Collaborative Research: The Evolution of Magnetic Skeletons During 3D Reconnection

Final Technical Report

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Abstract

We investigated how the plasmoid instability affects the evolution of topological features of a magnetic field and the process of magnetic reconnection with three sub-projects. (i) We extensively studied the criterion for plasmoid-mediated current sheet disruption and the onset of fast reconnection. Scaling relations with respect to plasma parameters have been established, using both direct numerical simulations and analytic theories, for the disruption time, the current sheet width, the instability linear growth rate, and the dominant mode wavenumber. (ii) We applied the theories of plasmoid-mediated current sheet disruption to magnetohydrodynamic turbulence and predicted a steepening of the turbulence energy spectrum. This steepening has been confirmed by direct numerical simulations. (iii) We performed numerical simulations of ultraviolet burst events in the solar atmosphere with a spine-dome magnetic topology. The plasmoid instability leads to unsteady reconnection, which is consistent with solar observations.

1 Project Summary

Magnetic skeletons are features such as null points, spine field lines, separatrix surfaces, and separator field lines that divide a region permeated with a magnetic field into topologically distinct domains. For a magnetized plasma, the frozen-in theorem of the ideal magnetohydrodynamics (MHD) implies the preservation of magnetic topology. Consequently, the magnetic topology can only change in localized regions where the ideal MHD breaks down. This process of local breakdown of the ideal MHD and the resulting changes of magnetic topology is called magnetic reconnection.

The objective of this project is to address the following key science questions: How do magnetic skeletons topologically and geometrically evolve during reconnection? How does this evolution impact the reconnection process? To address these questions, we have investigated several sub-projects using a combination of analytical theory and numerical simulations. Specifically, we focused on a common theme of the "plasmoid instability," which is a tearing-type instability in intense current sheets around reconnection sites. The plasmoid instability is an important mechanism that causes bifurcations of null points. As a consequence of the proliferation of the null points, the magnetic reconnection rate drastically increases. We summarize the highlights and principal conclusions of these sub-projects below.

Plasmoid Instability in Evolving Current Sheets and the Onset of Fast Reconnection

Magnetic reconnection usually starts from the formation of a current sheet, which gradually thins down as time progresses. During this period, the plasmoid instability develops and eventually triggers the transition from slow to fast reconnection. This project seeks to determine the current sheet width, the instability linear growth rate, and the dominant mode wavenumber at the moment of the transition. Most importantly, how do these features scale with the plasma conditions such as the Lundquist number and the noise level?

Through a series of simulations, we found that the transition from slow to fast reconnection occurs when the plasmoid instability enters the nonlinear regime [8]. The precise criterion is that the sizes of plasmoids exceed the inner layer width of the tearing mode. When this criterion is satisfied, the reconnecting current sheet is "disrupted" and rapidly goes through a sequence of fractal-like fragmentation that generates a large number of new null points. Figure 1 shows a series of snapshots of this process in a simulation.

These simulations scan over a wide range of the Lundquist number and various amplitudes of the initial perturbation. With these simulations, we have obtained the scalings of important quantities, including the current sheet width, the instability linear growth rate, and the dominant mode wavenumber at the moment of the disruption, with respect to the Lundquist number and the noise level. The scaling relations of these quantifies all exhibit a shift of trend as the Lundquist numbers go from low to high values. Furthermore, the outcomes also depend on the noise level.

We have developed analytic theories to obtain the scaling relations for these quantities. We first employed a "principle of least time" that demands the dominant mode to be the one that takes the least time to satisfy the condition that the island size exceeds the inner layer width [3, 4]. Analytic calculation using the principle of least time yields scaling relations that are valid in the high-Lundquist-number regime. These scaling relations are not simple power-laws. Instead, to the leading order approximation, they take the form of a power-law multiplied by a logarithmic factor depending on the Lundquist number and the noise amplitude.

We have developed a further refined model that incorporates the effect of the outflow jet, which stretches the wavelengths of the unstable modes [8, 9]. Numerical solutions of this model yield scaling relations in agreement with the results obtained from direct numerical simulations. Turning off the effect of the outflow jet, the analytic scaling relations from this new model also agree with earlier results using the principle of least time up to the leading order logarithmic factor. Importantly, the model also yields a critical Lundquist number below which the current sheet disruption will not occur. This critical Lundquist number is not a fixed value but depends on the current sheet thinning process and the amplitude and the form of the noise.

Plasmoid-mediated Turbulence Energy Cascade

In addition to triggering the onset of fast reconnection, the plasmoid instability also plays significant roles in the turbulence energy cascade. Due to the scale-dependent dynamic alignment in MHD turbulence, current sheets at smaller scales tend to have larger aspect ratios, making them more susceptible to the plasmoid instability. Consequently, the plasmoid instability becomes the dominant energy cascade mechanism at small scales.

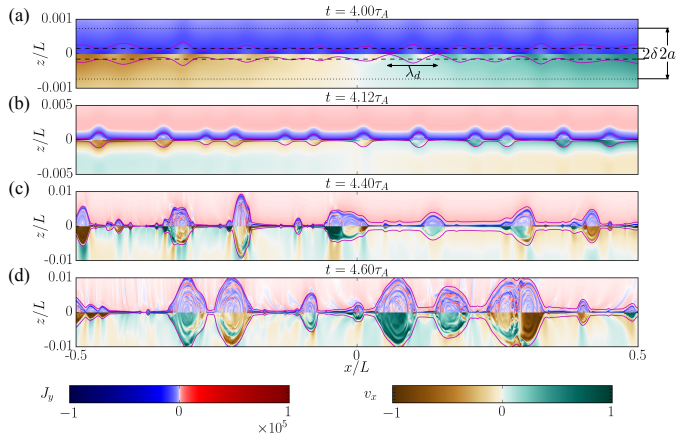

Figure 1: Time sequence of fractal-like fragmentation of current sheets. (a) The primary current sheet is disrupted when the sizes of plasmoids exceed the inner layer width 2δ. (b) The current sheets between plasmoids become extended and (c) unstable to the plasmoid instability again. (d) Multiple levels of fractal-like current sheet fragmentation lead to a hierarchy of plasmoids of different sizes (from Ref. [8]).

We have applied our theories of plasmoid-mediated current sheet disruption to the MHD turbulence energy cascade. Because the plasmoid instability leads to a more rapid energy cascade, the resulting energy power spectrum is steeper than the prediction of traditional MHD turbulence theories. The leading order power spectrum is a power-law with a power index of -2.2, while the next order correction is a logarithmic multiplication factor [2]. This steepening of energy spectrum occurs at small scales; hence, for a turbulence system with a sufficiently high Reynolds number and a substantial separation between the injection scale and the dissipation scale, there will be two different slopes for the power spectrum for at the large scale and the small scale, respectively. We have confirmed this theoretical prediction by performing large-scale MHD simulations with the Reynolds number $Rm = 10^6$ [5].

We also found similar steepening of the energy spectrum in self-generated turbulence within a large-scale plasmoid-mediated reconnection layer [7].In this case, because the global scale is the reconnecting current sheet, only the steepened slope is observed. We have developed a theory to describe plasmoid-mediated turbulence in the presence of a large-scale mean-field. In this framework, the unstable eigenmodes of the mean-field act as sources injecting energy into the turbulence, whereas stable eigenmodes act as sinks of the turbulence energy. The resulting energy power spectrum is a power-law multiplied by a factor of exponential fall-off [6].

Plasmoid Instability in Ultraviolet Bursts at the Lower Solar Atmosphere

As an application of our basic studies to real-world problems, we have investigated plasmoid-mediated null point bifurcation in the solar ultraviolet (UV) bursts by performing numerical simulations with a configuration that mimics a UV burst event. Prior to the event, the magnetic field in the region had a spine-dome topology with magnetic footpoints anchored at the lower boundary, as was inferred from a force-free extrapolation of the magnetogram data [1]. The UV burst was driven by convection at the footpoints of the magnetic field lines on the photosphere. In our numerical simulations, we imposed a flow at the footpoints with the observed speed. The motion at footpoints deformed the magnetic field, leading to the formation of a current sheet at the null-point. The current sheet subsequently developed plasmoid instabilities, causing bifurcations of magnetic nulls. This bifurcation of the null points can be seen in Figure 2, showing a snapshot of the plasma temperature with two plasmoids in the reconnection site. The presence of plasmoids makes the reconnection process unsteady, consistent with the observed variability during the transient events

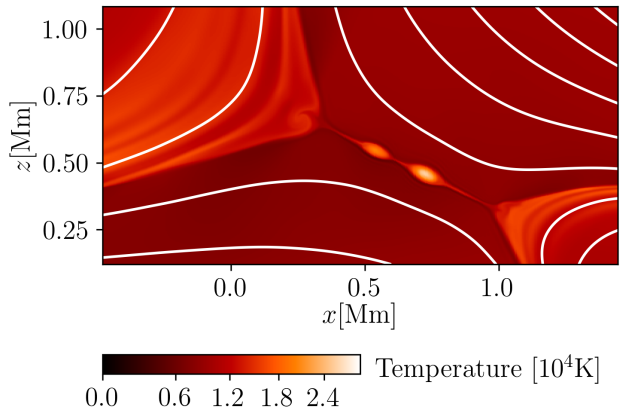

Figure 2: A numerical simulation of a UV burst event. In this configuration, a magnetic null point in the initial condition develops into a current sheet when the footpoints at the lower boundary are driven by an imposed flow. Subsequently, the current sheet breaks and forms plasmoids. Color shading shows the temperature, overlaid with magnetic field lines (from Ref. [10]).

on a timescale of minutes.

We have performed a series of simulations with different ambient plasma β to investigate how reconnection of this spine-dome configuration behaves at different altitudes of the solar atmosphere. We found that the ambient plasma beta plays an important role in determining both the time scale of current sheet formation and whether the plasmoid instability takes place. If the ambient plasma β is too high, the null point will not collapse to form a current sheet, and the amount of energy release is small. On the other hand, if the ambient plasma β is too low, then the magnetic energy gets released immediately after the imposed flow shifts the footpoints. For the latter case, the magnetic energy cannot build up sufficiently before it is rapidly released. Therefore, there is an "optimal" ambient β for magnetic energy storage that leads to a maximal energy release. The results of this numerical study are published in Ref. [10].

2 Publications, Presentations, and Products

Publications Related to this Grant

- L. Comisso, M. Lingam, Y.-M. Huang, and A. Bhattacharjee, "General Theory of the Plasmoid Instability," Phys. Plasmas **23**, 100702 (2016).
- L. P. Chitta, H. Peter, P. R. Young, and Y.-M. Huang, "Compact solar UV burst triggered in a magnetic field with a fan-spine topology," Astron. Astrophys. **605**, A49 (2017).
- Yi-Min Huang, Luca Comisso, and A. Bhattacharjee, "Plasmoid Instability in Evolving Current Sheets and Onset of Fast Reconnection," Astrophys. J. **849**, 75 (2017).
- L. Comisso, M. Lingam, Y.-M. Huang, and A. Bhattacharjee, "Plasmoid Instability in Forming Current Sheets," Astrophys. J. **850**, 142 (2017).
- L. Comisso, Y.-M. Huang, M. Lingam, E. Hirvijoki, and A. Bhattacharjee, "Magnetohydrodynamic Turbulence in the Plasmoid-mediated Regime," Astrophys. J. **854**, 103 (2018).
- Di Hu, Amitava Bhattacharjee, and Yi-Min Huang, "Energy spectrum of tearing mode turbulence in sheared background field," Phys. Plasmas **25**, 062305 (2018) (PoP Featured Article).

- Chuanfei Dong, Liang Wang, Yi-Min Huang, Luca Comisso, and Amitava Bhattacharjee, "Role of the Plasmoid Instability in Magnetohydrodynamic Turbulence," Phys. Rev. Lett. **121**, 165101 (2018).

- H. Peter, Y.-M. Huang, L. P. Chitta, and R. P. Young, "Plasmoid-mediated reconnection in solar UV bursts," Astronomy and Astrophysics **628**, A8 (2019).

- Yi-Min Huang, Luca Comisso, and Amitava Bhattacharjee, "Scalings Pertaining to Current Sheet Disruption Mediated by the Plasmoid Instability," Physics of Plasmas **26**, 092112 (2019).

Presentations Related to this Grant

The results of this project have been presented in numerous talks and posters in national and international conferences and workshops.

- "Onset of Plasmoid Instability in an Evolving Current Sheet," poster presented in the 58th Annual Meeting of the APS Division of Plasma Physics October 31 – November 4, 2016, San Jose, California.

- "Plasmoid Instability in an Evolving Current Sheet," oral presentation in Max Planck/Princeton Center for Plasma Physics Workshop, December 5 – 8, 2016, Princeton, NJ.

- "Plasmoid Instability in Evolving Current Sheet and Onset of Fast Reconnection," poster presented in NSF/DOE Partnership in Basic Plasma Science and Engineering 20th Anniversary Workshop, Jan. 9 – 11, 2017, National Science Foundation, Arlington, VA.

- "Plasmoid Instability in Evolving Current Sheet and Onset of Fast Reconnection," oral presentation in the US-Japan Workshop on Magnetic Reconnection (MR2017), March 19 – 23, 2017, Matsuyama, Japan.

- "Plasmoid Instability in Evolving Current Sheet and Onset of Fast Reconnection," poster presented in the SHINE workshop, July 24 – 28, 2017, Saint-Sauveur, Quebec, Canada.

- "Plasmoid Instability in Evolving Current Sheets and Onset of Fast Reconnection," Fourth Interdisciplinary Consortium Meeting on Modeling and Simulation, August 15, 2017, National Institute of Aerospace, Hampton, VA.

- "Plasmid Instability in Evolving Current Sheets and Onset of Fast Reconnection," Plenary Session in Max Planck/Princeton Center for Plasma Physics General Meeting, September 19 – 22, 2017, Greifswald, Germany.

- "Plasmoid Instability in Evolving Current Sheet and Onset of Fast Reconnection," poster presented in the 59th Annual Meeting of the APS Division of Plasma Physics, October 23 – 27, 2017, Milwaukee, Wisconsin.

- "Plasmoid Instability Mediated Current Sheet Disruption and Onset of Fast Reconnection," poster presented in the AGU Fall Meeting, December 11 – 15, 2017, New Orleans, LA.

- "Scalings of the Plasmoid Instability in Evolving Current Sheets," oral presentation in Max Planck/Princeton Center for Plasma Physics Workshop, April 23 – 26, 2018, Princeton, NJ.

- "Scalings of Plasmoid-Mediated Current Sheet Disruption and Onset of Fast Reconnection," oral presentation in US-Japan Workshop on Magnetic Reconnection (MR2018), September 4 – 8, 2018, Princeton, NJ.
- "Scalings of Plasmoid-Instability-Mediated Current Sheet Disruption," poster presented in the 60th Annual Meeting of the APS Division of Plasma Physics, November 5 – 9, 2018, Portland, Oregon.
- "Scalings of Plasmoid-Instability-Mediated Current Sheet Disruption and Onset of Fast Reconnection," poster presented in the AGU Fall Meeting, December 10 – 14, 2018, Washington D. C.
- "Roles of Plasmoid Instability in Magnetic Reconnection and Magnetohydrodynamic Turbulence," invited talk in the 61st APS DPP Meeting, Oct. 21–25, 2019, Fort Lauderdale, Florida.
- "Scalings Pertaining to Current Sheet Disruption Mediated by the Plasmoid Instability," poster presented in the 61st APS DPP Meeting, Oct. 21-25, 2019, Fort Lauderdale, Florida.
- "The Plasmoid Instability in Partially Ionized Plasmas," oral presentation in the AGU Fall Meeting, December 9 – 13, 2019, San Francisco, California.

References

[1] L. P. Chitta, H. Peter, P. R. Young, and Y.-M. Huang. Compact solar UV burst triggered in a magnetic field with a fan-spine topology. *Astron. Astrophys.*, 605:A49, 2017.

[2] L. Comisso, Y.-M. Huang, M. Lingam, E. Hirvijoki, and A. Bhattacharjee. Magnetohydrodynamic turbulence in the plasmoid-mediated regime. *Astrophys. J.*, 854(2):103, 2018.

[3] L. Comisso, M. Lingam, Y.-M. Huang, and A. Bhattacharjee. General theory of the plasmoid instability. *Phys. Plasmas*, 23:100702, 2016.

[4] L. Comisso, M. Lingam, Y.-M. Huang, and A. Bhattacharjee. Plasmoid instability in forming current sheets. *Astrophys. J.*, 850:142, 2017.

[5] Chuanfei Dong, Liang Wang, Yi-Min Huang, Luca Comisso, and Amitava Bhattacharjee. Role of the plasmoid instability in magnetohydrodynamic turbulence. *Phys. Rev. Lett.*, 121:165101, 2018.

[6] Di Hu, Amitava Bhattacharjee, and Yi-Min Huang. Energy spectrum of tearing mode turbulence in sheared background field. *Physics of Plasmas*, 25(6):062305, jun 2018.

[7] Yi-Min Huang and A. Bhattacharjee. Turbulent magnetohydrodynamic reconnection mediated by the plasmoid instability. *Astrophys. J.*, 818:20, 2016.

[8] Yi-Min Huang, Luca Comisso, and A. Bhattacharjee. Plasmoid instability in evolving current sheets and onset of fast reconnection. *Astrophys. J.*, 849(2):75, 2017.

[9] Yi-Min Huang, Luca Comisso, and Amitava Bhattacharjee. Scalings pertaining to current sheet disruption mediated by the plasmoid instability. *Physics of Plasmas*, 26(9):092112, 2019.

[10] H. Peter, Y.-M. Huang, L. P. Chitta, and P. R. Young. Plasmoid-mediated reconnection in solar UV bursts. *Astronomy & Astrophysics*, 628:A8, 2019.