Turbulence in Three-Dimensional Simulations of Guide-Field Magnetopause Reconnection

Marc Swisdak
University of Maryland

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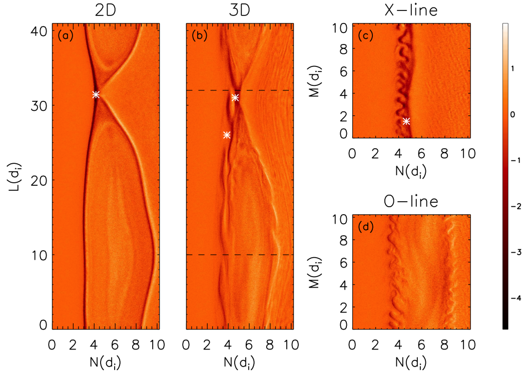
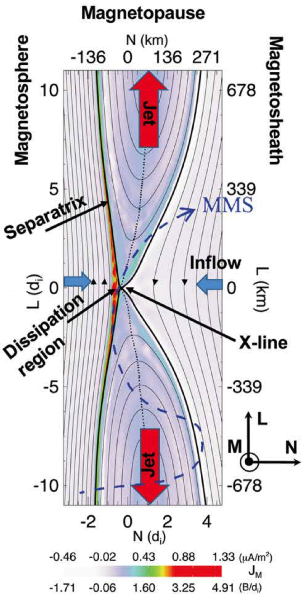
Co-Authors: **Lora Price**, Jim Drake

Background & Previous Work

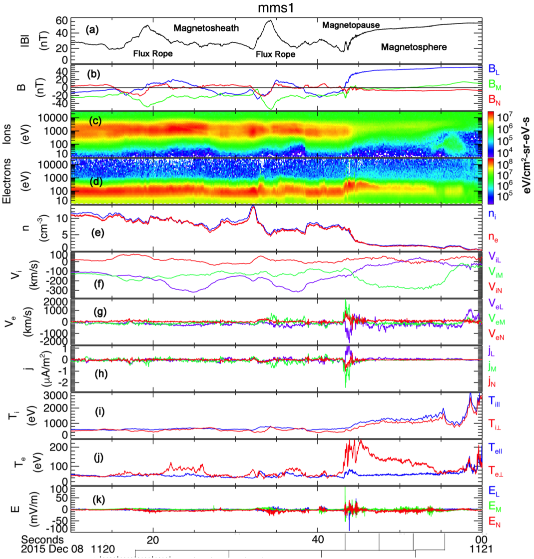
- PIC simulations of MMS events
- 2D (no *M* variation; right) is simpler; 3D is expensive but more realistic
- Turbulence develops in anti-parallel case
- Lower-hybrid drift instability (LHDI) has ∇n as energy source





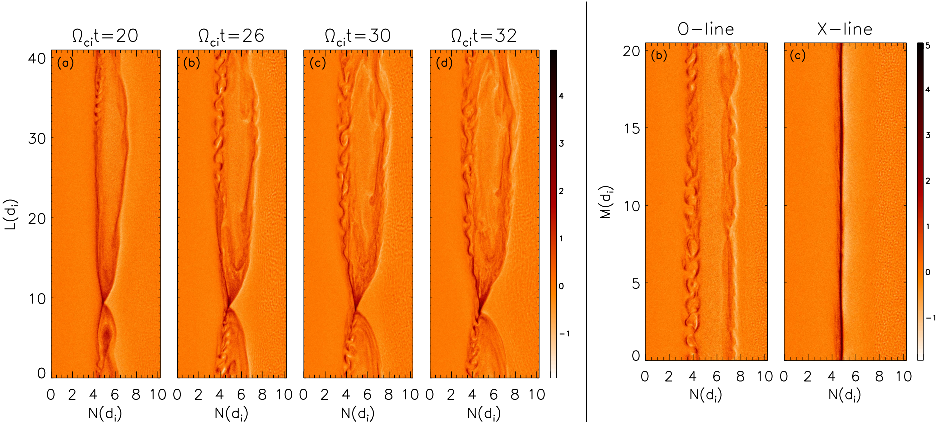
2015 December 8 Event: Guide Field Reconnection

Burch and Phan, GRL (2016); Shear angle ≈ 120°



- Intense $\mathbf{J}_{eM}$
- Bursty electric field and current, $E_M \approx 30$ mV/m $\gg$ expected E_{rec}. Suggestive of a turbulent dissipation region.
- Strongest turbulence and current on the magnetospheric side
- But: LHDI is strongly stabilized by magnetic shear (Huba et al., 1982)

3D Simulation: Development of Turbulence

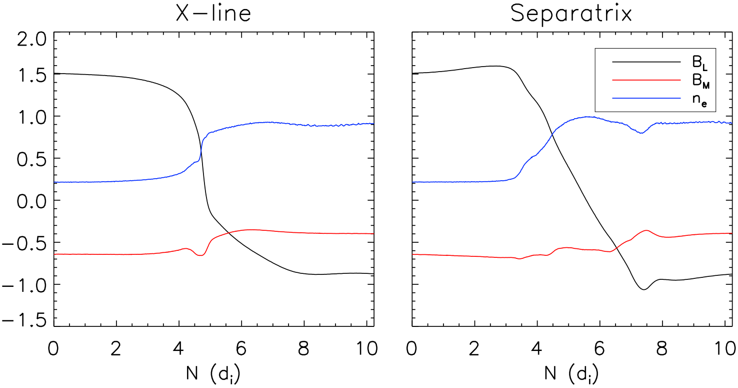


- Left: Development in time.
- Right: Different plane at $t = 26$.
- LHDI is significant along the separatrices ($\mathbf{k} \cdot \mathbf{B} = 0$) but not at the X-line.

Why No LHDI at the X-line?

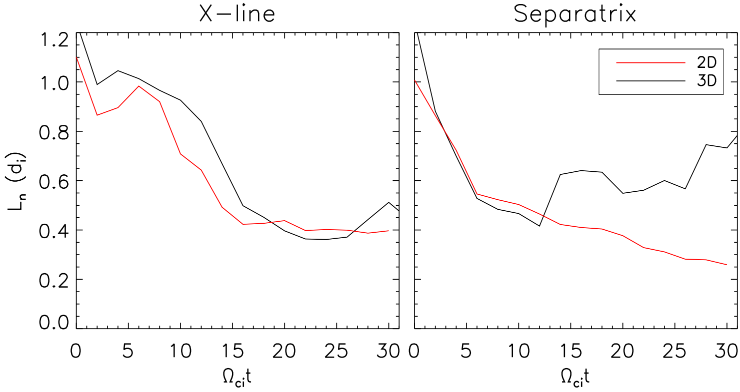
Stabilization by magnetic shear; *Huba et al., (1982), JGR*

- Strong magnetic shear in the region of strong density gradient across the X-line
- The magnetic field undergoes very little rotation across the density jump at the magnetospheric separatrix
- **Most of the magnetic rotation takes place across the exhaust**



One Consequence: Broadened Current Sheets

- $L_n = n/|\nabla n|$
- 2D (red): No turbulence so L_n decreases at both X-line and separatrix
- 3D (black): LHDI broadens gradient at separatrix. No LHDI & no broadening at X-line



How (if at all) Does Turbulence Affect Reconnection?

Averaging Ohm's Law

Begin with the electron equation of motion

$$mn\frac{d\mathbf{v}}{dt} = -en\mathbf{E} - \nabla \cdot \mathbb{P} - en(\mathbf{v} \times \mathbf{B})/c$$

Average of the M component over the M-direction, $\langle \ldots \rangle$

$$m\left\langle n\frac{dv_M}{dt}\right\rangle = -e\langle nE_M\rangle - \langle(\nabla \cdot \mathbb{P})_M\rangle - e\langle n(\mathbf{v} \times \mathbf{B})_M\rangle/c$$

Break everything into mean and fluctuating parts:

- $f = \langle f\rangle + \delta f$ with $\langle \delta f\rangle = 0$
- $\langle fg\rangle = \langle f\rangle\langle g\rangle + \langle \delta f \delta g\rangle$

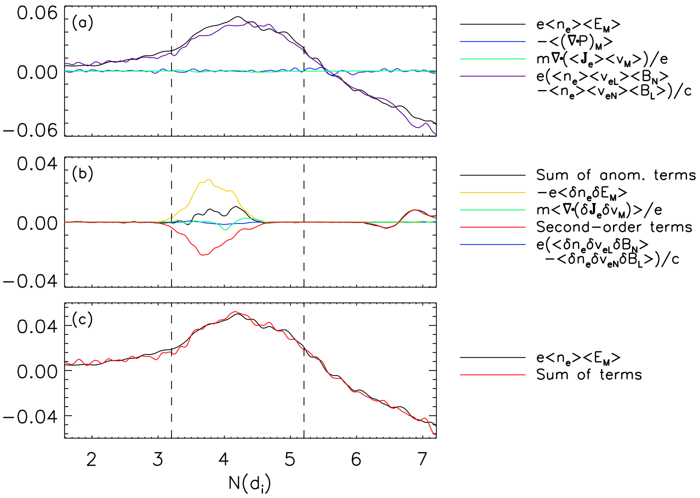
Sorry!

Laminar (top three lines) and turbulent (the rest)

$$
\begin{aligned}
e\langle n\rangle\langle E_M\rangle = & \frac{e}{c}\Big(\langle n\rangle\langle v_L\rangle\langle B_N\rangle - \langle n\rangle\langle v_N\rangle\langle B_L\rangle\Big) \\
& - \frac{\partial}{\partial L}\langle P_{LM}\rangle - \frac{\partial}{\partial N}\langle P_{NM}\rangle \\
& + \frac{m}{e}\left(\frac{\partial}{\partial t}\langle J_M\rangle + \frac{\partial}{\partial L}\langle J_L\rangle\langle v_M\rangle + \frac{\partial}{\partial N}\langle J_N\rangle\langle v_M\rangle\right) \\
& - e\langle \delta n \delta E_M\rangle \\
& + \frac{e}{c}\Big(\langle n\rangle\langle \delta v_L \delta B_N\rangle - \langle n\rangle\langle \delta v_N \delta B_L\rangle \\
& \quad + \langle B_N\rangle\langle \delta n \delta v_L\rangle - \langle B_L\rangle\langle \delta n \delta v_N\rangle \\
& \quad + \langle v_L\rangle\langle \delta n \delta B_N\rangle - \langle v_N\rangle\langle \delta n \delta B_L\rangle \\
& \quad + \langle \delta n \delta v_L \delta B_N\rangle - \langle \delta n \delta v_N \delta B_L\rangle\Big) \\
& + \frac{m}{e}\left(\frac{\partial}{\partial L}\langle \delta J_L \delta v_M\rangle + \frac{\partial}{\partial N}\langle \delta J_N \delta v_M\rangle\right)
\end{aligned}
$$

Ohm's Law: Separatrix

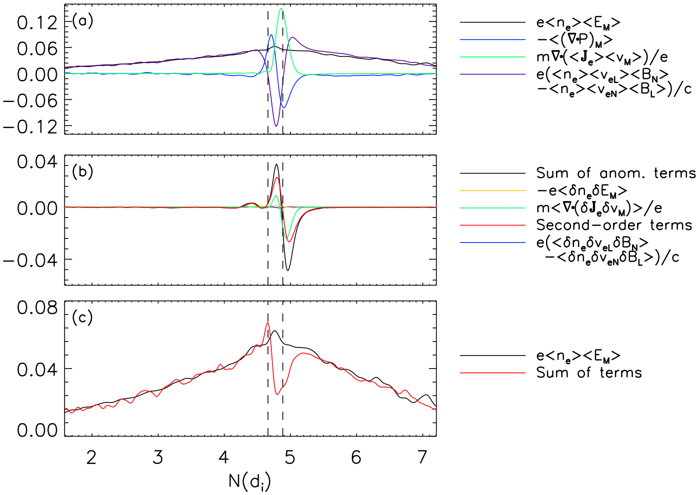
Frozen-in electrons



- Anomalous resistivity (yellow) is largely balanced by other terms (red): $\mathbf{E} \approx -\mathbf{v} \times \mathbf{B}$.

Ohm's Law: X-line

Frozen-in electrons



- Electrons not frozen-in.

Conclusions

- 3D simulations of MMS guide-field reconnection events produce turbulence similar to observations (see also Le et al., *PoP*, 2018).
- LHDI is not stabilized despite the magnetic shear due to the development of the reconnection.
- Despite turbulence, electrons are frozen-in on the separatrices, but not at the X-line.

Extra Slides

Non-LHDI Fluctuations at the X-line