Chaotic Ion Orbits in Alfvénic Magnetic Reconnection Outflows

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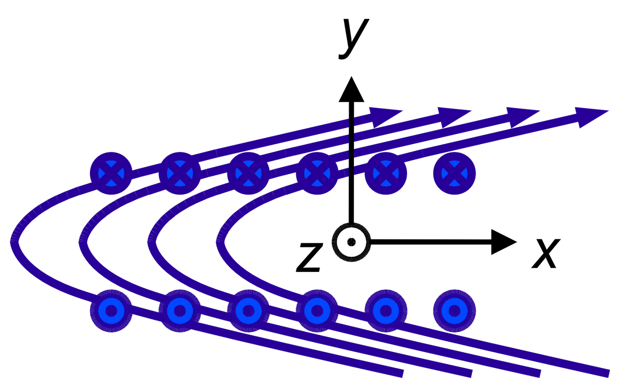
Abstract

In our research, we simulate the unbound orbits of ions in the Alfvénic outflows of various magnetic reconnection events. Expanding on previous research, we include the influence of the out-of-plane Hall magnetic field inside the ion diffusion region. We focus on the behavior of the ions near the discontinuities of the Hall field, especially at the field reversal midplane, comparing results from numerical and analytical models. We present results of particular interest on the chaotic reflections of the ions at the reversal midplane and the resulting ion temperature distribution.

Introduction

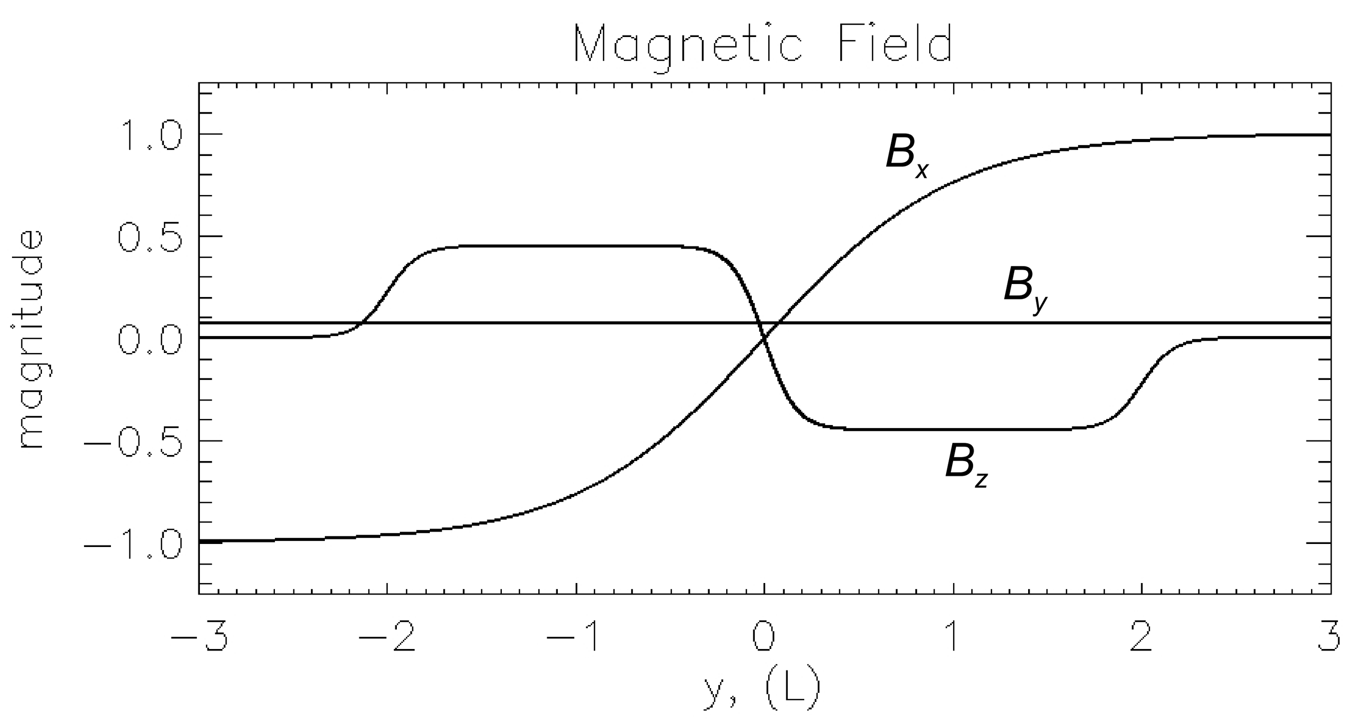
We describe the motion of particles in the outflowing regions of a magnetic reconnection event by creating a one-dimensional approximation of the magnetic field.



We transform to the DeHoffman-Teller frame that moves with the expelled magnetic field lines, ignoring the variation of the magnetic field along *x* direction:

$$\vec{B} = B_{x_0}\tanh\left(\frac{y}{L}\right)\hat{x} + B_{y_0}\hat{y} + B_{z_0}\left(\frac{1}{2}\left(\tanh\left(\frac{y+2L}{d}\right)+\tanh\left(\frac{y-2L}{d}\right)\right)-\tanh\left(\frac{y}{d}\right)\right)\hat{z}$$

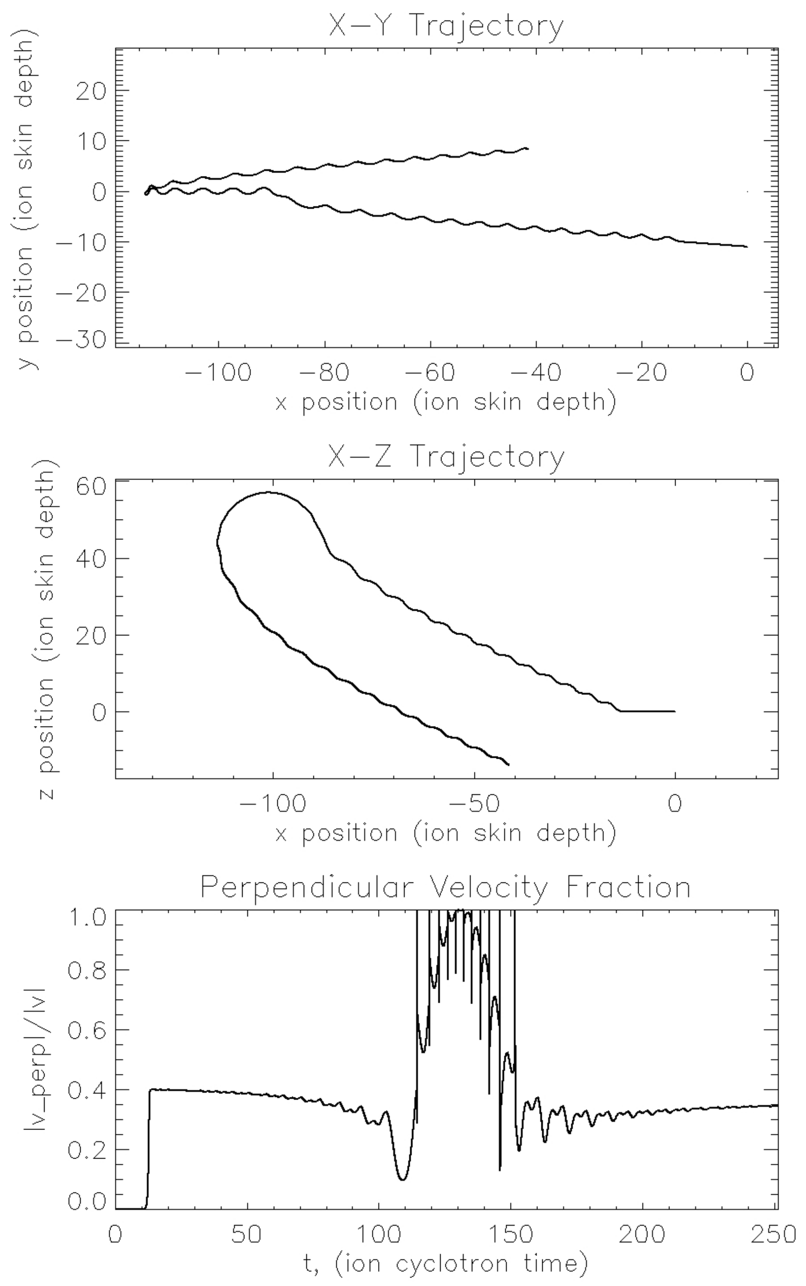
The length scale (L) is measured in ion skin depths and can be varied to model particle behavior at different distances downstream of the reconnection x-line.



Numerical Modeling

Numerical integration of particle orbits:

- Modified Boris Method
  - Rotation of position, velocity
  - Preserves magnitude of velocity
  - Second order accuracy
- Variable Time Step
  - Limited change in magnetic field
  - Limited deviation from linear trajectory

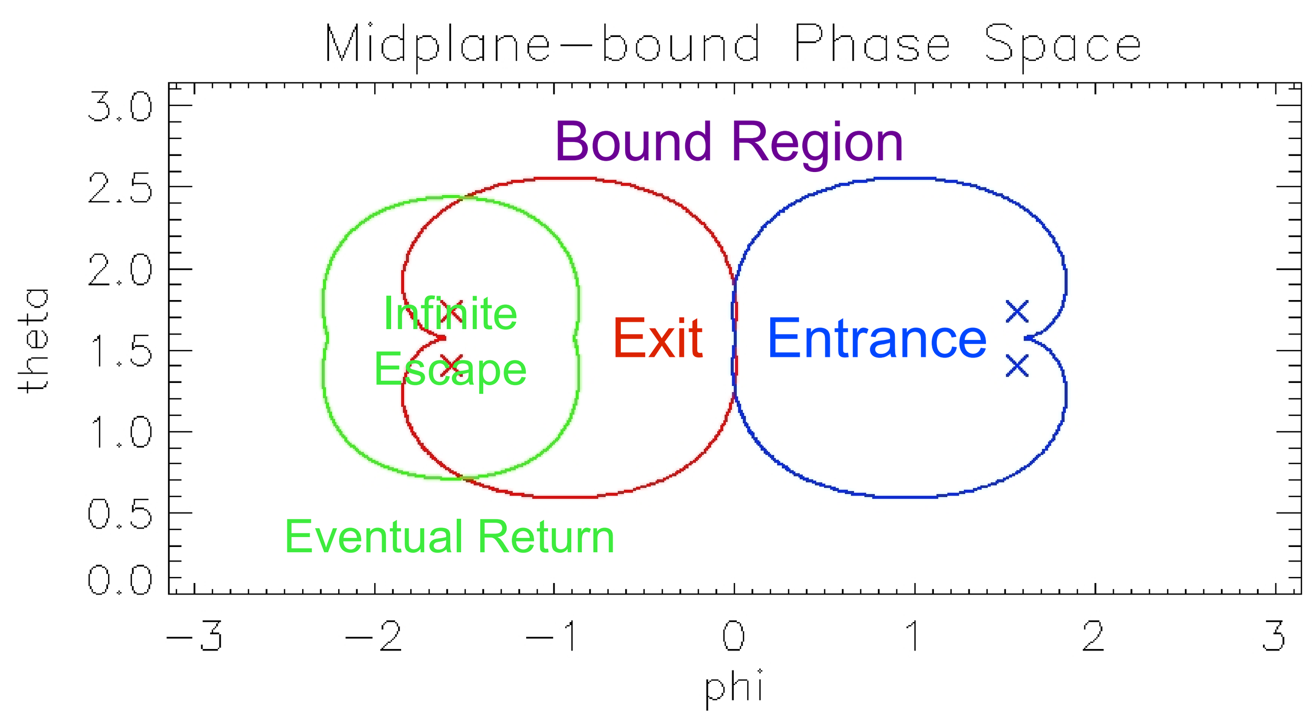


Particle velocities are normalized to the Alfvén speed of the magnetic field far from the midplane ($|y| >> 2L$).
Accurate analysis at short length scales ($L < \sim 1000$).

Analytical Modeling

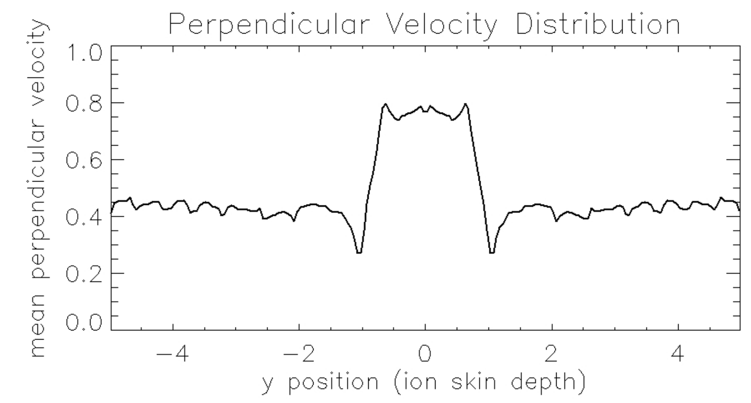
The motion of the particle about the field reversal midplane can be described analytically for large L ($B_x \sim 0$) and small d ($d \sim 0$, discontinuous B_z).

- Magnitude of velocity does not effect particle dynamics
- Describe velocity with spherical coordinate angles
  - *Theta* indicates the angle between velocity and $+y$
  - *Phi* indicates the angle in the x-z plane

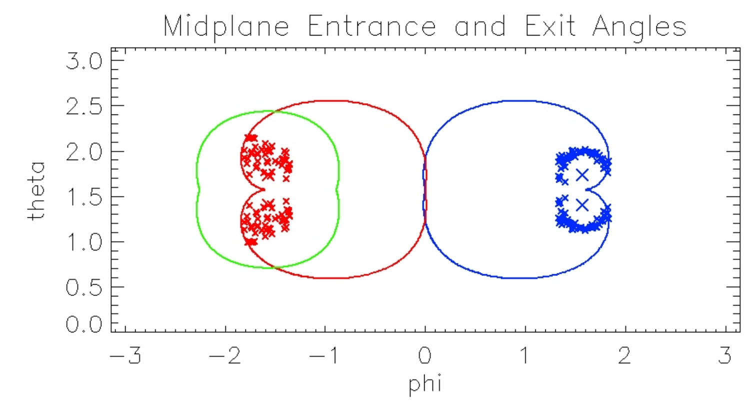


Conclusions

Combining modeling techniques, we were able to make some general observations about the particle orbits on a variety of length scales.



Mean perpendicular velocity distribution ($L = 2.5$)



Particle midplane entrance and exit angles ($L = 50$)

- Short ($L < \sim 25$)
  - Analytical assumptions invalid
  - Fast numerical modeling
  - Mean v_{perp} distribution
- Medium ($\sim 25 < L < \sim 100$)
  - Analytical assumptions approximately valid
  - Analyticity breaks down for *theta* $\sim \pi/2$ and edge of entrance/exit regions
  - Slower numerical modeling
  - Typical ions diffusing into outflow magnetic field remain on unbound orbits (even after scattering at midplane)

Generally, results indicate significant ion heating upon diffusion into the reconnection outflow regions.
Longer length scales remain infeasible to model due to limitations in the accuracy and increasingly long run time of the numerical simulation.

Future Work

This research has helped provide an initial look at the behavior of ions that have diffused from low temperature inflow regions to the outflow regions of the reconnection event. Further research on this phenomenon may include the following:

- Incorporate μ-conservation for long length scales
- Investigate perturbations of the midplane-bound phase space as analyticity becomes invalid
  - Decreasing L such that B_x varies nearly linearly
  - Increasing d to observe effects of B_z continuity
- Resolve approximate parallel temperature distribution