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KINETIC SIMULATIONS OF PLASMA TURBULENCE

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EXECUTIVE SUMMARY

Our 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 the majority of situations encountered in space and in 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 a distinct population of the same species (e.g., the thermal part of the distribution or the energetic particles). An understanding of these issues may help advance our knowledge of systems where turbulence operates. For example, both the solar wind and the solar corona are famously known to be significantly hotter than could be explained with simple models, with local heating by turbulence often proposed as one of the likeliest explanations.

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 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.

METHODS & CODES

The most complete description of the plasmas of interest is provided by so-called Vlasov–Maxwell equations, a six-dimensional system of partial differential equations. In order to solve these equations, we use two complementary approaches. One is the well-known particle-in-cell (PIC) technique, which represents plasma as a collection of computational particles, while equations describing electromagnetic fields are solved on a computational grid. A typical large-scale simulation can simultaneously track upwards of a trillion particles in order to obtain a reliable statistical description. This requires a petascale computational resource such as Blue Waters. In this work, we use VPIC: a general-purpose, high-performance plasma simulation code.

While PIC simulations have been quite successful in describing many microscopic physical phenomena, they also have a number of well-recognized limitations. For example, particle methods tend to have low accuracy or, more precisely, slow convergence rates associated with a finite number of particles per cell. To overcome these limitations, we investigated another approach based on fully spectral decomposition of the plasma species distribution function in the phase space. We use the code SpectralPlasmaSolver (SPS), developed in collaboration with Los Alamos National Laboratory. SPS uses dual Fourier–Hermite bases, is fully implicit, and possesses exact conservation laws for long-term, accurate simulations.

RESULTS & IMPACT

During the last year, we focused the investigation on characterizing kinetic plasma turbulence in the regimes where the ratio of plasma internal energy to the magnetic energy density (the so-called plasma parameter β) is small. Such regimes are encountered, for example, in the solar corona, the Earth's magnetosheath, interplanetary coronal mass ejections, regions downstream of collisionless shocks, hot accretion flows, and elsewhere.

In the summer of 2018, NASA will launch a revolutionary spacecraft mission—the Parker Solar Probe (PSP)—a "NASA mission to touch the Sun." PSP will pass as close as 9.8 solar radii from the Sun's surface, providing measurements that are expected to revolutionize our understanding of the solar corona and the solar wind, and will eventually lead to better models of space weather. There exists an urgent need to develop theoretical models and computational tools that correctly treat plasma turbulence in the regimes to be encountered by PSP.

Meanwhile, the majority of prior investigations of kinetic processes in turbulence focused on the regimes with β order unity, which is typical of the solar wind at the distances corresponding to the Earth's orbit. Recent theoretical analyses suggest that kinetic plasma turbulence is strongly modified under the parameters expected to be encountered close to the Sun, relative to solar wind turbulence at the Earth's orbit [1,2]. This change in the nature of fluctuations affects many of the practically important processes, such as the mechanisms of energy dissipation. Using a combination of 3D SPS and 2D VPIC simulations, we have been able to confirm the existence of this new regime of plasma turbulence. Statistical properties of the turbulence measured in the simulations agree well with the theoretical predictions. These results are summarized in a publication submitted to the *Astrophysical Journal* [3].

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 a high-performance computing resource like Blue Waters and cannot be conducted on cloud resources.

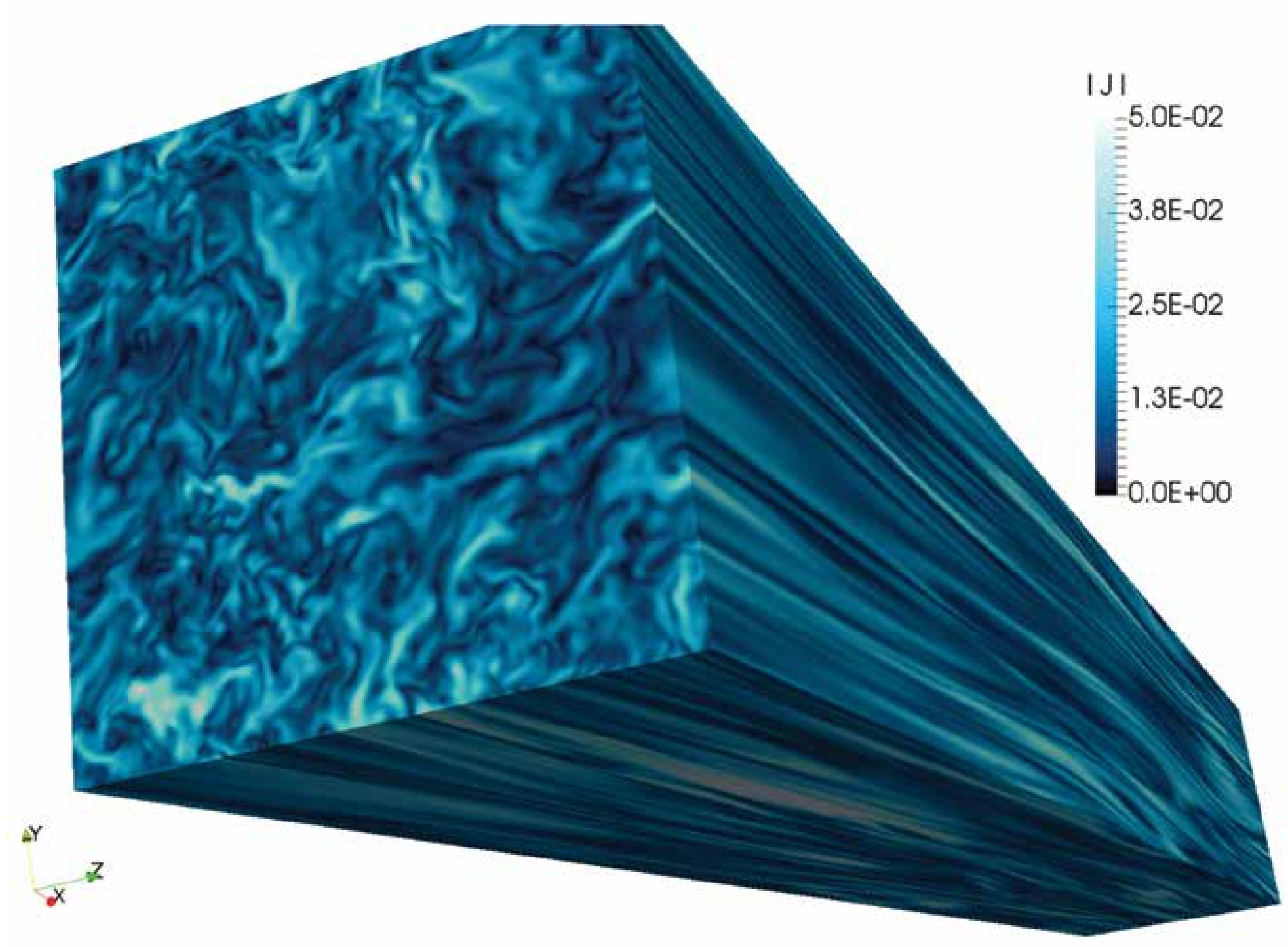

Figure 1: Visualization of small-scale structure in kinetic plasma turbulence. The simulation was conducted using a newly developed version of spectral, fully implicit code SPS [4].

PUBLICATIONS & DATA SETS

Roytershteyn, V., and G.L. Delzanno, Spectral Approach to Simulations of Kinetic Phenomena in Plasmas Based on Hermite Decomposition in the Velocity Space. *Frontiers in Astronomy and Space Sciences*, submitted (2018).

Roytershteyn, V., et al., Numerical Study of Inertial Kinetic–Alfvén Turbulence. *Astrophysical Journal*, submitted (2018).