KINETIC SIMULATIONS OF LARGE-SCALE PLASMA TURBULENCE

Allocation: NSF PRAC/3,850 Knh
PI: Vadim Roytershteyn[1]
Co-PIs: Yuri Omelchenko[1], Kai Germaschewski[2]
Collaborators: John Podesta[1], William Matthaeus[3]

[1]Space Science Institute
[2]University of New Hampshire
[3]University of Delaware

EXECUTIVE SUMMARY

This project seeks to gain a better understanding of turbulence in hot rarified plasmas typical of space and astrophysical environments. Specifically, we use large-scale kinetic simulations tracking upwards of a trillion particles at a time to analyze how the energy of turbulent motions is dissipated in such plasmas. The insights generated by the project may explain such long-standing puzzles as the properties and origins of the solar wind or the anomalously high temperature of the solar corona.

RESEARCH CHALLENGE

Plasma turbulence plays a significant role in the dynamics of many systems in the universe, from laboratory fusion experiments, to the Sun, and to astrophysical objects such as accretion disks. While parameters, geometry, and some aspects of the physics may differ among these systems, there is also a large degree of universality, which makes understanding plasma turbulence a grand challenge problem relevant to many fields of study. This project seeks to conduct simulations of plasma turbulence using codes that are capable of faithfully describing microscopic physical effects. This is important since plasma turbulence is a truly multiscale phenomenon, where the very nature of physical processes governing dynamics changes with scales. For example, in plasmas that are sufficiently hot and not too dense (as is typical of space and astrophysical systems), processes operating at small scales determine the ultimate fate of the turbulent energy. Depending on which of the many possible processes dominates, the energy could be transferred to different species (e.g., electrons, protons, or heavier ions), or to distinct populations of the same species. Understanding these issues may help advance our knowledge of the systems where turbulence operates. For example, both the solar wind and the solar corona are significantly hotter than can be explained with simple models, with local heating by turbulence often proposed as one of the likeliest explanations.

METHODS & CODES

The most complete description of the plasmas of interest is provided by the Vlasov–Maxwell equations, a six-dimensional system of partial differential equations. In order to solve these equations, we use the particle-in-cell technique, where plasma is represented as a collection of particles while equations describing electromagnetic fields are solved on a grid. A typical large-scale simulation can simultaneously track upwards of a trillion particles in order to obtain reliable statistics. This requires petascale computational resources, such as Blue Waters. Some of the simulations performed in this project were guided by and directly compared against observations conducted by the WIND spacecraft in the solar wind.

RESULTS & IMPACT

During the first year of the project, we have mainly targeted two problems: study of current sheet formation in large-scale simulations with conditions modeling solar wind and the so-called selective decay problem.

Solar wind is a stream of plasma, emitted by the Sun, which fills interplanetary space. Interaction of the solar wind with the Earth's magnetic field gives rise to the Earth's magnetosphere and its complex dynamical behavior, often referred to as "space weather." Space weather has a significant impact on us: For example, extreme solar events may affect or damage the power grid and communication satellites. Understanding of the solar wind in general and its turbulence in particular may help develop better models that improve our ability to understand and forecast space weather. Moreover, thanks to the measurements performed by multiple spacecraft operating in the solar wind, it is the best-studied example of large-scale plasma turbulence, making it also very interesting from the perspective of basic research.

While considerable progress has been made, many puzzles remain. One of them concerns identifying specific mechanisms responsible for conversion of turbulent energy into thermal energy (heat) and energetic particles. In typical space plasmas, collisions between particles are relatively rare and cannot provide sufficient randomization, as would be the case in fluid or regular gases. The relevant theoretical ideas focus on collective processes that invoke interaction of charged particles with electromagnetic fields. These processes are thought to operate most efficiently in the regions where the magnetic field is highly sheared. Geometrically, these regions typically resemble sheets or strings embedded in the plasma and are referred to as the current sheets. Due to their small transverse scale, which often approaches internal plasma scales, the dynamics of current sheets inherently depend on microscopic (kinetic) physics.

On the other hand, the large-scale motions in plasma form current sheets. Thus, in order to satisfactorily describe the dynamics of current sheets, simulations need to resolve a large range of scales and include the relevant microscopic physics. We have conducted simulations using a hybrid approximation that treats heavier species in plasma (e.g., protons) using a first-principle kinetic formulation, while representing lighter electrons using an approximate fluid model. The simulations were initialized with conditions modeling solar wind plasma and were directly compared against spacecraft observations. The results were in remarkable agreement with observations [1], indicating that the hybrid model can properly describe dynamics of current sheets at scales comparable to proton kinetic scales. A detailed characterization of the current sheets was performed as the first step necessary to identify the physical processes responsible for their formation and evolution. Ultimately, this will help advance understanding of energy dissipation mechanisms in the solar wind.

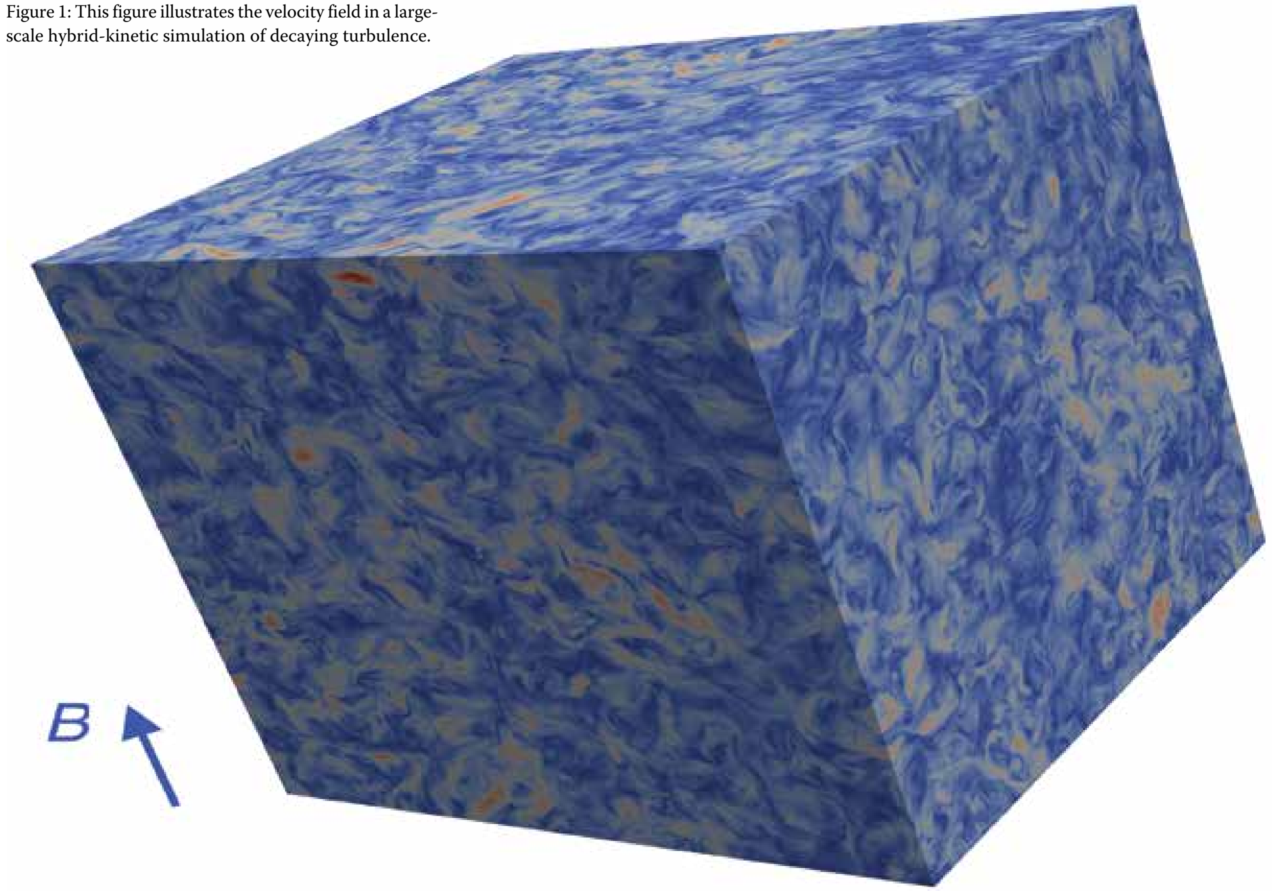

Figure 1: This figure illustrates the velocity field in a large-scale hybrid-kinetic simulation of decaying turbulence.

The second problem considered in the project concerns the problem of selective decay in kinetic plasma. Broadly speaking, the concept of selective decay is the notion that a turbulent system decays toward special states that, somewhat counterintuitively, are characterized by a high degree of correlation among various quantities. A large body of existing work investigated these issues within the framework of a macroscopic approximation known as the magnetohydrodynamcs (MHD) model. In the more complete kinetic model used in the present study, some of the inherent symmetries of MHD are broken, which may lead to significant differences between predictions of MHD and the kinetic models for decay toward certain states. Fig. 1 demonstrates a turbulent field in one of the simulations conducted for the study. While a full analysis of the results is ongoing, preliminary results point to substantial differences with existing predictions, possibly signaling previously unappreciated significance of microscopic physics for global evolution.

WHY BLUE WATERS

The simulations needed to address the scientific questions of this project solve a global problem that cannot be split into a series of smaller simulations. As such, they require large memory, fast on-node computation, and fast internode communications. For this reason, they require an HPC resource like Blue Waters and cannot be conducted on cloud resources.

PUBLICATIONS AND DATA SETS

Podesta, J. J., and V. Roytershteyn, The most intense electrical currents in the solar wind: Comparisons between single spacecraft measurements and plasma turbulence simulations. *J. Geophys. Res. Sp. Phys.* (2017), DOI: 10.1002/2017JA024074.