SIMULATING PLASMA TURBULENCE FROM DRIVING SCALES TO DISSIPATIVE SCALES

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PI: Kirit Makwana[1]
Co-PIs: Fausto Cattaneo[2], Fan Guo[3], Hui Li[3], and Xiaocan Li[4]
Collaborators: Vladimir Zhdankin[5] and William Daughton[5]

[1]Center for mathematical Plasma Astrophysics
[2]University of Chicago
[3]Los Alamos National Laboratory
[4]University of Alabama-Huntsville
[5]University of Colorado-Boulder

EXECUTIVE SUMMARY

Magnetized plasmas are ubiquitous in space, astrophysical, and laboratory environments. Energy is injected into them at large scales by external forcing or some intrinsic instability of the system. This energy gets transferred to smaller scales by the nonlinear interaction of the system and is ultimately converted into heat. We simulate this entire process using both magnetohydrodynamic (MHD) and kinetic (particle-in-cell) codes for different plasma parameters. We observe striking similarities between the two codes in their energy dynamics and energy spectrum. Thin, current-sheet-like, dissipative structures are formed in both codes. A statistical analysis of their morphological characteristics is performed, to reveal that their length scales with the driving scale of the turbulence. The kinetic simulation reveals that their thickness is the skin-depth scale. The dissipation is concentrated in current sheets with magnetic-field-parallel dissipation dominant at lower plasma beta. This leads to non-thermal particle energization at low plasma beta.

INTRODUCTION

Plasma turbulence is present in a variety of laboratory, space, and astrophysical plasmas. For example, the solar corona is interspersed by magnetic field lines that are constantly moving, led by their footpoint motion [1]. This motion launches Alfven waves in the corona which then reflect, interact, and produce turbulence. Turbulence cascades energy from larger to smaller scales, where it is converted into heat. This process has the potential to explain the observed heating of solar corona and solar wind [2]. Similar processes occur or are thought to occur in laboratory tokamaks, planetary magnetospheres, accretion disks, and nearly all turbulent plasmas. Understanding the turbulent cascade process and its consequential heating is thus a very important problem with numerous applications to various systems.

Past simulations have mostly utilized the MHD framework, which is applicable at macro-length scales larger than the ion gyro-radius scale. However, in typical collisionless plasmas, the conversion of turbulent energy into heat occurs due to wave-particle interactions below this scale. To understand these interactions, kinetic simulations are required. We simulated the turbulent cascade of energy using both MHD and kinetic codes. This simulation tells us whether MHD is the correct limit of plasma turbulence at macro scales, and also where MHD breaks down and kinetic physics becomes important. We were able to analyze the dissipative, current sheet structures that form in both simulations. This project helps us in characterizing turbulent energy dissipation in the solar wind and other similar plasmas, which can be further used in interpreting their observations and making predictions.

METHODS & RESULTS

We used the MHD code PLUTO [3] and the particle-in-cell code VPIC [4]. We simulated decaying plasma turbulence by specifying an initial condition and allowing the system to decay. The initial condition was an ensemble of superimposed shear Alfven waves, same for both the codes. As these waves interact, they generate turbulence, which cascades energy to smaller scales where it is converted into heat.

We found remarkably similar decay rates in both the simulations, despite the fact that the small-scale dissipation physics in the two codes is very different. Our MHD simulations relied purely on artificial numerical dissipation, whereas the PIC simulations included all kinetic processes involved in dissipation. Still, the dissipation rate was same, indicating that the dissipation scales adjust themselves to balance the rate of energy transfer arriving from larger scales. The energy spectra also matched between the two codes. This match showed that MHD simulations of turbulence produce reliable energy dynamics.

At smaller scales, important differences appear between the two descriptions. We observed the formation of current sheets in both the codes. The thickness of current sheets in MHD depends directly upon the grid-size, which is unphysical. However, VPIC correctly identifies the current sheet thickness as the skin-depth, which is a kinetic scale. We also find the generation of a significant non-thermal tail in the particle energy distribution function in VPIC at low plasma beta (ratio of thermal to magnetic energy density), as shown in Figure 1. It is observed that particle heating mainly takes place via the work done by the parallel electric field on the current density. However, this parallel electric field is not necessarily associated with reconnection.

This project shows that we can achieve a direct comparison between the MHD and fully kinetic description of plasma turbulence. It gives us the confidence that MHD simulations of turbulence produce reliable energy dynamics. Conversely, it also shows that Blue Waters and high-performance computing are now capable of reproducing MHD results from first principle, particle-in-cell simulations. This result opens up the small-scale physics of energy dissipation to the investigation by first principle codes. We can expect to unravel the mystery of collisionless dissipation in hot plasmas, which will inform us about plasma heating and particle energization in the solar corona, solar wind and in planetary magnetospheres. This discovery will help in understanding space weather and its implications for our technology which is hugely affected by space weather.

WHY BLUE WATERS

The petascale computing ability of Blue Waters was essential for carrying out this project. We used the particle-in-cell code VPIC for carrying out the kinetic simulations. VPIC is a part of the NCSA Blue Waters Sustained Petascale Performance (SPP) suite. NCSA and Cray worked to improve compiler optimization of loops not already using optimized vector compiler intrinsic functions, optimizations to eliminate extra data copies, added FMA4 compiler intrinsic functions to improve compute performance and used Cray I/O buffering functionality. Our simulations utilized a 1176x1176x1176 cell domain with 5.0E+12 particles. Blue Waters is the only system where such a large simulation can be run. The Blue Waters staff was also helpful in the data analysis and visualization. They helped us in using Paraview to visualize the data in 3D, handling and storing our data, and troubleshooting routine technical issues that came up.

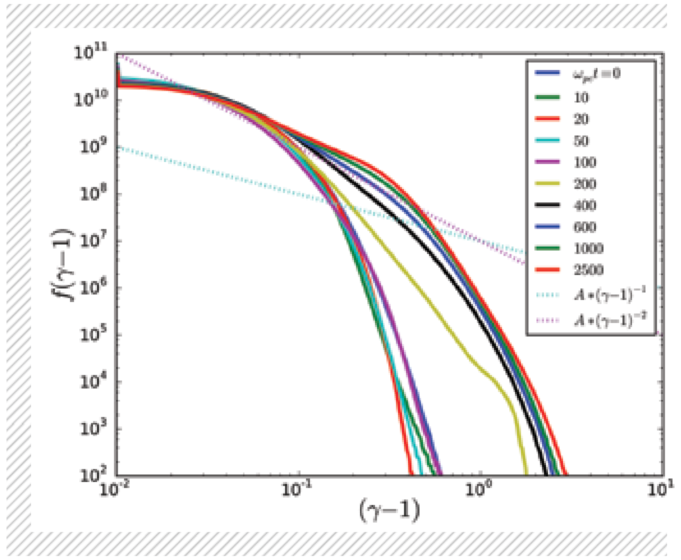

FIGURE 1: This image shows the time evolution of the particle distribution as a function of kinetic energy in a low plasma beta simulation. It begins with a Maxwellian shape initially, and particles are energized to higher energies as the turbulence dissipates with time. It develops a flattening between energies of 0.05 and 0.3, indicating a non-thermal feature.

NEXT GENERATION WORK

The next Track-1 system can help us in simulating plasmas with even lower beta, thereby giving significant non-thermal particle energization. The present system only allows simulations with an unrealistic ion to electron mass ratio of unity. The next Track-1 system can help us simulate realistic mass-ratio plasmas. These improvements will help us in studying relativistic astrophysical plasmas.

PUBLICATIONS AND DATA SETS

Makwana, K., et al., Energy dynamics and current sheet structure in fluid and kinetic simulations of decaying magnetohydrodynamic turbulence. *Physics of Plasmas*, 22 (2015), 042902.