“Smoking-Gun” Observables of Magnetic Reconnection: Elucidating the Electron Diffusion Region in the MMS Era

Jason Shuster[1] (jrf63@wildcats.unh.edu), Li-Jen Chen[2], Roy B. Torbert[1], Shan Wang[1], Naoki Bessho[2], Guanlai Li[1], Matthew Argall[1], William S. Daughton[3]

[1]Space Science Center, University of New Hampshire, Durham, New Hampshire, U.S.A.

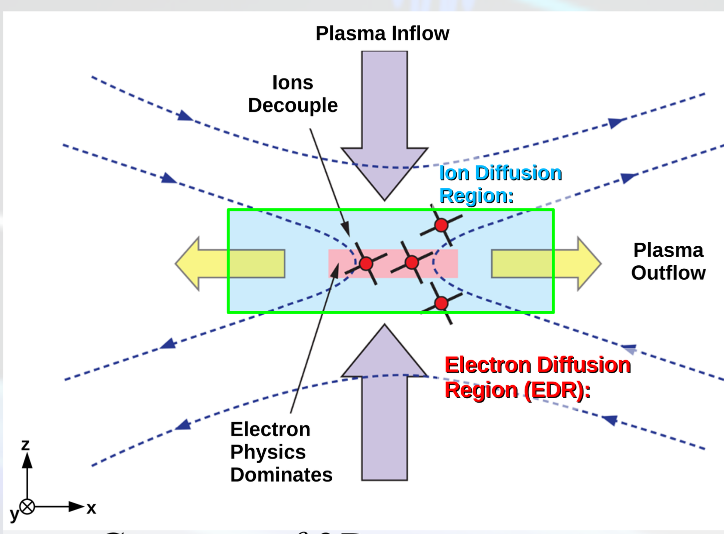
[2]Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

[3]Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Background

Motivation and Context

How can magnetic reconnection occur in a collisionless plasma? This outstanding mystery fueled the successful launch of NASA's Magnetospheric Multiscale (MMS) mission. The primary science goal of MMS is to reveal the small-scale, 3D structure and dynamics of the elusive electron diffusion region (EDR) believed to hold the key to the reconnection puzzle.



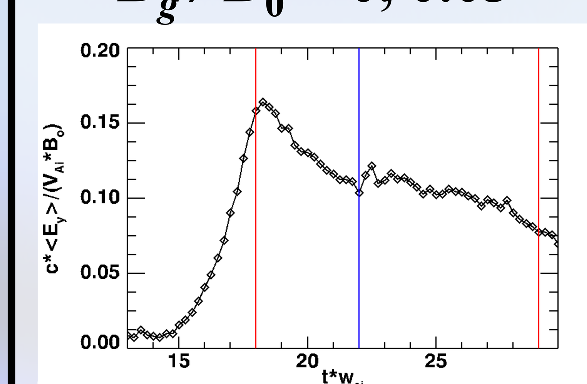
Cartoon of 2D reconnection.

We are motivated to determine ***how, where, and when electrons are energized during magnetic reconnection***. Recent Cluster observation and particle-in-cell (PIC) simulation studies have demonstrated the use of particle distribution functions as *in situ* observables of the reconnection process [1,2]. Electron distribution functions offer the kind of "*smoking-gun*" evidence of EDR acceleration and heating mechanisms required for identifying and elucidating the EDR's 3D structure and electron-scale dynamics [3,4,5,6,7].

Knowledge of the spatiotemporal evolution of electron distributions and their nonlinear wave signatures throughout the EDR, including the inflow edge, X-line, electron outflow jet, and exhaust transition regions, is still lacking. ***Here, we report PIC predictions for the structure of electron distributions in each of these regions, and the implications for electron acceleration and heating.*** We address the robustness of our predictions [3,4] by varying both the guide field and mass ratio and considering asymmetric reconnection geometries. Our work advances the understanding of electron distribution evolution throughout the EDR, setting a foundation to successfully interpret the high resolution electron data and 3D wave measurements anticipated from MMS.

Results

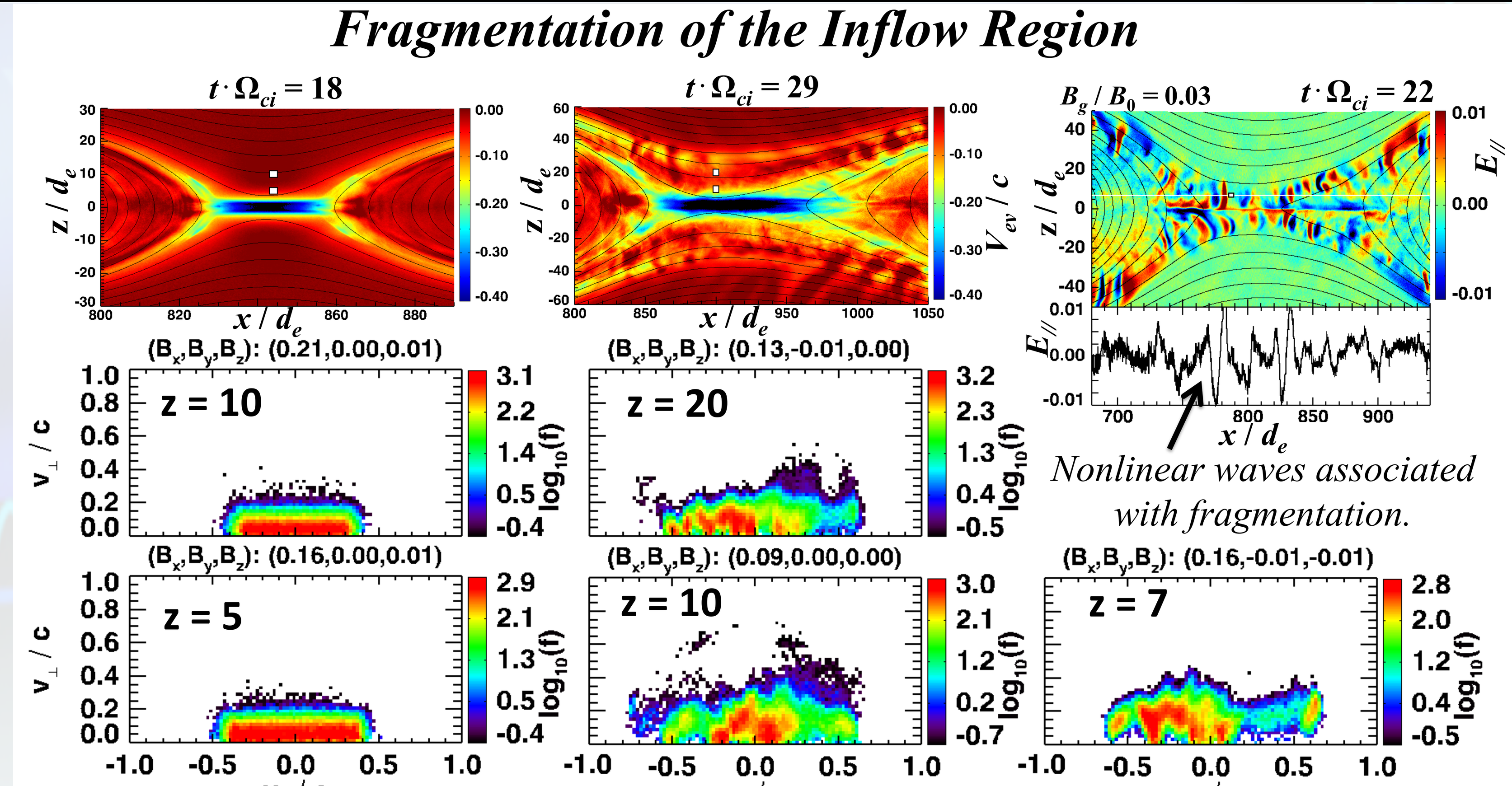
$m_i / m_e = 400$, $B_g / B_0 = 0, 0.03$



Reconnection Rate, $\langle E_y \rangle$

→ Elongated structure near peak reconnection becomes disjointed at later times with non-uniform phase-space density along $v_{//}$.

Fragmentation of the Inflow Region

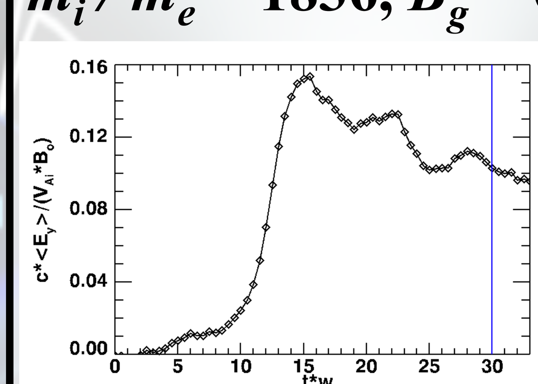


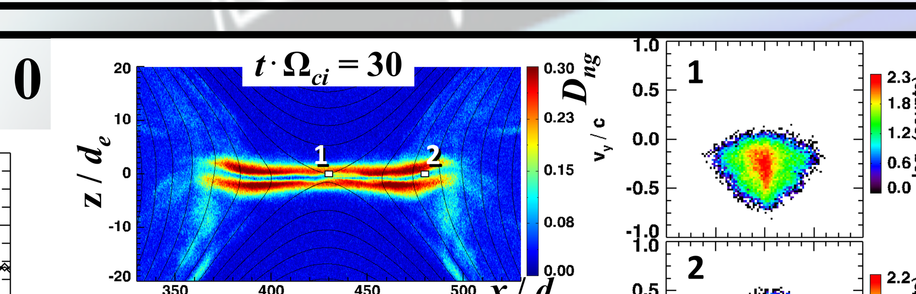
Nonlinear waves associated with fragmentation.

→ Fragmentation region extends to d_i-scales with the broadening of the current layer.

→ Upstream analytical approximation [6] may only be valid for early stages of reconnection.

$m_i / m_e = 1836$, $B_g = 0$

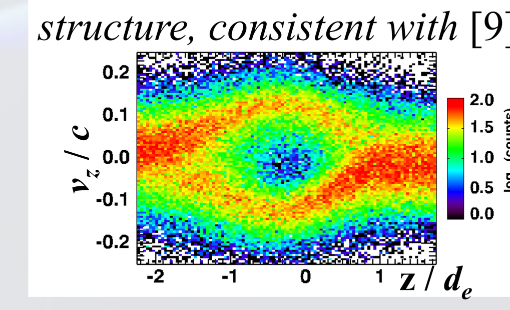




→ Double layer structure in the degree of electron nongyrotropy D_{ng}, and density n_e, indicative of electron meandering motion.

→ Triangular X-line distribution, swirls & arcs downstream, as in [3,5], though striations are not as discernible.

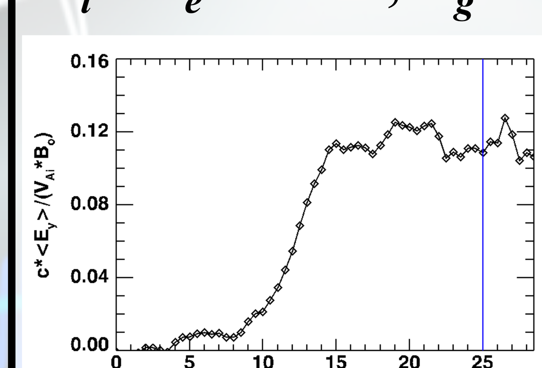
Electron phase-space-hole structure, consistent with [9].

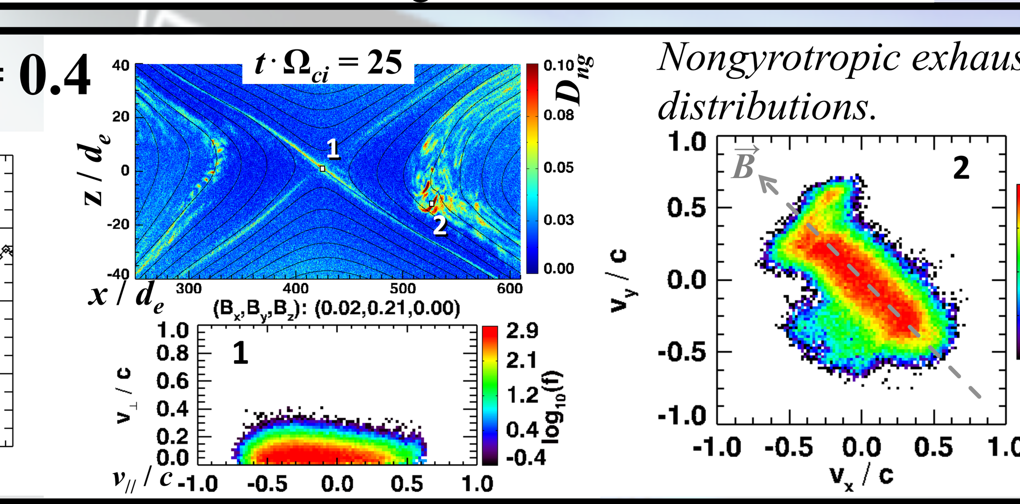


→ $T_{e\perp}/T_{e//} > 1$ only for e- outflow jets, unlike [4].

→ No inflow fragmentation, small $E_{//}$ variations.

$m_i / m_e = 1836$, $B_g = 0.4$



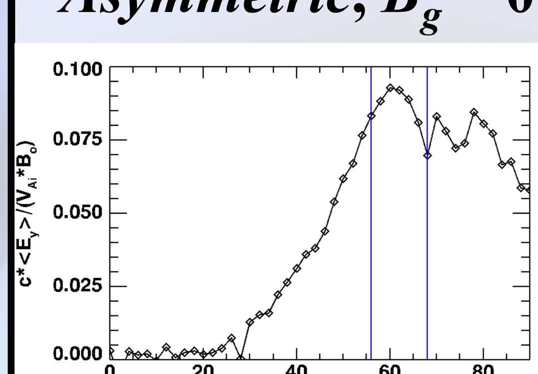


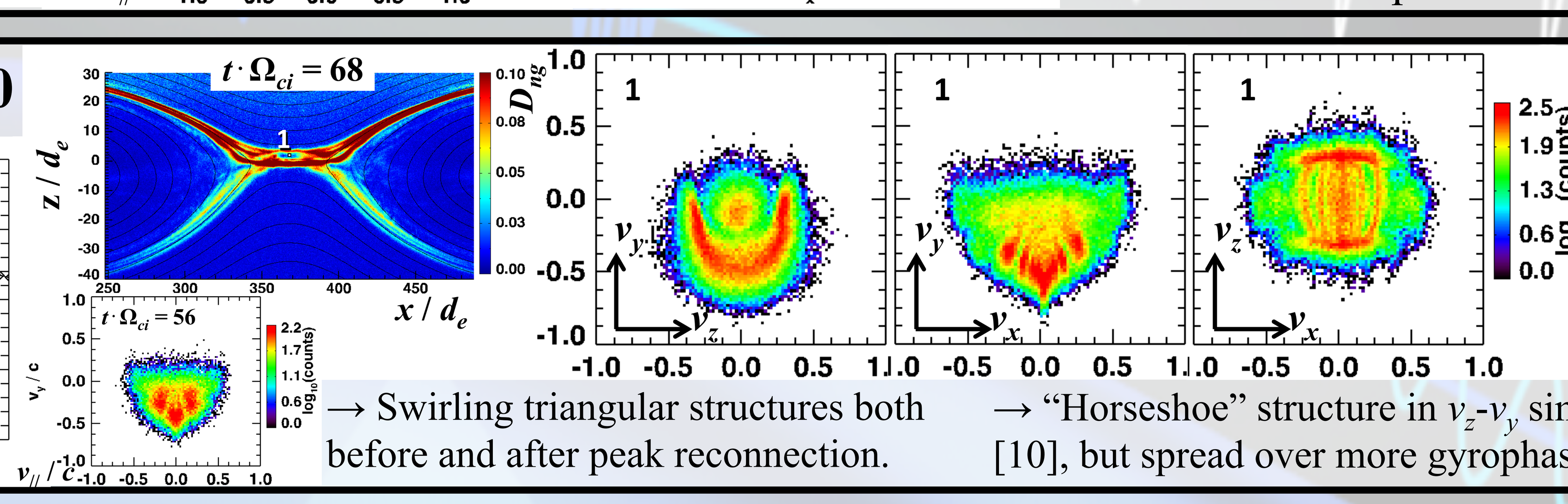
Nongyrotropic exhaust distributions.

→ No double layer in electron nongyrotropy, only nonzero faintly along separatrices and isolated exhaust field lines.

→ No triangular distributions, electrons are still magnetized near the X-line where distributions have a shifted-ellipsoidal shape.

Asymmetric, $B_g = 0$





→ Swirling triangular structures both before and after peak reconnection.

→ "Horseshoe" structure in v_z-v_y similar to [10], but spread over more gyrophase.

PIC Simulations

Geometry	m_i / m_e	B_g / B_0	$\omega_{pe} / \Omega_{ce}$	*# of cells (in d_i)*	*# of particles per cell*
symmetric[3,4]	400	0, 0.03	2	10240 × 2560 ($80d_i \times 20d_i$)	600
symmetric[7]	1836	0	2	5120 × 5120 ($20d_i \times 20d_i$)	400
symmetric[7]	1836	0.4	2	5120 × 5120 ($20d_i \times 20d_i$)	400
asymmetric $n_{MSH} / n_{MSP} = 8$	100	0	2	3072 × 2048 ($75d_i \times 25d_i$)	3000

Conclusions

Triangular electron distributions are found in the electron diffusion region for real mass ratio symmetric and asymmetric PIC simulations, suggesting that the acceleration and heating mechanisms explained in [3] are a general characteristic of the EDR in anti-parallel reconnection. However, the triangular structure is lost for guide fields stronger than some $0.03 < B_{g,max} / B_0 < 0.4$, which is yet to be determined.

Future Work

- Self-consistent particle tracing for PIC **E** & **B** fields to further understand electron energization.
- Analyze e- distribution functions predicted by 3D PIC simulations.
- Dependence on: $\omega_{pe} / \Omega_{ce}$ and v_{the} / c, e.g. [8], what is the $B_{g,max}$ guide field threshold?
- Investigate nonlinear wave signatures in PIC to interpret anticipated high resolution MMS data from FPI and FIELDS instruments.

References

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Acknowledgements

Research at UNH is supported in part by the NSF grants PHY-0903923 and AGS-1202537, and the NASA grant NNX11AH03G.