

Onset of Fast Magnetic Reconnection Induced by Resistivity Gradients with Application to the Lower Solar Atmosphere

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Abstract

Magnetic reconnection onset marks the transition from a slow energy-storage phase to the rapid conversion of magnetic energy into plasma heating, flows, and particle energization. However, the mechanism that controls this transition in strongly inhomogeneous plasmas remains unclear. We use fully kinetic VPIC simulations with self-consistent Coulomb collisions to study reconnection in a transition-region-like system containing a cold, dense plasma adjacent to a hot, rarefied plasma. Because the classical Spitzer resistivity scales as $\eta \propto T_e^{-3/2}$, the temperature gradient produces a strong spatial resistivity gradient. We show that this gradient introduces an additional induction contribution, $-(\partial_x \eta)_y$, which localizes magnetic-flux processing on the high-resistivity side of the transition layer, resulting in a Petschek-type configuration. We find that resistivity gradients trigger much earlier reconnection onset than uniform-resistivity and collisionless reference cases, especially for thicker current sheets relevant to large-scale astrophysical plasmas. The measured onset times are consistent with a scaling law derived from classical resistive diffusion. These results identify resistivity gradients as a self-consistent pathway for rapid reconnection onset in stratified plasmas, with potential application to the lower solar atmosphere and spicules.

Keywords: Magnetic reconnection; reconnection onset; resistivity gradients; kinetic simulations; solar transition region; spicules

Introduction

- Magnetic reconnection converts stored magnetic energy into plasma heating, bulk flows, and particle energization.
- A key open question is what controls reconnection onset, especially the transition from a slow energy-storage phase to rapid magnetic-energy release.
- In uniform-resistivity systems, reconnection often remains slow unless the current sheet thins to kinetic scales or becomes unstable to plasmoids.
- In stratified plasmas such as the lower solar atmosphere, strong temperature gradients produce strong resistivity gradients, which may localize the diffusion region and trigger earlier onset.

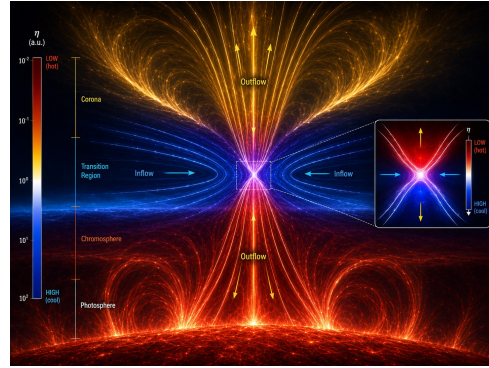


Fig 1 (Conceptual illustration) : Localization of reconnection in the solar transition region.

Theory and Method

We perform fully kinetic VPIC particle-in-cell simulations of guide-field magnetic reconnection in a two-dimensional $x-z$ geometry. The initial magnetic field is a force-free current sheet with guide field $B_y/B_0 = 1$, mass ratio $m_i/m_e = 25$, and density contrast $n_d/n_r = 4$. To model a transition-region-like plasma, we prescribe an initial density profile $n(x)$ that connects a cold, dense region to a hot, rarefied region. Since the Spitzer resistivity scales as $\eta \propto T_e^{-3/2}$, this temperature profile produces a spatially varying resistivity across the transition layer. We compare four cases: resistivity-gradient, uniform dense, uniform rarefied, and collisionless reference runs, while varying the current-sheet half-thickness over $\delta/d_i = 1-5$. The central diagnostic is the reconnection onset time as a function of current-sheet thickness which for a resistivity gradient case yields;

$$t_{\text{onset}}^{(\text{grad})} \Omega_{ci} \sim \frac{4(\delta/d_{i,c})^2}{\eta_0}$$

$\delta/d_{i,c}$ is the current sheet thickness with respect to the ion inertial scale and η_0 is the resistivity both measured at the chromosphere.

Results & Analysis

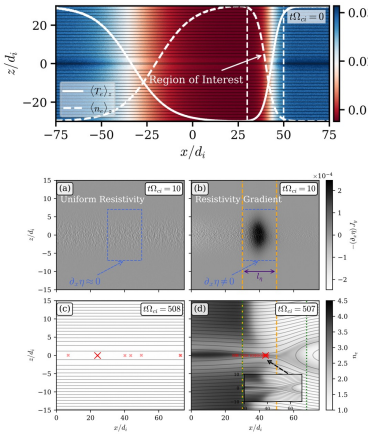


Fig 2 (Resistivity Gradient Run): Initial setup and the effect of resistivity gradients on reconnection dynamics.

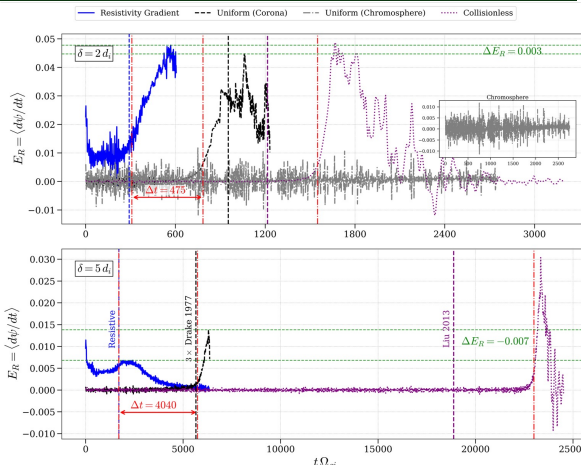


Fig 3 (Onset time scales): Onset times across runs with varying sheet thickness.

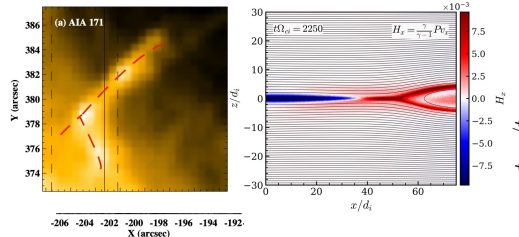


Fig 5 (Extrapolation): Spicule-like feature.

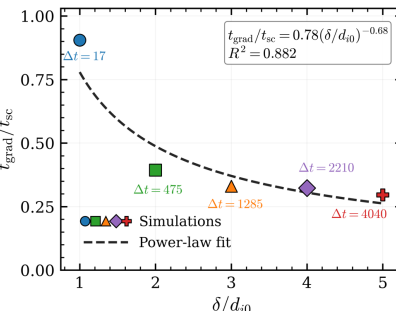


Fig 4 (Extrapolation): Extrapolation to real system.

Summary

- We use fully kinetic VPIC simulations to study reconnection onset in a stratified, transition-region-like plasma.
- Resistivity gradients localize magnetic-flux processing near the high-resistivity side of the transition layer, producing a Petschek-type open-outflow configuration.
- Reconnection onset occurs much earlier than in uniform-resistivity and collisionless reference systems, especially for thicker current sheets.
- The measured onset times follow a classical resistive-diffusion scaling, suggesting potential application to the lower solar atmosphere and spicules.

Future Work

- Include partial ionization, ion-neutral coupling, and radiative cooling to make the model more realistic for the lower solar atmosphere.
- Extend the mechanism to larger-scale global MHD simulations, such as MURaM, to test how resistivity-gradient localization operates in realistic solar atmospheric structures.
- Connect the simulations to observations of spicules and transition-region brightenings by comparing predicted onset locations, heating signatures, and outflow morphology.

Acknowledgements

This research used resources of the National Energy Research Scientific Computing Center (NERSC), a Department of Energy User Facility.

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