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Collaborative Research: Unveiling the Interplay Between Magnetic Reconnection and Turbulence — Theory and Modeling

Final Technical Report

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1 Executive Summary

This project investigated the interplay between two fundamental plasma processes — turbulence and magnetic reconnection — and the associated heating and particle acceleration. In particular, we focused on a new regime where the plasmoid instability mediates the turbulent energy cascade. In this new regime, reconnecting current sheets are disrupted by the growth of plasmoids/flux ropes on time scales shorter than the typical turnover times of eddies, speeding up the energy cascade and steepening the turbulence energy spectrum. This project addressed the following outstanding open questions: (1) What are the fundamental differences between plasmoid-mediated turbulence cascade in three dimensions (3D) and two dimensions (2D)? (2) What are the essential features of plasmoid-mediated turbulence in weakly collisional or collisionless regimes beyond resistive MHD? (3) How does the interplay of turbulence and reconnection regulate the energy release and dissipation in space and astrophysical plasmas?

To address these questions, we have carried out three investigations: (1) Three-dimensional plasmoid-mediated turbulence energy cascade; (2) plasmoid-mediated reconnection and turbulence in three-dimensional Hall MHD; (3) reconnection and heating in coronal loops. The results of these investigations have been published in three major publications, one in Science Advances and two featured articles in the Physics of Plasmas. We summarize the highlights and principal conclusions of these investigations below.

Study 1: Three-Dimensional Plasmoid-mediated Turbulence Energy Cascade

Plasmoid instability plays a crucial role in triggering the onset of fast reconnection by fragmenting reconnection current sheets. This process profoundly influences the turbulent energy cascade. The scale-dependent dynamic alignment inherent in MHD turbulence results in smaller-scale current sheets exhibiting larger aspect ratios, thereby increasing their susceptibility to the plasmoid instability. Consequently, the plasmoid instability emerges as the dominant mechanism governing the energy cascade at smaller scales.

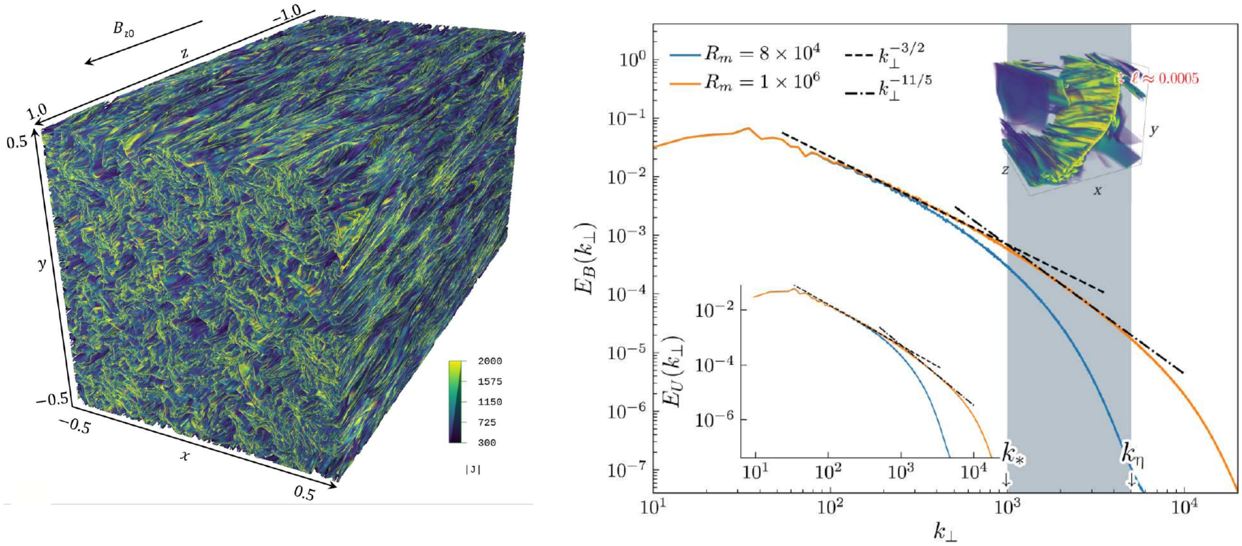

Figure 1: Three-dimensional plasmoid-mediated turbulence energy cascade simulations. The left panel shows the current density distribution of the $R_m = 10^6$ simulation, where numerous current sheets densely populate the entire simulation box. The right panel shows the magnetic energy spectrum E_B and the kinetic energy spectrum E_m from two simulations of $R_m = 8 \times 10^4$ and 10^6, respectively. The energy spectra in the $R_m = 10^6$ case show two distinct regimes with different slopes. The regime mediated by the plasmoid instability (shaded region) has a steeper slope $\sim k_\perp^{-11/5}$ in the perpendicular wavenumber. The inset shows a 3D zoom-in of a current sheet, where several flux ropes are visible. (Adapted from Publication 4)

In our previous studies, we applied our theories of plasmoid-mediated current sheet disruption [3] to the MHD turbulence energy cascade. Because the energy cascade mediated by the plasmoid instability is more rapid than that mediated by wave interaction, the resulting energy power spectrum is steeper than predicted by traditional MHD turbulence theories. The predicted power spectrum in this new regime is a power law with an index of -11/5, multiplied by a logarithmic factor.[2] This steepening of energy spectrum occurs at small scales. For a turbulence system with a sufficiently high Reynolds number and substantial separation between the injection scale and the dissipation scale, there will be two different slopes for the power spectrum at the large and small scales. This theoretical prediction was confirmed with large-scale 2D MHD simulations performed by our team with the magnetic Reynolds number — a parameter that quantifies the relative importance of plasma convection and resistive diffusion — up to $Rm = 10^6$.[4]

During this project, we extended the previous 2D study to full 3D. Our 3D simulations employed a newly developed fifth-order scheme of the BATS-R-US MHD code, as opposed to the second-order scheme of BATS-R-US in the previous study. Using the fifth-order scheme enabled us to achieve desirable accuracy without excessively high grid resolutions. The largest simulation simulation of this study had a grid resolution $10000 \times 10000 \times 5000$ and the magnetic Reynolds number $Rm = 10^6$. This was the largest MHD simulation ever performed at the time of publication.[5]

The simulations revealed that magnetic reconnection disrupted elongated current sheets, forming chains of small magnetic flux ropes, which were a 3D generalization of 2D plasmoids. As in

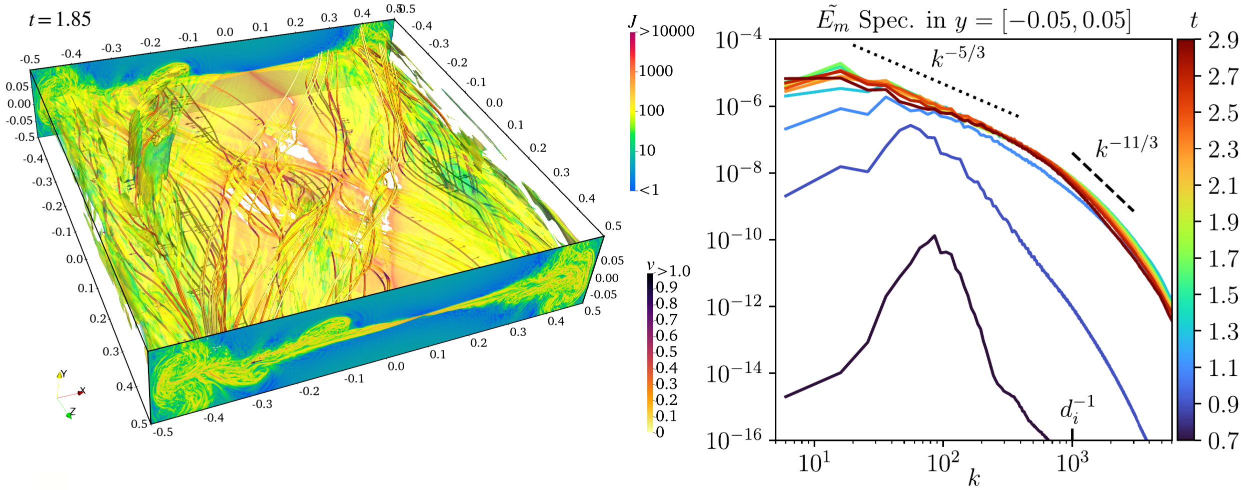

Figure 2: Self-generated turbulent Hall reconnection. The left panel shows a snapshot of a 3D simulation with $S = 2 \times 10^5$ and $L = 1000 d_i$. The magnitude of the current density J is plotted on the two end plates at $z = \pm 0.5$ and the isosurfaces of the flow speed at $v = 0.4$. Representative magnetic fieldlines are colored according to the flow speed v. The right panel shows the time evolution of the magnetic energy power spectrum. The spectrum evolves to a quasi-steady state when the turbulence is fully developed. The spectrum approximately follows a $k^{-5/3}$ power law at the MHD scales, and steepens at sub-d_i scales (Adapted from Publication 1)

the 2D case, this disruption led to a new range of energy cascade at small scales, where the energy transfer rate was controlled by the growth rate of these plasmoids. This plasmoid-dominated cascade resulted in a steeper turbulent energy spectrum, characterized by a spectral index of -11/5 (Figure 1). We also observed changes in the scalings of anisotropy of turbulence eddies in the plasmoid-mediated regime. Computation of shell-to-shell energy transfer rate further supported the distinct nature of reconnection-driven energy cascade.

The study highlights the need for further investigation into the implications of these findings in astrophysical problems, such as solar coronal heating, using current and future spacecraft and telescopes. The omnipresence of plasmoids and their influence on energy transfer could have significant implications for our understanding of various astrophysical phenomena.

Study 2: Plasmoid-Mediated Reconnection and Turbulence in Three-Dimensional Hall MHD

Study 1 investigated a plasmoid-mediated energy cascade in homogeneous turbulence. Another arena where reconnection and turbulence interplay with each other is in a large-scale, high Lundquist number (S) reconnection layer, where S is a dimensionless parameter that quantifies the relative importance of Alfvén wave and resistive diffusion. In a previous 3D resistive MHD study, we found that plasmoid instability can facilitate self-generated turbulent reconnection without the need for external forcing. The turbulence is strongly inhomogeneous, and the energy power spectrum is found to be steeper than the usual MHD turbulence energy spectrum, similar to the steeper spectrum observed in the plasmoid-mediated regime in Study 1.[6]

In many astrophysical and space systems, the onset of plasmoid instability may occur in the collisional regime but eventually become collisionless as the current sheet fragmentation progresses toward kinetic scales. This highlights the importance of investigating plasmoid-mediated turbulent reconnection in models beyond MHD. Hall MHD models are widely regarded as a simplified yet effective representation of the transition from collisional to collisionless reconnection. However, in 2D simulations, the onset of Hall reconnection often expels all the plasmoids, leading to a single-X-line reconnection configuration. This behavior significantly differs from fully kinetic particle-in-cell (PIC) simulation results, where new plasmoids continue to form even after the onset of collisionless reconnection. The primary objective of this study is to investigate whether a single-X-line reconnection configuration remains a favored state in fully 3D Hall MHD reconnection. Moreover, can 3D Hall MHD realize self-generated turbulent reconnection?

We performed 2D and 3D simulations with two sets of parameters, varying the system sizes while the Lundquist number remained fixed. In 2D simulations, both cases settled to a single-X-line configuration after the onset of Hall reconnection. In contrast, one of the 3D simulation with the system size $L = 500d_i$ (d_i is the ion skin depth) gradually self-organized to a quasi-2D, single-X-line configuration, whereas the other one with $L = 1000d_i$ developed into a turbulent reconnection state (Figure 2). Our results demonstrate that 3D simulations are less prone to single-X-line reconnection than 2D simulations. Depending on the parameter regimes of the Lundquist number and the ratio between the system size and the kinetic scale, Hall MHD can realize self-generated turbulent reconnection or single-X-line reconnection.

We analyzed the turbulence energy power spectra. We also examined the scale-dependence of turbulent eddy anisotropy using two-point structure functions. In our previous resistive MHD study, analysis of the structure functions indicated a deviation from the Goldreich-Sridhar critical balance scaling, which relates the parallel and perpendicular wavenumbers of turbulent eddies ($k_\parallel \sim k_\perp^{2/3}$). This deviation persists in the present Hall MHD case in the vicinity of the reconnection mid-plane. However, further from the mid-plane, the Goldreich-Sridhar scaling is partially recovered for large-scale eddies at MHD scales.

Our simulations indicate that single-X-line Hall reconnection typically yields the fastest reconnection rate, while turbulent Hall reconnection is slightly slower but still significantly faster than resistive MHD turbulent reconnection. The turbulent region in Hall reconnection is also considerably wider than in resistive MHD. The significant widening of the reconnection layer due to turbulence in Hall MHD could potentially explain the observed thickness of post-CME current sheets. However, the system sizes in simulations (relative to kinetic scales) are still many orders of magnitude smaller than the sizes of post-CME current sheets. In the future, the Hall MHD description of self-generated turbulent reconnection should be further compared with PIC simulations or more elaborated fluid models such as high-moment multi-fluid models, particularly in the regime where the system size is much larger than kinetic scales.

Study 3: Reconnection and Heating in Coronal Loops

Building upon the foundational physics explored in the previous two studies with idealized simulations, this third study investigates a problem directly relevant to an astrophysical application — the coronal heating problem. According to Parker's coronal heating model,[7] the footpoints of magnetized coronal loops are constantly shuffled by convection on the solar surface, twisting and

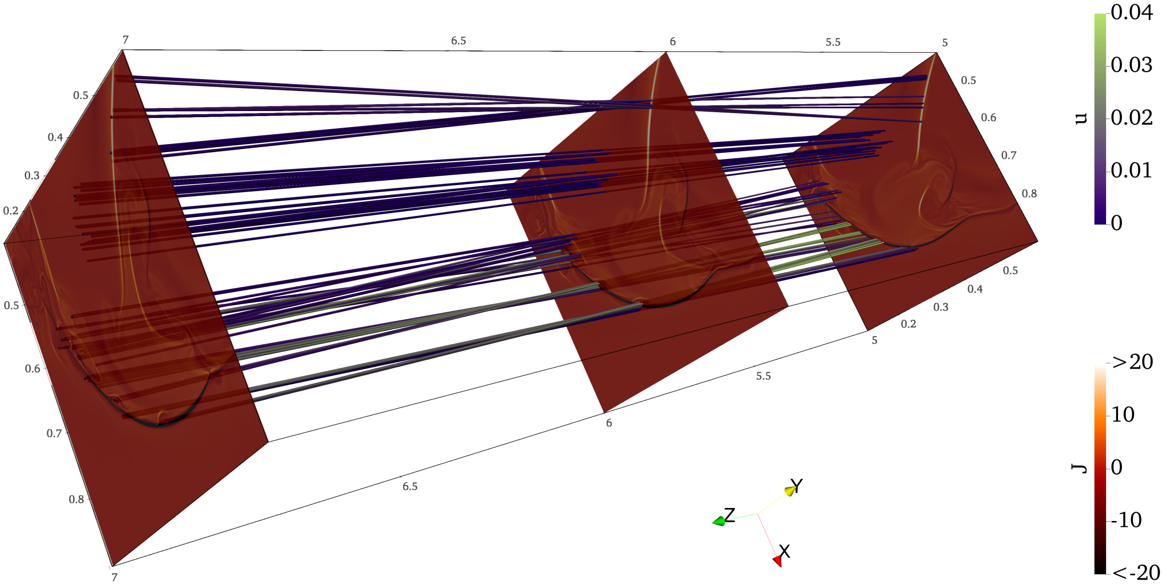

Figure 3: Simulation of a coronal loop driven by footpoint motion. This figure shows a zoom-in view of a sub-domain of 5% of the entire simulation box. The color shading on the slices shows the current density J along the z direction. The current ribbon with $J < 0$ has become unstable to the tearing (plasmoid) instability. This instability has led to the development of flux-rope-like structures within the ribbon. Magnetic field lines are color-coded according to the plasma flow speed u. (Adapted from Publication 3)

braiding the magnetic field lines. The intertwining of magnetic field lines results in the formation of highly intense current sheets. These current sheets drive reconnection, thereby converting magnetic energy into plasma energy. Recently, Boozer and Elder proposed a model to test the idea of fast reconnection facilitated by chaotic separation of 3D magnetic field lines.[1] The Boozer-Elder model is essentially identical to Parker's model, but their predictions regarding the formation of current sheets are drastically different from Parker's.

Over the years, Boozer has argued that 3D magnetic reconnection is fundamentally different from 2D reconnection because the separation between neighboring field lines almost always increases exponentially over distance in a 3D magnetic field. This exponential separation makes 3D field line mapping highly sensitive to small non-ideal effects. As a consequence, 3D reconnection can occur without intense current sheets. Specifically, the role of intense current sheets is where the predictions of Boozer-Elder differ from that of Parker. In Parker's scenario, intense current sheets play a critical role, whereas in Boozer-Elder's scenario, the field line chaos facilitates reconnection, and the intensities of current filaments only increase logarithmically with respect to the Lundquist number.

To test the predictions of Parker and Boozer-Elder, we conducted ideal and resistive reduced magnetohydrodynamic simulations. Our ideal simulation shows that Boozer and Elder's calculation significantly under-predicts the intensity of current density due to omitted terms. Furthermore, resistive simulations of varying Lundquist numbers indicate that the maximal current density scales linearly with the Lundquist number, in contrast to Boozer-Elder's prediction of a logarithmic dependence. Therefore, our simulation results are in favor of Parker's theory. In fact, in the highest Lundquist number simulation we have performed, the current sheets become so intense that some of them become unstable to the plasmoid instability and break into flux ropes, in spite of the stabilizing effects of line-tying (Figure 3).

Previously, Parker's model has been extensively studied using resistive magnetohydrodynamic models. However, in the coronal environment, collisionless reconnection is likely important as current sheets develop at kinetic scales, especially when intensive current sheets can become unstable to the plasmoid instability. Because collisionless reconnection is faster, it may in turn affect the storage and release of magnetic energy and the overall heating rate. To further explore this, we conducted a follow-up study investigating the impact of collisionless reconnection in Parker's model using a reduced two-field model that incorporates the electron skin depth and the ion sound Larmor radius as free parameters. We conducted a series of simulations, varying the ratios between the system size and kinetic scales, and compare the results with those obtained using the resistive reduced MHD model. Our simulation results suggest that the heating rate may be insensitive to the details of the reconnection mechanism, remaining relatively constant across different regimes. However, details of the dynamic activities of coronal loops depend on the reconnection mechanism. When reconnection is dominated by collisionless physics, the coronal loop is more dynamic, with strong flows throughout a large fraction of the volume. In contrast, with collisional reconnection, the coronal loop is mostly quasi-static, and strong flows only appear in reconnection outflow jets. This qualitative difference also affects how energy is dissipated. In collisionless-reconnection-dominated loops, dissipation is predominantly viscous, whereas in collisional-reconnection-dominated loops, dissipation is mostly resistive. How to distinguish these two scenarios with observations is an area of future research.

2 Publications, Presentations, and Products

Publications Supported by this Project

1. Yi-Min Huang and Amitava Bhattacharjee, "Three-dimensional plasmoid-mediated reconnection and turbulence in Hall magnetohydrodynamics," Physics of Plasmas, **31**, 082119 (2024) (Featured Article). [Link]

2. Yi-Min Huang, "Plasmoid instability, magnetic field line chaos, and reconnection," Radiation Effects and Defects in Solids **178**, 1362 (2023). [Link]

3. Yi-Min Huang and Amitava Bhattacharjee, "Do chaotic field lines cause fast reconnection in coronal loops?" Physics of Plasmas, **29**, 122902 (2022) (Featured Article). [Link]

4. Chuanfei Dong, Liang Wang, Yi-Min Huang, Luca Comisso, Timothy A. Sandstrom, and Amitava Bhattacharjee, "Reconnection-Driven Energy Cascade in Magnetohydrodynamic Turbulence," Science Advances, **8**, eabn7627 (2022). [Link]

Presentations of the Outcomes of this Project

The results of this project have been extensively presented in seminars, conferences, and workshops. Below is a partial list of the presentations related to this project.

1. “Does the Coronal Heating Rate Depend on Microscopic Reconnection Physics?” poster presented in the SHINE Workshop, August 12–16, 2024, Juneau, Alaska.

2. “Three-dimensional Plasmoid-Mediated Reconnection and Turbulence in Hall Magnetohydrodynamics,” NASA Goddard Solar Theory and Modeling Personnel (STAMP) Meeting, June 7, 2024.

3. “Collisionless Effects in Parker’s Coronal Heating Model,” e-poster presented in the AGU Fall Meeting, December 11–15, 2023, San Francisco, California.

4. “Reconnection-Driven Energy Cascade Revealed by 3-D Magnetohydrodynamic Turbulence Simulations,” poster presented in the AGU Fall Meeting, December 11–15, 2023, San Francisco, California.

5. “Self-generated Turbulent Reconnection in Three-dimensional Hall Magnetohydrodynamics,” oral presentation in the 65th APS DPP Meeting, October 31, 2023, Denver, Colorado.

6. “Role of Tearing Instability in Magnetohydrodynamic Turbulence,” oral presentation in the 65th APS DPP Meeting, October 30 – November 3, 2023, Denver, Colorado.

7. “Do chaotic field lines cause fast reconnection in coronal loops? ” poster presented in the 65th APS DPP Meeting, October October 30 – November 3, 2023, Denver, Colorado.

8. “Plasmoid Instability and Field Line Chaos in Solar Magnetic Reconnection,” Interdisciplinary Consortium Meeting on Modeling and Simulation, October 27, 2023, National Institute of Aerospace, Hampton, VA (presented via Zoom).

9. “Do chaotic field lines cause fast reconnection in coronal loops? ” poster presented in the MR2023 Workshop, June 26–29, 2023, Ise Shima, Japan.

10. “Reconnection-Driven Energy Cascade Revealed by the World’s Largest Magnetohydrodynamic Turbulence Simulation,” oral presentation in the MR2023 Workshop, June 26–29, 2023, Ise Shima, Japan.

11. “Plasmoid Instability in Solar Reconnection: Theories, Simulations, and Observations,” Center for Computational Astrophysics, Flatiron Institute, February 28, 2023.

12. “Do chaotic field lines cause fast reconnection in coronal loops? ” oral presentation in the AGU Fall Meeting, December 12–16, 2022, Chicago, Illinois.

13. “Reconnection-Driven Energy Cascade in Magnetohydrodynamic Turbulence,” poster presented in the AGU Fall Meeting, December 12–16, 2022, Chicago, Illinois.

14. “Reconnection-Driven Energy Cascade in Magnetohydrodynamic Turbulence,” oral presentation in the APS DPP Meeting, October 17–21, 2022, Spokan, Washington.

15. “Onset and Saturation of 3D Plasmoid-mediated Reconnection in Hall Magnetohydrodynamics,” poster presented in the AGU Fall Meeting, December 13–17, 2021, New Orleans, Louisiana.

16. “Roles of the Plasmoid Instability in 2D and 3D Magnetohydrodynamic Turbulence,” AGU Fall Meeting, December 13–17, 2021, New Orleans, Louisiana.
17. “Three-dimensional Plasmoid-Mediated Reconnection in Hall MHD,” oral presentation in MPPC Annual Meeting (Virtual), January 19, 2021.
18. “MHD Turbulence Mediated by the Plasmoid Instability,” oral presentation in MPPC Annual Meeting (Virtual), January 26, 2021.
19. “Three-dimensional Plasmoid-Mediated Reconnection in Hall MHD,” oral presentation in the 62nd APS DPP Virtual Meeting, November 9-13, 2020.

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