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Unveiling Fast-Mode Turbulence: Cascade Dynamics and Mode Conversion

Our research investigates the cascade properties of fast-mode magnetohydrodynamic (MHD) turbulence in compressible plasmas, which play a crucial role in cosmic ray scattering and acceleration. Fast modes are known to scatter cosmic rays much more efficiently than Alfvén modes, yet the dynamics behind their energy transfer remain under-explored. To address this gap, we conduct high-resolution, isothermal, 3D MHD simulations of fast mode turbulence in magnetized plasmas. These simulations allow us to probe the complete energy cascade—from large-scale injection to the small-scale dissipative regime.

Fast-mode turbulence in our study is generated via isotropic wave-vector injection. This approach ensures a homogeneous forcing mechanism that minimizes the contamination by other MHD modes. We analyze the energy cascade using both 1D and 2D energy spectra to characterize the energy distribution across scales. In addition, we compute 2D structure functions to assess the isotropy of the cascade relative to the mean magnetic field, providing simultaneous insights into global energy transfer and local statistical properties.

We examine the cascade rate by tracking the nonlinear energy transfer through temporal decay of turbulent energy at the different scales. We further explore the dependence of this cascade on plasma β. Our results are tested against the expected scaling behavior of an acoustic cascade, which is proposed to be the case for fast modes. This also provides important clues about the interactions and energy transfer between the different MHD modes. This is tested further through mode decomposition of the velocity and magnetic field data from the simulations to understand the conversion of fast modes into other MHD modes.

Overall, our work provides a detailed quantitative analysis of fast-mode turbulence, offering new insights into energy dissipation, isotropy, and the broader implications for cosmic ray propagation in high-energy astrophysical settings.

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