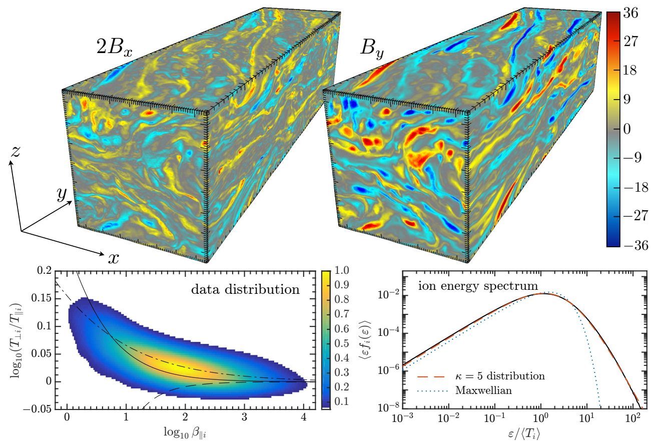
Magnetorotational Turbulence and Dynamo in a Collisionless Plasma

The Science

Many astrophysical plasmas are so hot and diffuse that the collisional mean free path is larger than the system size. Perhaps the best examples of such systems are low-luminosity accretion flows onto black holes such as Sgr A* at the center of our Galaxy. Theoretical models of these accretion flows are largely based on magnetohydrodynamics, sometimes extended to mimic plasma-kinetic effects such as magnetic-field-aligned viscosity and conduction. While these extensions have been recognized as crucial for capturing the correct dynamics, they require *ad hoc* assumptions about the role of microscopic kinetic instabilities (firehose, mirror) in regulating the transport properties. These assumptions affect the outcome of the calculations, and thus ought to be tested using more fundamental models.



In a recent paper highlighted in PRL [1], this is precisely what we have done. We have conducted the first 3D kinetic numerical simulation of magnetorotational turbulence and dynamo in a collisionless accretion disk. The magnetorotational instability grows from a subthermal magnetic field having zero net flux over the computational domain to generate self-sustained turbulence and outward angular-momentum transport. Significant Maxwell and Reynolds stresses are accompanied by comparable viscous stresses produced by field-aligned ion pressure anisotropy, which is regulated primarily by the mirror and ion-cyclotron instabilities through particle trapping and pitch-angle scattering. The latter endow the plasma with an effective viscosity that is biased with respect to the magnetic-field direction and spatiotemporally variable. Energy spectra indicate an Alfvén-wave cascade at large scales and a kinetic-Alfvén-wave cascade at small scales, with strong small-scale density fluctuations and weak nonaxisymmetric density waves. Ions undergo nonthermal particle acceleration, their distribution accurately described by a kappa distribution.

The Impact

Our work provides an *ab initio* kinetic foundation for recent efforts to include kinetic effects into the equations of general relativistic magnetohydrodynamics for studies of black-hole accretion [2,3], as well as for the pioneering fluid simulations of magnetorotational turbulence in a collisionless plasma by Sharma et al. [4]. The theory of black-hole accretion is central to many areas of theoretical, computational, and observational astronomy. Not only does accretion power some of the phenomenologically richest electromagnetic sources in the Universe, but also black-hole accretion flows serve as excellent laboratories for the study of basic plasma dynamics and general relativity. Accurate modeling of these systems is required for the interpretation of the observed X-ray, infrared, and millimeter emission, as well as for maximizing the scientific output of the next generation of gravitational wave observatories by identifying electromagnetic counterparts to gravitational-wave sources. More fundamentally, black-hole accretion is a challenging testbed for our understanding of how magnetized plasmas behave in extreme environments, and how the free energy stored in a differentially rotating plasma is converted into kinetic, magnetic, and non-thermal energy.

References: [1] M. W. Kunz, J. M. Stone, and E. Quataert, Phys. Rev. Lett. **117**, 235101 (2016); [2] M. Chandra, C. F. Gammie, F. Foucart, and E. Quataert, Astrophys. J. **810**, 162 (2015); [3] F. Foucart, M. Chandra, C. F. Gammie, and E. Quataert, Mon. Not. R. Astron. Soc. **456**, 1332 (2016); [4] P. Sharma, G. W. Hammett, E. Quataert, and J. M. Stone, Astrophys. J. **637**, 952 (2006)

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