. 2017
Bessho et al. 2020

What's the impact?

Schwartz et al. 2021



Current sheets & twisted field structures visible in the magnetic structure of the shock transition. (Gingell et al. 2019)

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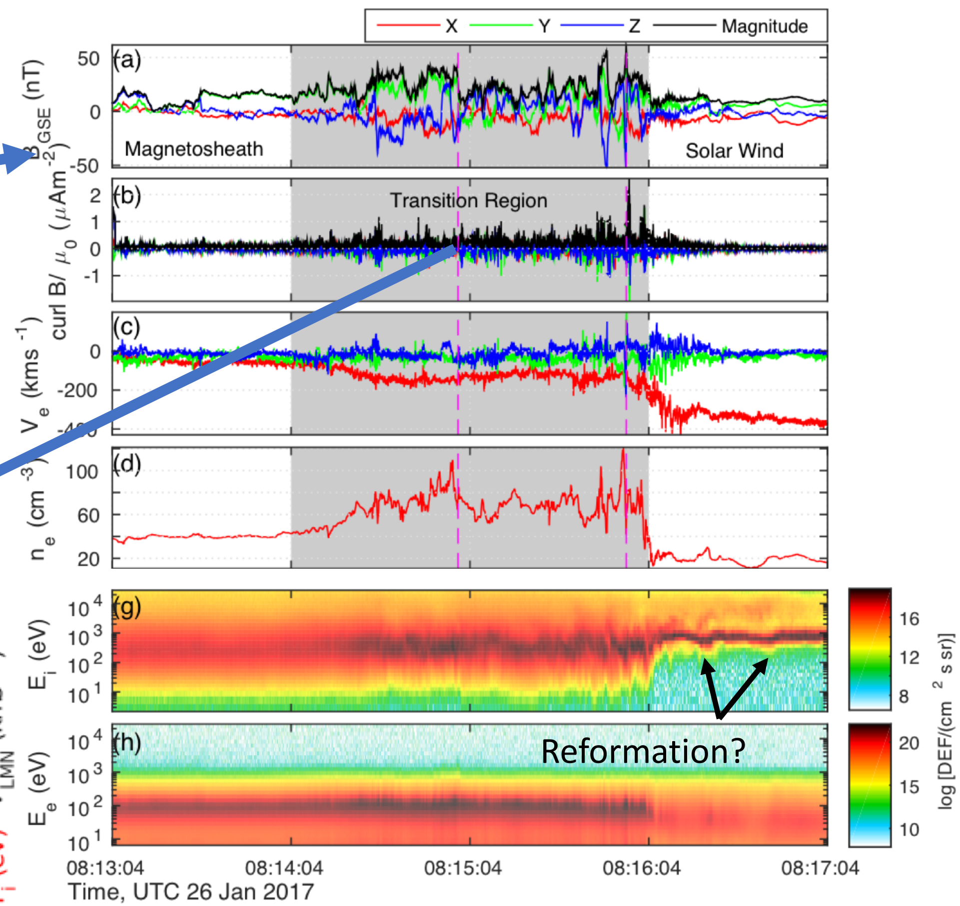
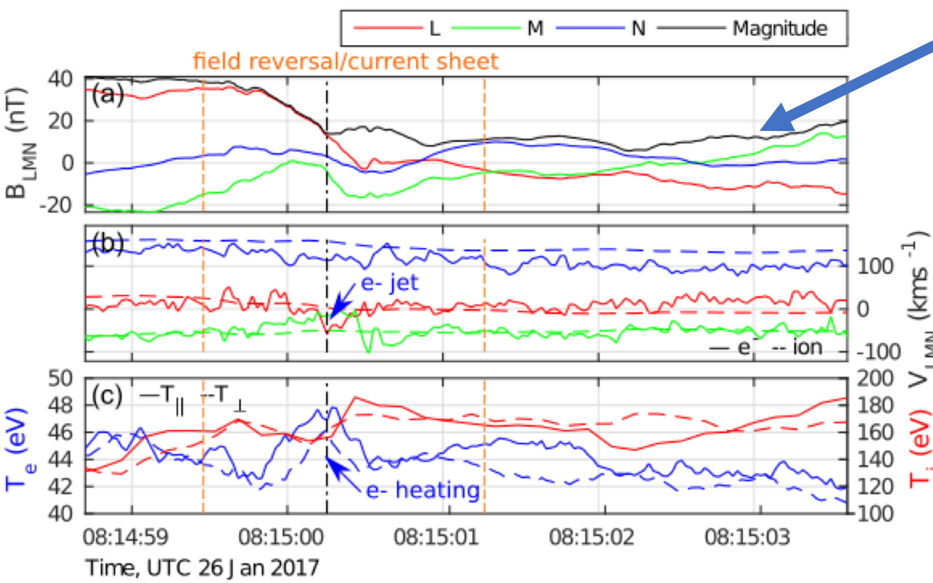
Observations of Reconnection – Case Studies

- Magnetospheric Multiscale (MMS) is the ideal reconnection microscope.
- Reconnection observed at shocks for:
  - Quasi-parallel shocks (Gingell et al 2019)
  - Quasi-perpendicular shocks (Wang et al 2019)





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Surveys: Identifying Current Structures at the Shock (and beyond)

Gingell et al. (2020): survey of all 223 MMS shock crossings during Phase 1

Input list of shock burst intervals.

↓

Calculate |J| from curlometer across the full burst interval.

↓

Label regions with $|J| > 3\sigma_J$

↓

Perform minimum variance analysis on $\mathbf{B}_{\mathbf{GSE}}$ to get $\mathbf{B}_{\mathbf{LMN}}$ for each interval.

↓

Does the max variance component B_L change sign?

↓

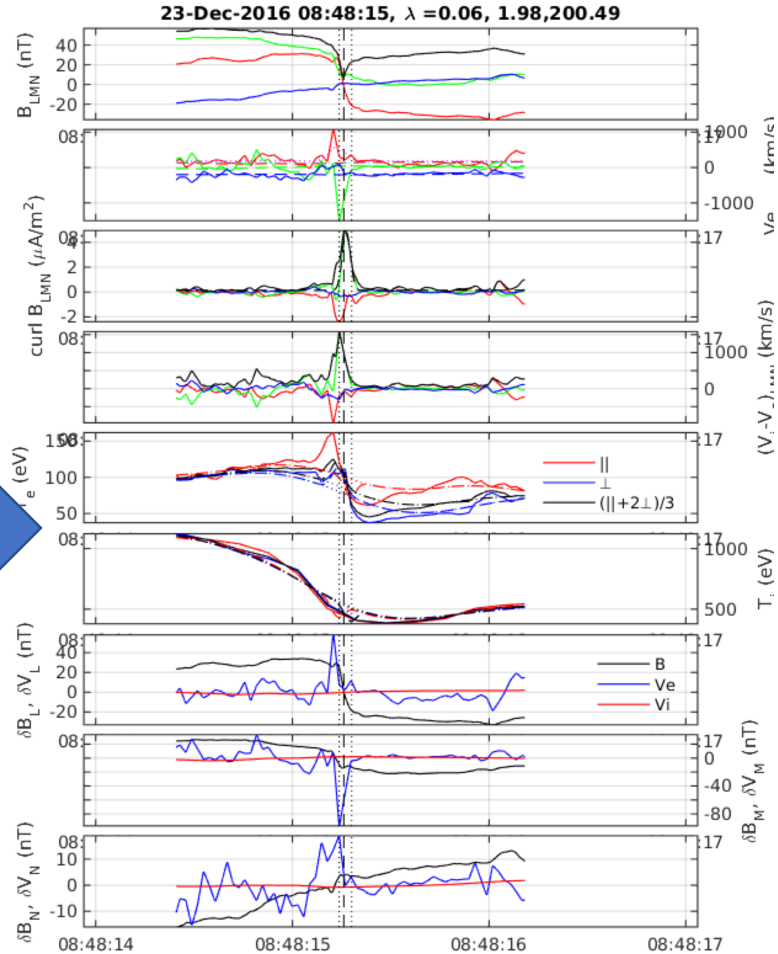
Is there a peak in V_{eL} within the current carrying region?

Good sheet structure?
MVAB worked?

Clear jets?

Walen Test

903 Candidates



165 Events!

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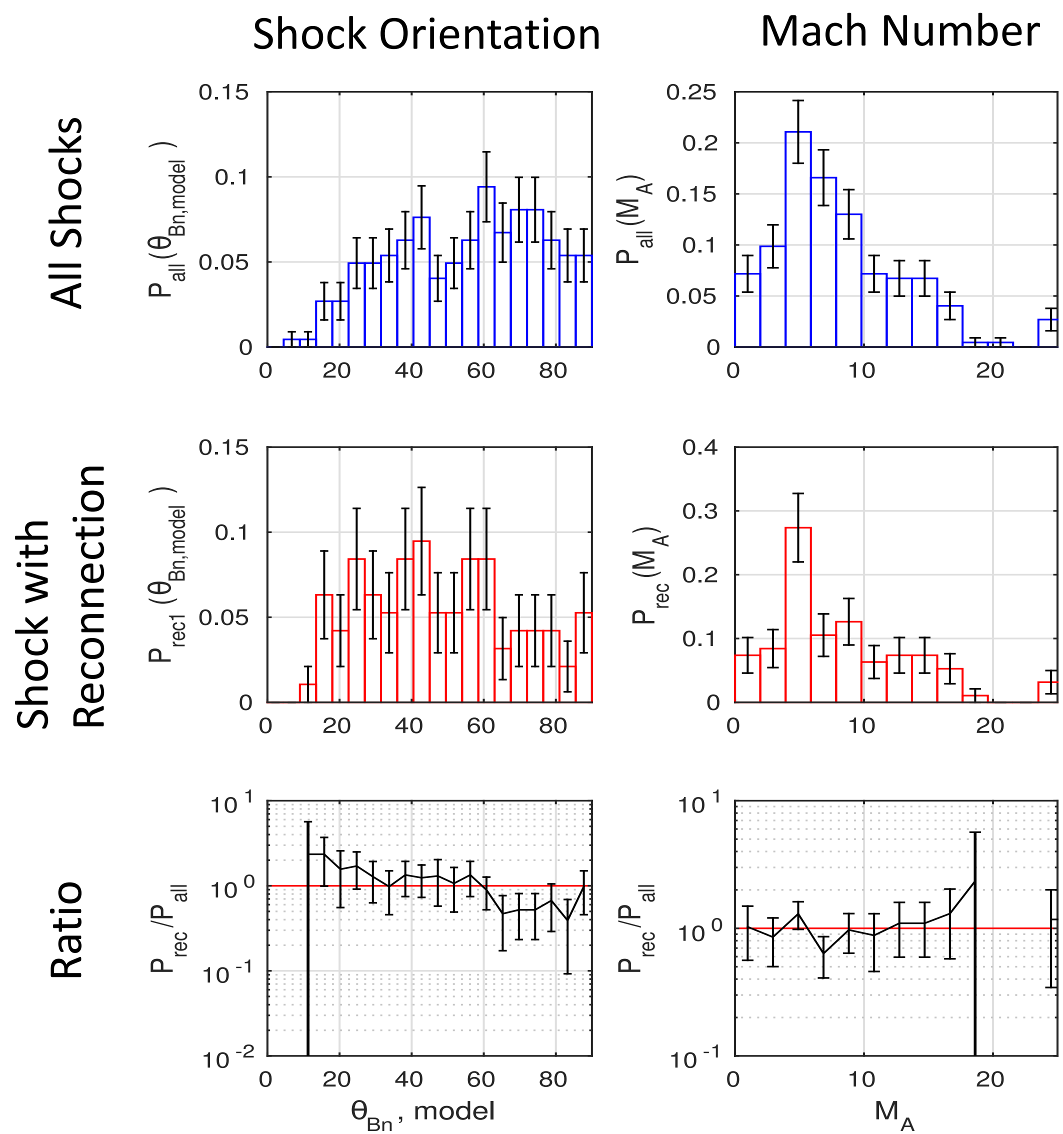
Survey Results – Shock Parameters

- **90 of 223 shocks (40%) contained at least one reconnecting current sheet.**
- Shock reconnection is a **universal process**, occurring across all parameter regions.
- Reconnection is (slightly) more common at:
    - Quasi-parallel (θ_{Bn} < 45) shocks
    - High M_A shocks



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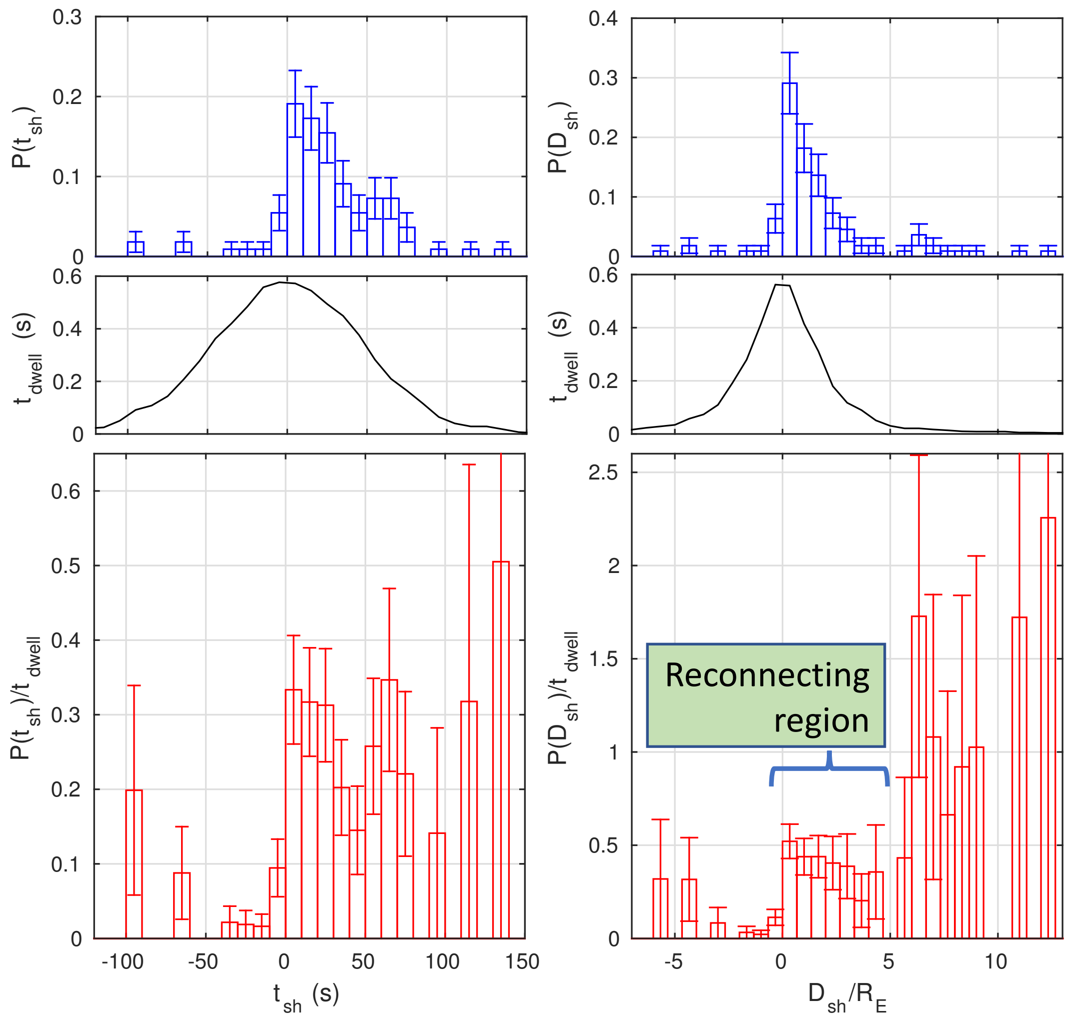
Survey Results – Sheet Locations

- "Pseudo-distance" from the shock $D_{sh} = t_{sh}.v_{sh}$, where v_{sh} is from timing analysis and t_{sh} is the time since crossing the ramp.
- Must account for selection biases – weight the results by the time MMS spends at any given pseudo-distance.
- Population generally localized to the shock, within ~5R_E downstream.
- Only 12% are upstream.
- **Mechanism?** "turbulent" transition region propagates downstream (e.g. Gingell et al 2017) rather than ion Weibel instability in the foot (Matsumoto et al 2015, Bohdan et al 2017)



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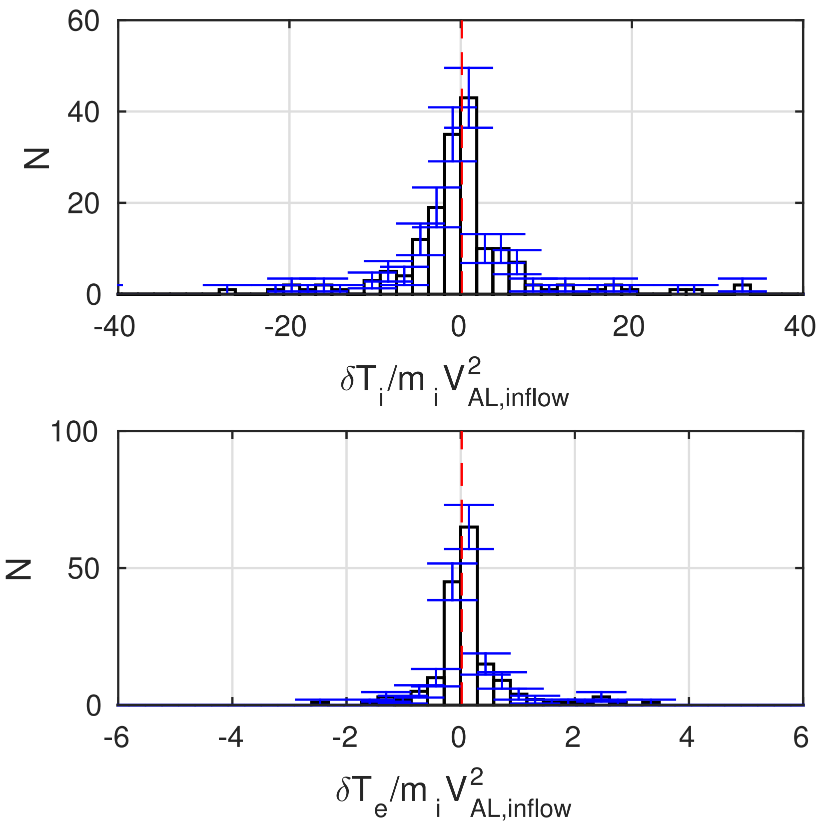
Survey Results – Heating



- Check the mean temperature change across the current carrying region δT_e, δT_i against the magnetic inflow energy:

$$E_{inflow} = m_i V^2_{AL,inflow}$$

- At the magnetosheath we expect (Phan et al 2013,2014):
  - Electrons: $\delta T_e = 0.017\ m_i V^2_{AL,inflow}$
  - Ions: : $\delta T_i = 0.13\ m_i V^2_{AL,inflow}$
- Gingell et al 2019 and Wang et al 2019 observations were consistent with those results.

- In the survey, heating is generally **not distinguishable from background inhomogeneities** in the turbulent region – careful manual treatment is required for each event.

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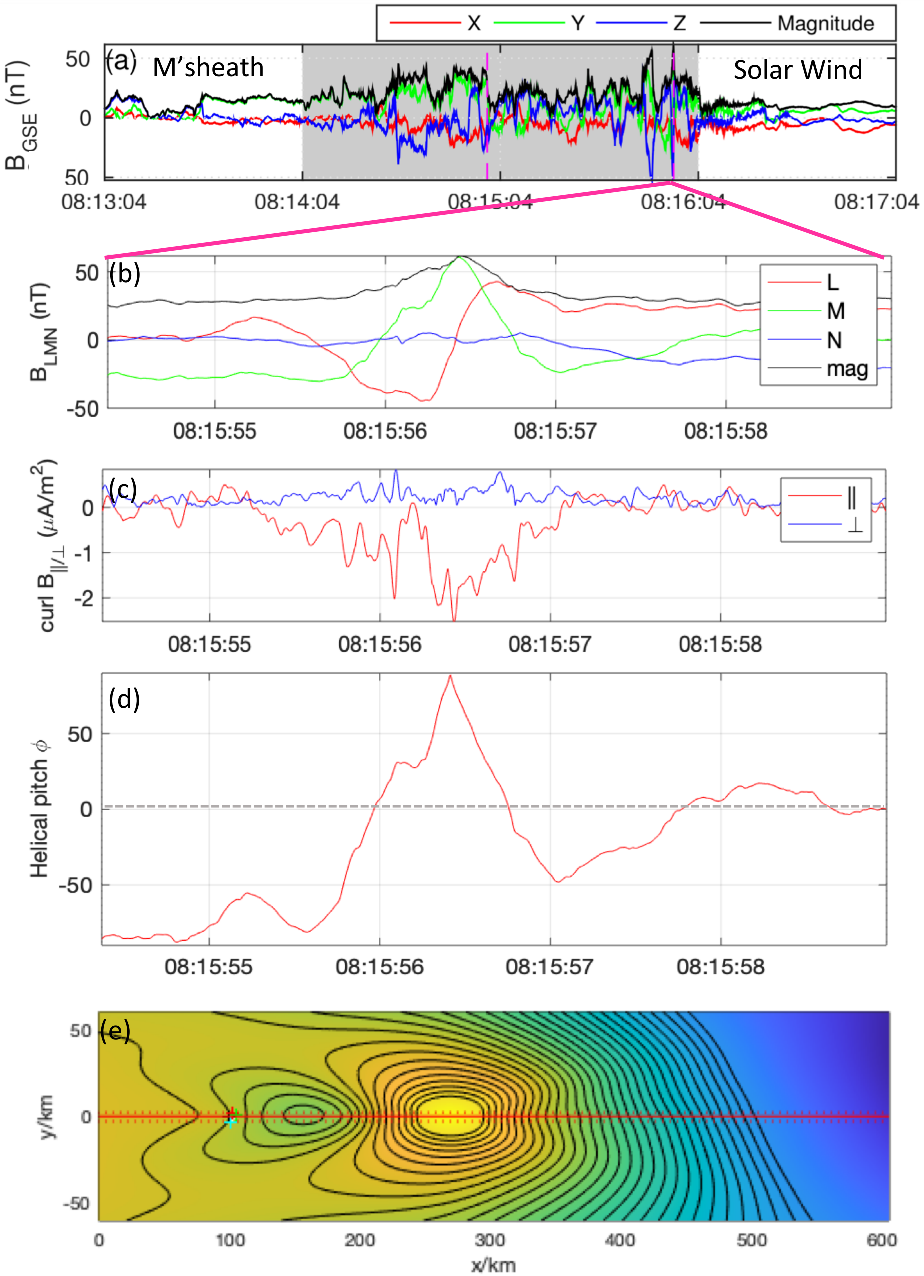
Other Reconnection Structures – "Inverted" Flux Ropes



Structure embedded in the transition region of a quasi-parallel shock, which also exhibits reconnection (see Gingell et al. 2019).

Unipolar B_M
Bipolar B_L
} Typical for a flux rope.

External B_M –ve
Internal B_M +ve
} Atypical for a flux rope.

Core $J_{||}$ dominates, like a flux rope.

The helical pitch angle with respect to the structure's axial (M) direction reverses from -ve in the background, to +ve in the core.

This structure is an **"inverted" flux rope** – its core field is oppositely directed to the background.

Grad-Shafranov reconstruction shows 2D magnetic island field structure, as expected for a flux rope-like structure.

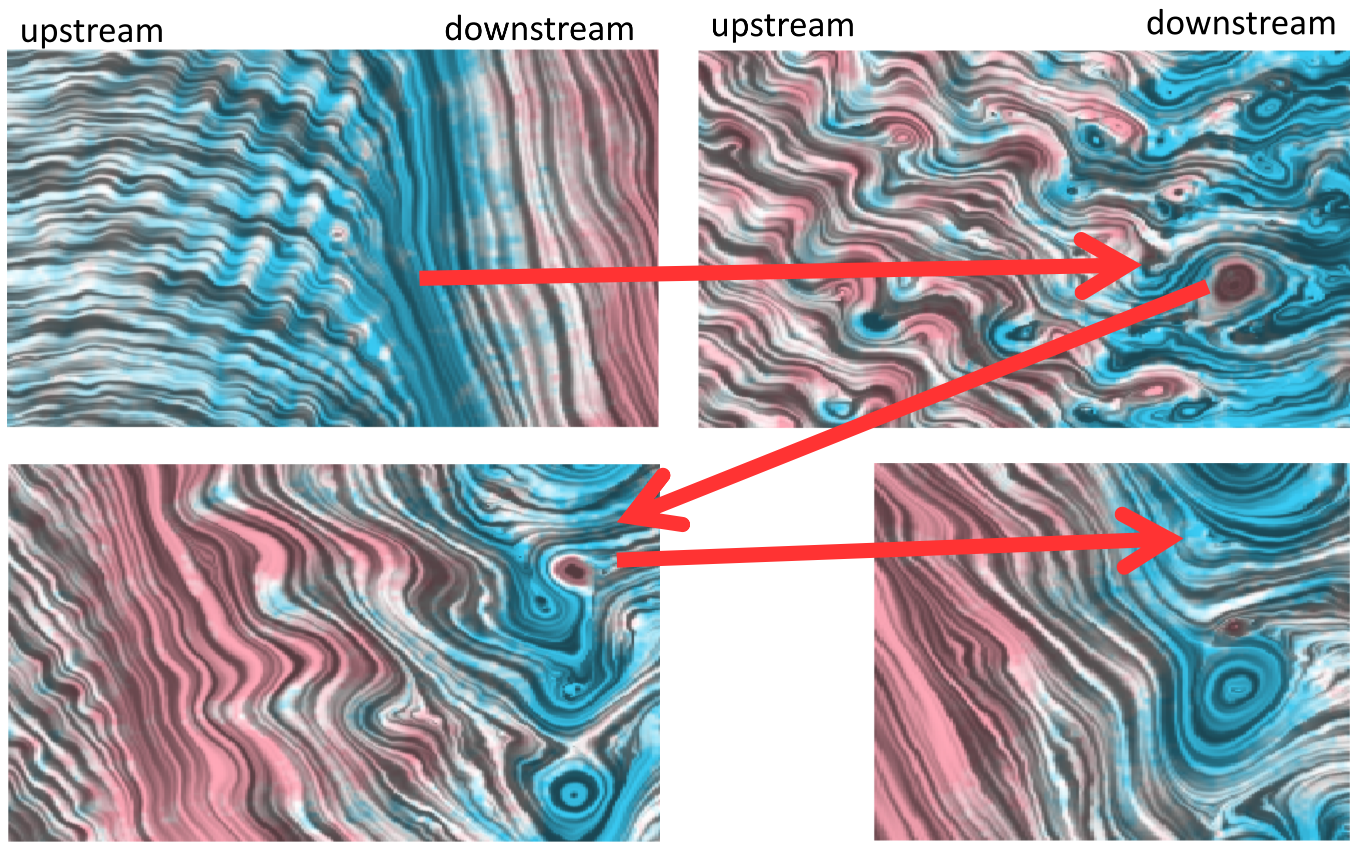
Inverted Flux Ropes in Hybrid Simulations – Links to Mechanism

- Initial condition replicates parameters observed at quasi-parallel shock (left).
- Reconnection at unstable waves in the shock foot creates a turbulent region **(Gingell et al. 2017, Bessho et al 2020)** containing both regular and inverted flux ropes.

Waves steepen and reconnect in the foot, generating turbulent transition region with magnetic islands.

Regular FRs persist downstream.

Inverted FRs rapidly contract, collapsing on ion timescales.



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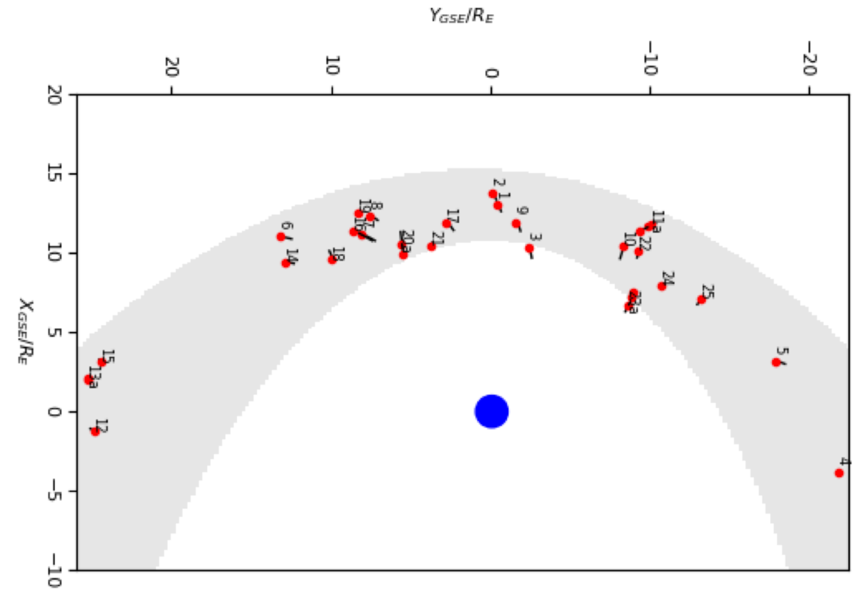
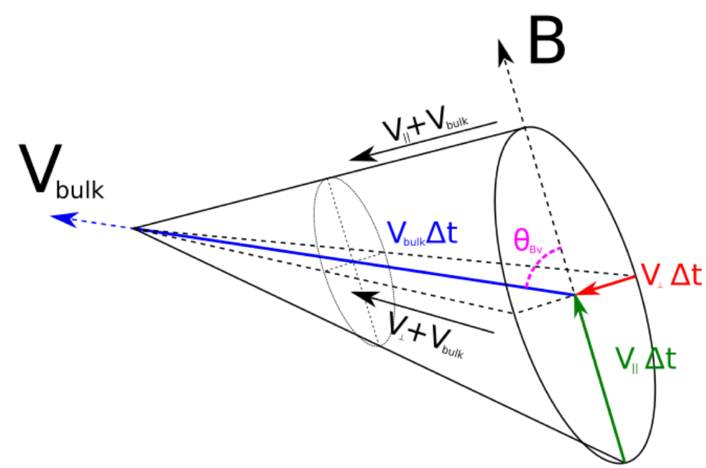
Surveying Current Sheets Downstream of the Shock

- Under the wave steepening mechanism, shock reconnection generates current sheets that propagate downstream towards the magnetosheath.
- How many are there? Where are they? Are they distinguishable from current sheets associated with magnetosheath reconnection, or are they one and the same? Seek a measurement of the current sheet number density or 3D **'packing factor'.**
- We have performed a survey current structures for 30 extended (~20 min) magnetosheath intervals.
- Estimate 3D packing factor by comparing heating measures (e.g. j.E' or inflow energy) at individual structures to the integrated measure across the full interval.





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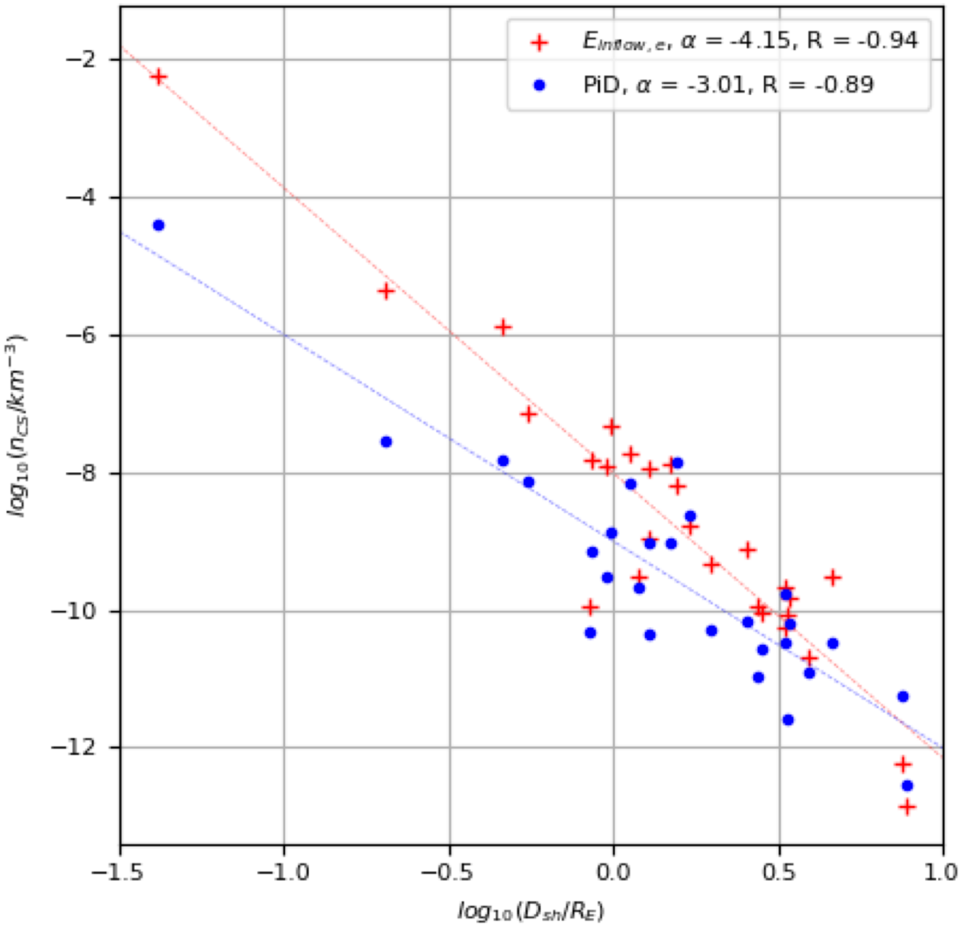

shock distance

Power law decrease packing factor of current sheets with distance behind the bow shock (from 0.1-10 R_E)

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Shock Reconnection - Conclusions

WHICH?

- 40% of shocks exhibited at least one reconnection site, across all shock parameters - it is a common, **universal process.**
- Slight bias towards quasi-parallel and higher Mach number shocks.

WHERE?

- Shock reconnection is most common in the region **adjacent and downstream of the shock ramp**.
- Occurrence of current sheets falls with a power law with distance downstream of the shock.

MECHANISM?

- Generation by the **ion Weibel instability** in the shock foot, seen in High Mach number, quasi-perpendicular shocks (e.g Matsumoto et al 2015, Bohdan et al 2017) is unlikely to be the dominant mechanism at Earth.
- Results are more broadly consistent with downstream propagation of turbulent transition region, driven by **reconnection at steepened waves in the foot** (e.g. Gingell et al 2017, Bessho et al 2020)
- Observation of "inverted" rope-like current structures is consistent with latter mechanism.

IMPACT?

- Heating statistics are difficult to extract on a per-sheet basis.
- Schwartz et al. 2021 demonstrate 5-11% energy conversion rate of energy incident at the bow shock (see e-only reconnection session)

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