Spatial and Temporal Evolution of Electron Distributions in the Electron Diffusion Region of Collisionless Magnetic Reconnection

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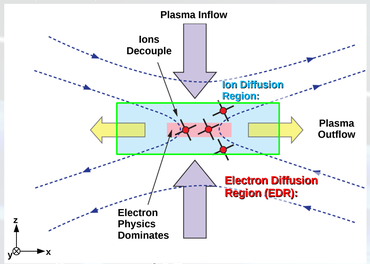
Background

Motivation and Context

How, where, and when electrons are energized in the electron diffusion region (EDR) during collisionless magnetic reconnection are active research questions highly relevant to NASA's upcoming Magnetospheric Multi-Scale (MMS) mission.

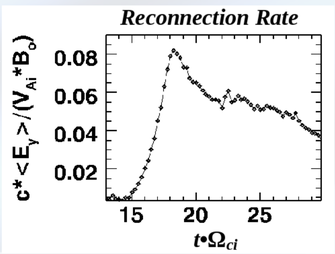


Cartoon of 2D reconnection.

Analyzing electron distribution functions from particle-in-cell (PIC) simulations offers a promising way to help answer these questions [1,2]. Previous simulation studies have reported the three-dimensional velocity space structure of electron distributions in the vicinity of the X-line [3, 4]. **We discover that the three-dimensional velocity space structure of EDR distributions evolves spatially from the X-line toward the end of the electron outflow jet, providing a fully kinetic perspective into the outstanding questions concerning electron agyrotropy [5] and the structure of the electron diffusion region [6,7,8]**. Furthermore, we find that this spatial variation of the electron distribution function evolves in time, suggesting that observation of highly structured EDR distributions could permit inference of the temporal evolution stage of the reconnection process.

PIC Simulation

- 2.5D, symmetric
- collisionless, undriven
- open boundaries
- antiparallel ($B_g = 0$)
- # of particles: ~3.1×10^{10}
- $m_i / m_e = 400$
- Domain size:
  x: [0, 1600]d_e
  z: [-200, 200]d_e
- Cells: 10240×2560

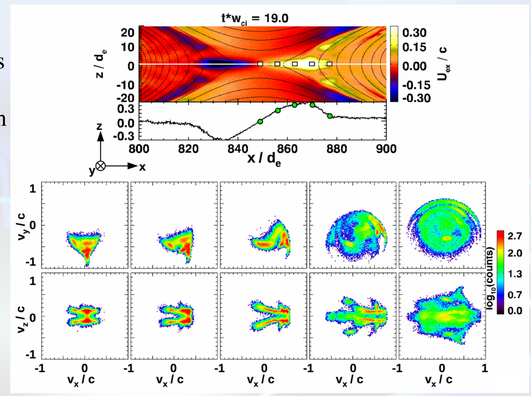


Evolution of the reconnection rate as measured by the average of the reconnection electric field, <E_y>.

Results

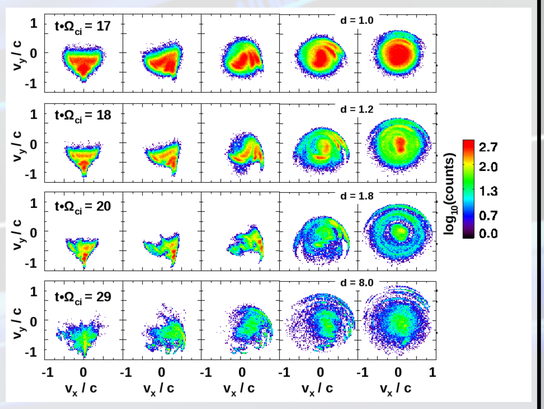
EDR: Spatial Evolution

- Striations in X-line distributions evolve spatially and coherently downstream throughout electron outflow jet as accelerated electrons re-magnetize, giving rise to discrete "arc" and "ring" structures [2].
- Spatial evolution reveals where and how accelerated electrons begin to thermalize in the exhaust region.



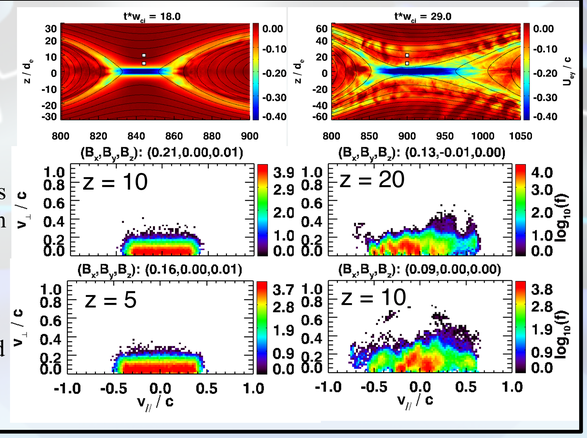
EDR: Temporal Evolution

- Striations, rings and arcs structures exhibit temporal and spatial dependence.
- Striations become less coherent at late times while arcs persist at all times.
- Arc populations found many d_i away from X-line as electron current layer extends.



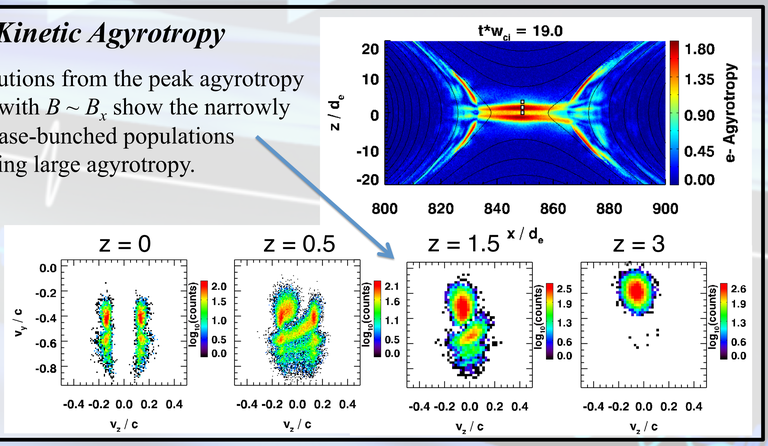
Inflow Region

- Upstream analytical approximation [3,4] only valid for early times.
- Elongated structure near peak reconnection becomes disjointed at late times with non-uniform phase-space density along $v_{//}$.
- $T_{e//} / T_{e\perp}$ does not necessarily increase toward $z = 0$ for late times due to broadening of E_z layer.



Kinetic Agyrotropy

- Distributions from the peak agyrotropy region with $B \sim B_x$ show the narrowly gyrophase-bunched populations producing large agyrotropy.

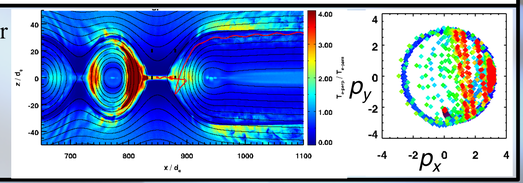


Conclusions

EDR electron structures exhibit spatiotemporal evolution throughout the electron outflow jet toward the exhaust and throughout the peak agyrotropy region toward the inflow. **We report (1) arc and ring formation as accelerated electrons re-magnetize in electron outflow jets at all times, and (2) X-line striations disappear at later times and may be caused by the disjointed, time-dependent structure of the inflow.**

Future Work

- Self-consistent particle tracing for PIC **E** & **B** fields to further understand electron energization.
- Analyze e^- distribution functions for asymmetric & 3D PIC cases.



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