Ubiquitous Power Laws in MDH Simulations of the Solar Atmosphere

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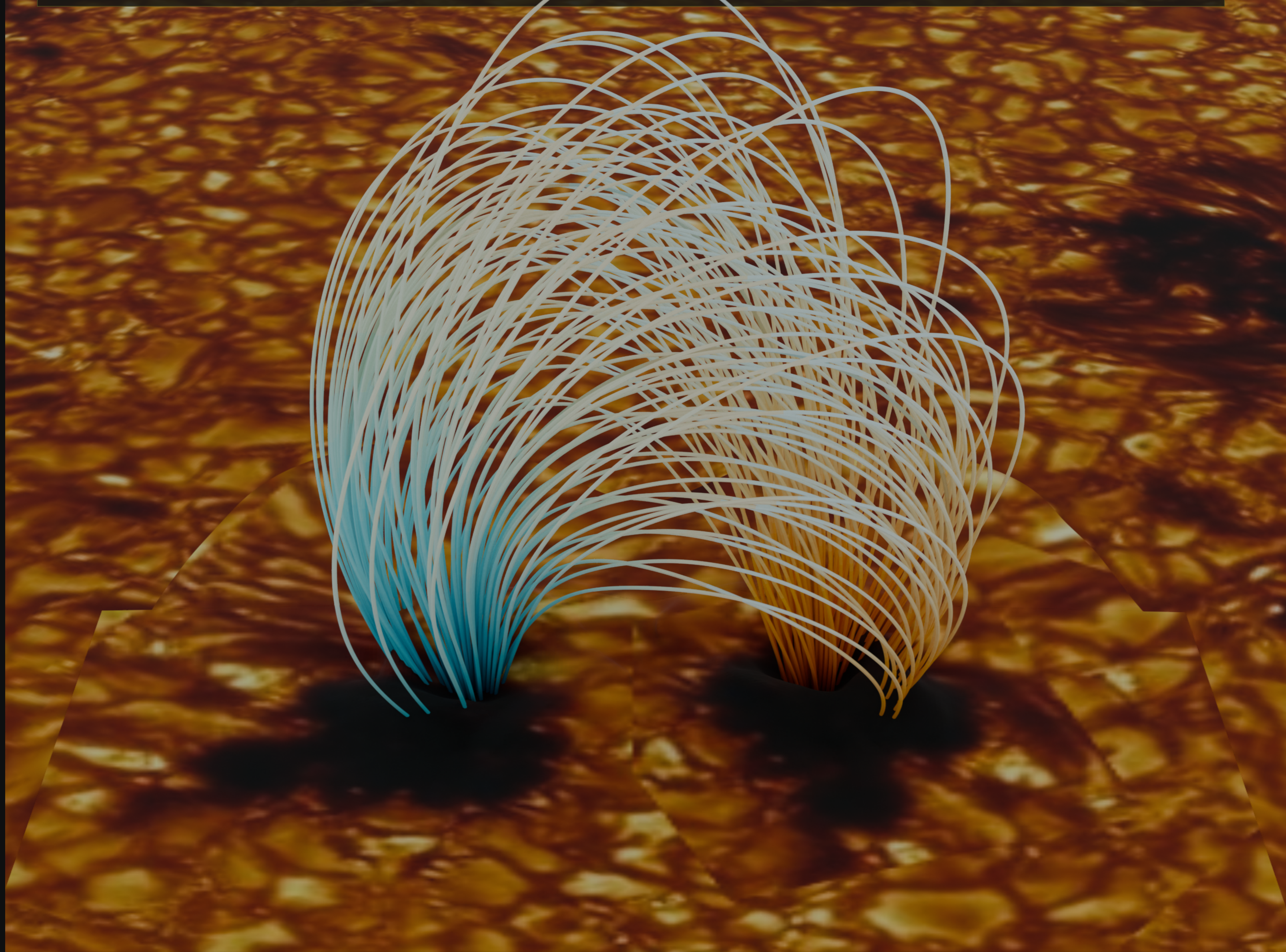
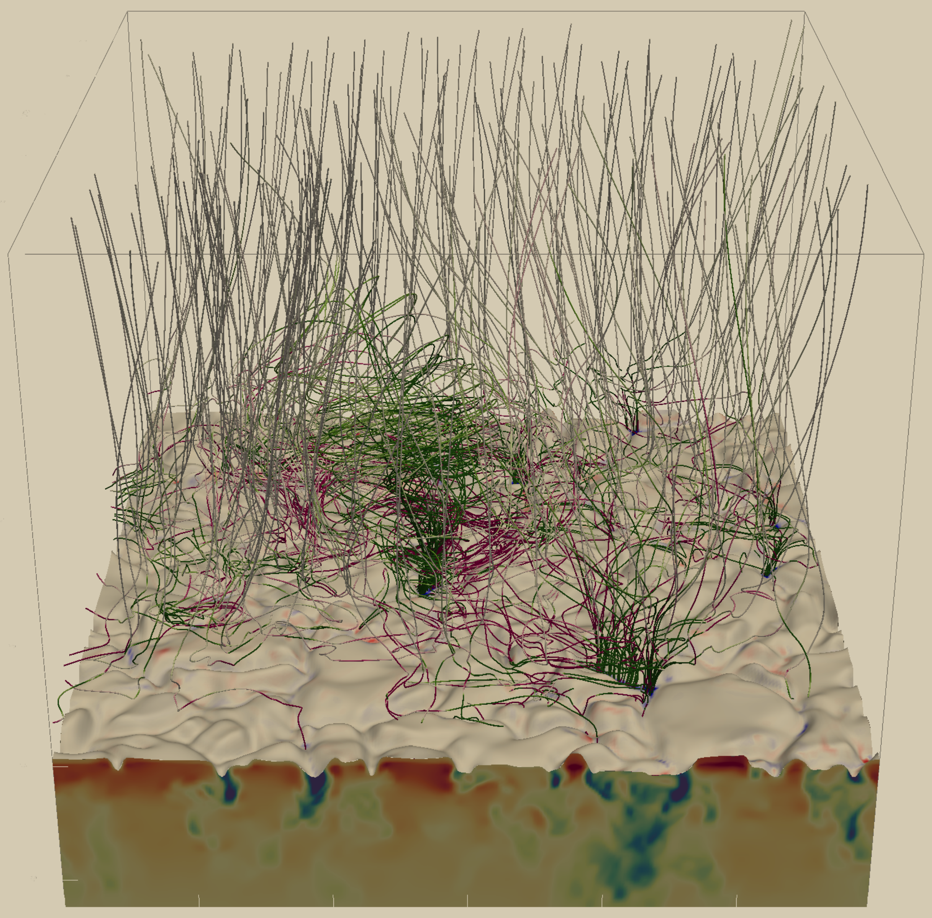
Introduction

In the past decade, MHD simulations have rapidly become more powerful and complex thanks to advances in computing power. These models are able to simulate both large and small scale processes, bringing us one step closer to understanding the physics behind magnetic reconnection as well as energy transfers in the solar atmosphere.

By analyzing the localized diffusion of magnetic energy in these cutting-edge simulations, we are able to compare them with observations as well as investigate the conditions under which magnetic reconnection occurs. In this work, we use two main sets of simulations to produce reconnection events.





(TOP) Bifrost[2] simulation (Noraz, et al. In Prep) of the quiet sun chromosphere, including both the surface of the convective zone and the beginning of a coronal-hole corona, and experiencing a network-like flux-emergence episode.

(LEFT) PLUTO[3] simulation of a magnetic dipole in a stratified atmosphere. Twist is inserted in the field via plasma rotation at the foot.

The Models

We study three setups with increasing complexity. Setup A1 (PLUTO) is a full-MHD magnetic bipole in a stratified atmosphere using a sub-grid background resistivity. Setup A2 (PLUTO) is similar except it also has a sub-grid augmented resistivity activated by a threshold on J/B. Setup B (Bifrost) is a hyperdiffusive simulation of the chromosphere exhibiting shocks and plasma turbulence.

Figure 1 shows the power law distribution of energy dissipation events for the three models and figure 2 describes the evolution of reconnection in simulation B.

Energy Dissipated by Reconnection Events

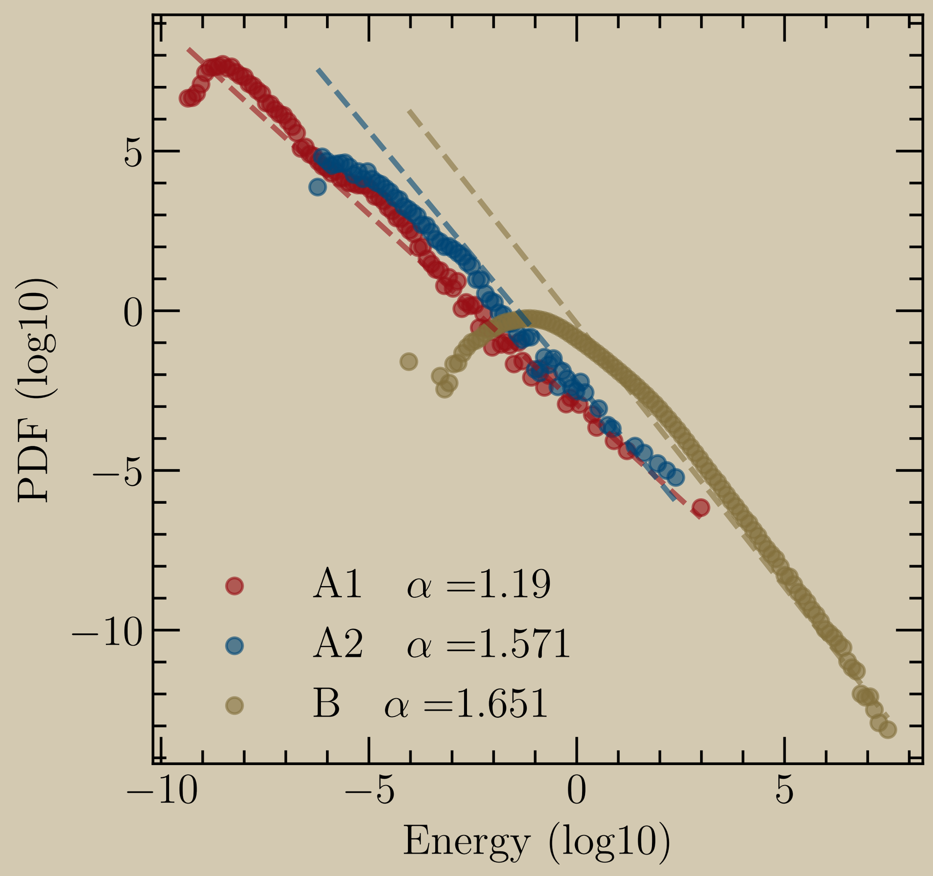


Figure 1: Frequency distribution for dissipated energies of reconnection events in three MHD simulations. A1 — PLUTO simulation with background diffusion only, A2 — PLUTO simulation with augmented diffusion and background diffusion, B — Bifrost simulation.

Statistical Methods

To identify the zones of interest, we use an algorithm[4] which identifies spatio-temporally connected clusters. After choosing a phyiscal quantity and a threshold value, we identify zones in the simulation that exceed the chosen value. These zones are labeled and tracked during the simulations. We can then compute how much magnetic energy is dissipated by each zone by summing the ohmic dissipation over its volume and lifespan. From this, we can study event statistics such as the probability distribution function (PDF) of the energy dissipated, as shown in Figure 1.

We can also study how the zones evolve. For example, we can compute spreading exponents for these simulations to learn how the zones grow and dissipate.

Spreading of the Reconnection Zones

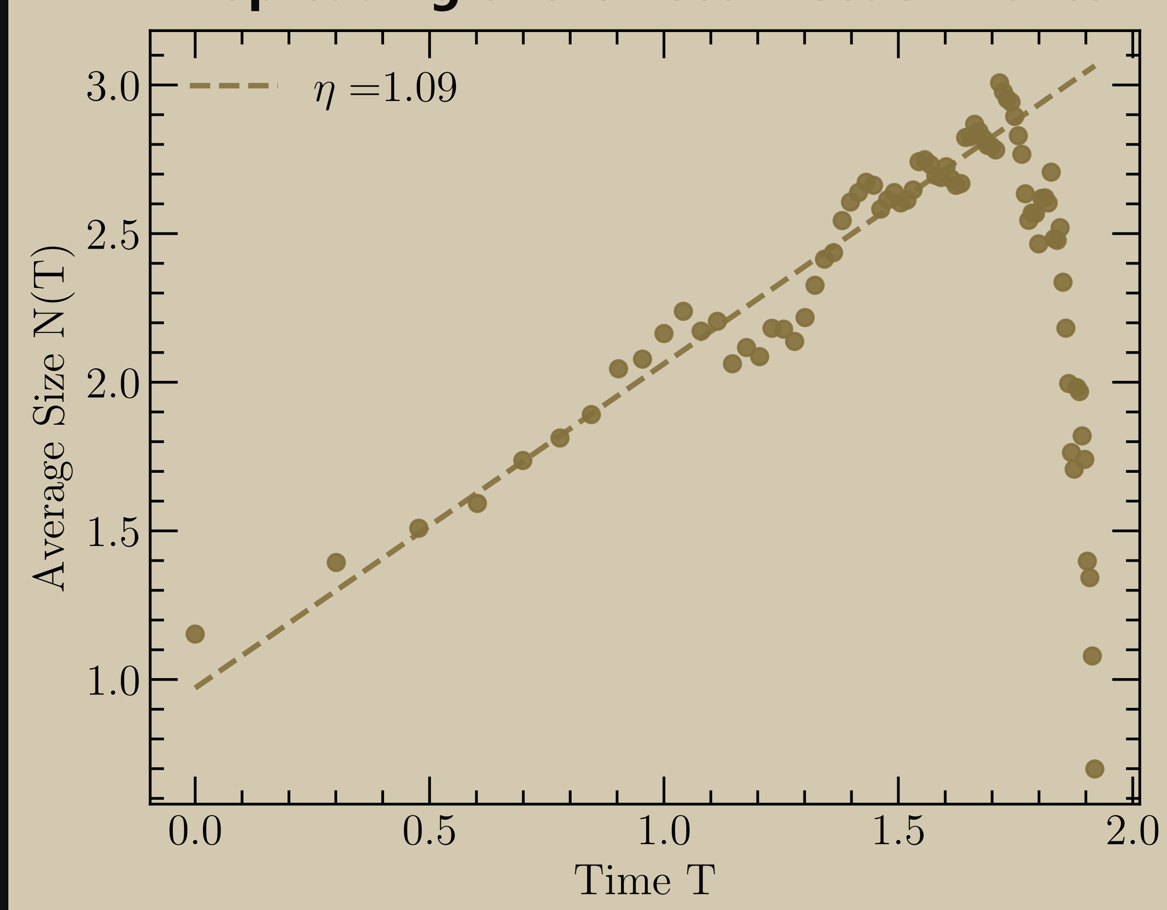


Figure 2: Ensemble average of the number of active cells in reconnection zones at each time step. A cell is considered active if it just started reconnecting (it was not reconnecting in the previous snapshot).

Discussion

Figure 1 shows that power laws in event statistics for reconnection events in MHD simulations are ubiquitous as they are found in all three setups and span multiple orders of magnitude in dissipated energy. It is very interesting to note that the more complex the setups get, the closer the power laws indexes get to the observed solar values[1] (~1.8). Indeed, activating augmented resistivity in the PLUTO yields a steeper power law index and the more complex Bifrost simulation has an even steeper one.

Figure 2 shows that reconnection events in MHD simulation are avalanche-like in that they start small on average and grow exponentially to reach a maximal size at which they diffuse magnetic energy and dissipate.

Conclusion

This study underlines the multiscale behaviour of magnetic energy dissipation in MHD simulations and suggests an interpretation of reconnection events as avalanche-like. This conjecture can be reached for very simple magnetic topologies (a reconnection twisting arcade modelled with PLUTO) as well as more complex and realistic simulations (Bifrost model of the upper convective zone, chromosphere and lower corona).

References:

1 **Aschwanden, Markus J., et al.** "Time variability of the "quiet" sun observed with TRACE. II. Physical parameters, temperature evolution, and energetics of extreme-ultraviolet nanoflares." The Astrophysical Journal 535.2 (2000): 1047.

2 **Gudiksen, Boris V., et al.** "The stellar atmosphere simulation code Bifrost-code description and validation." Astronomy & Astrophysics 531 (2011): A154.

3 **Mignone, Andrea, et al.** "PLUTO: a numerical code for computational astrophysics." The Astrophysical Journal Supplement Series 170.1 (2007): 228.

4 **Morales, Laura F., Pablo Dmitruk, and Daniel O. Gómez.** "Energy Dissipation in Coronal Loops: Statistical Analysis of Intermittent Structures in Magnetohydrodynamic Turbulence." The Astrophysical Journal 894.2 (2020): 90.