Damping of turbulent plasmas

Kinetic damping of Alfvénic versus compressible plasma turbulence

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In Short

- Plasma turbulence spans over many scales and changes in nature from large to small scales
- Damping of turbulence is important in star formation and cosmic ray transport, but it occurs due to kinetic effects not captured in fluid simulations
- Alfvénic turbulence is incompressible whilst interstellar medium turbulence is compressible and theory predicts several critical differences between them
- Kinetic simulations are needed to verify and deepen this theory
- We propose use of a semi-implicit PIC code which is suitable for spanning a large range of scales with large time steps, making large scale 3D kinetic simulations of turbulence possible

Turbulence is omnipresent in space and astrophysical plasmas. Spacecraft measurements of the solar wind have measured the nature of turbulence in the solar wind and show a broad turbulent spectrum. These measurements also show that the fluctuations in the fast wind are often Alfvénic in nature which do not show density fluctuations, meaning that such turbulence is incompressible [1]. On the other hand density fluctuations have been observed in the slow solar wind and in interstellar medium and they also show a broad range of turbulent spectrum [2]. Therefore such turbulence is compressible. The fast and slow modes of magnetohydrodynamics (MHD) are compressible modes and so it is expected that these modes play an important role in the interstellar medium turbulence and there is mode conversion between them and Alfvén modes.

An important aspect of turbulence is its damping mechanism. Damping of turbulence is closely related with the heating of plasmas. This plays in important role in heating of interstellar as well as intergalactic medium. This also controls the star formation rate. Most space and astrophysical plasmas are collisionless in nature. This means that collective effects are more important than collisions. These are often in the form of electromagnetic waves and their interactions with plasma particles. This effect is not captured in magnetohydrodynamic (MHD) simulations, it requires kinetic simulations like particle-in-cell (PIC) methods to simulate this, which are much more computationally demanding than MHD simulations..

We have performed simulations of turbulence with MHD and PIC methods previously [3]. These simulations were large-scale 3D PIC simulations of Alfvénic turbulence setup by an initial condition of strongly interacting Alfvén waves. These were compared to MHD simulations with the same setup. We found the same damping rate in both the methods with similar turbulent spectra. The turbulence produces strong current sheets which are visualized in Fig. 1. We

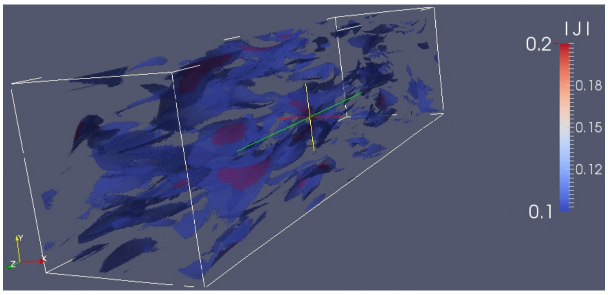

Figure 1: *An example of turbulence simulation with PIC method. The surfaces are isocontours of constant current density. We see that it forms sheet like (or pancake like) structures.*

measured the thickness of these current sheets and found them to be of the skin depth scale, which is a kinetic length scale. The turbulent spectra were also found to damp at this length scale.

Some of the drawbacks of these earlier studies is that they are limited to Alfvenic turbulence which is incompressible. These simulations generated some density fluctuations but not enough to explain turbulence in interstellar medium. Also, since this was an explicit PIC code, the simulations were limited to electron-positron plasmas (equal mass of ion and electrons), so as to reduce computational time by not having different electron and ion scales. With regards to compressible turbulence, it is expected that fast mode turbulence is damped at scales which are highly dependent on the angle of propagation. This is shown in Fig. 2. We see that the damping scale of fast mode turbulence varies greatly with propagation angle θ. This calculation is performed by taking into account kinetic physics. Therefore we can expect PIC simulations of compressible turbulence to verify this by showing angle dependent cutoff of the turbulent spectrum. Furthermore, mode conversion can convert Alfvénic modes into compressible modes at

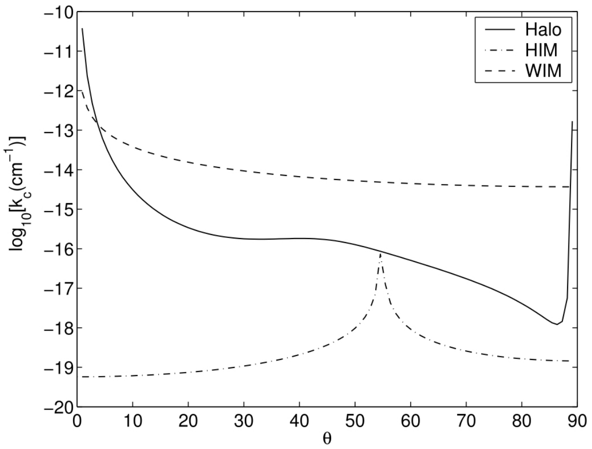

Figure 2: *Analytical calculation of the damping scale of fast modes as a function of angle θ between the wavevector $\mathbf{k}$ and magnetic field $\mathbf{B}$ in different astrophysical plasmas. Taken from Ref. [4].*

low Alfvén Mach number. This can also be studied by PIC simulations.

In this project we propose simulations with two goals

- Extend the study of PIC simulations of Alfvénic turbulence to a mass separation between electrons and ions
- Drive the simulations with fast modes to generate compressible turbulence and characterize the kinetic damping properties of fast mode turbulence compared to Alfvénic turbulence.

To overcome these difficulties we propose simulations with iPIC3D. iPIC3D is a semi-implicit moment method for PIC simulations of plasmas [5]. It solves a linearized version of the implicit Ampère's law to advance the electric field. Then the magnetic field is obtained from the induction equation and then the particles are moved implicitly. As a result of this semi-implicit scheme, iPIC3D can take larger grid spacing $(10\times - 50\times)$ and larger time steps $(5\times - 10\times)$ compared to explicit PIC codes. This code has been ported to a variety of supercomputers and shows excellent parallel scaling up to thousands of compute nodes. It has been used extensively for magnetic reconnection and turbulence studies.

Using this power of iPIC3D we propose 3D simulations of turbulence with 500^3 cells. driven in one instance by Alfvenic perturbations and in another by fast mode turbulence. These waves will be launched by giving the eigenfunctions of the dispersion relation as the initial conditions to the code. This capability has already been setup in iPIC3D. A number of simulations would be carried out varying the box-size, the resolution, the ion-to-electron mass ratio, and the Alfven Mach number. Also the injected wavenumbers profile would be varied. The first part will focus on simulations of Alfvénic turbulence as this provides a direct benchmark with previous work, while the second half will focus on the fast mode turbulence.

The analysis will involve calculation of the energy decay rate and comparing them between the Alfvénic and compressible modes turbulence. Then the power spectra would be evaluated and compared between the two. This will tell us about the kinetic damping mechanism of the turbulence. Even higher order structure functions can be computed to calculate the cascade rate and compare with theoretical predictions. Additionally, for the Alfvénic turbulence case we have the possibility of analyzing current sheets between electron and ion scales with these simulations which can then be compared with spacecraft observations of solar wind turbulence.

This project is relevant for turbulence in space and astrophysical plasmas. The kinetic damping mechanism of turbulence is the foundation of many theories of plasma heating and cosmic ray propagation. This project will provide a firm foundation to these theories.

WWW

http://www.uni-potsdam.de/astroparticle/plasmaastrophysik.html

More Information

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Project Partners

Deutsches Elektronen-Synchrotron (DESY), Zeuthen

Funding

This project is funded by the base funds that Prof. Dr. H. Yan received from the DESY institute on her dual appointments as leading scientist at the institute and as professor at the University of Potsdam.