Unraveling Fast Mode Mysteries in magnetized turbulence

Investigating Fast mode isotropy, spectrum and energy cascade in compressible magnetohydrodynamic turbulence

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In Short

- **Investigating Fast Mode Dynamics**: This project aims to explore the properties of fast MHD modes, such as isotropy and energy cascade characteristics, through high-resolution numerical simulations, shedding light on their role in turbulence and energy dissipation.
- **Analyzing Energy Transfer Mechanisms**: By simulating interactions between MHD modes, the project seeks to understand the rapid energy transfer dynamics within magnetized plasmas, which influence stability and plasma behavior.
- **Advancing Astrophysical Applications**: The findings will contribute to improved theoretical models for applications in cosmic ray scattering and transport, enhancing predictive capabilities for plasma dynamics in various astrophysical environments.

The motivation for this project stems from earlier studies and simulations that revealed intriguing, yet not fully understood, phenomena. In particular, simulations with lower numerical resolution highlighted rapid energy transfer between MHD modes, prompting further investigation (see appendix of Pavaskar et al. 2024). These initial findings, while significant, were limited by the computational resources available at the time, resulting in a need for more detailed, higher-resolution and higher-order studies to fully understand the underlying processes. By leveraging state-of-the-art supercomputing resources, this project aims to overcome the limitations of the previous works. High-resolution higher-order simulations will allow for a more detailed analysis of the fast mode mode isotropy and energy transfer mechanisms, providing deeper insights into MHD turbulence.

The fast MHD mode is defined by rapid compressional waves that propagate faster than both the Alfvén and slow modes. Under ideal plasma conditions, fast mode waves exhibit an isotropic energy cascade. However, real-world plasmas typically display non-ideal effects due to magnetic field configurations, boundary conditions, and external forces. Studies have shown that these anisotropies can significantly influence plasma behavior, impacting wave propagation, energy distribution, and turbulence characteristics (Makwana & Yan 2020). Understanding these anisotropic effects is essential for applications in astrophysics, such as investigating the solar wind and understanding cosmic ray transport (Yan & Lazarian 2002, 2004, 2008) in turbulent media.

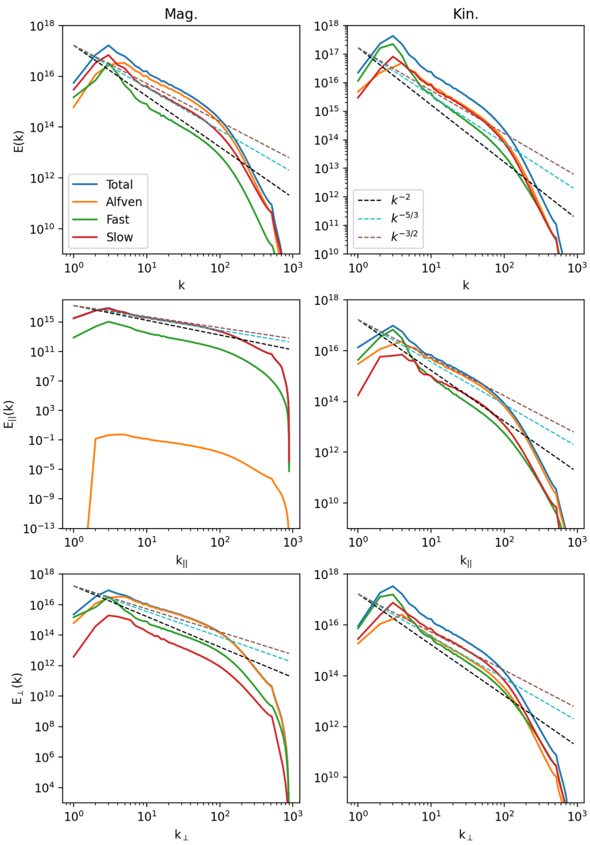

Figure 1: *Energy spectra of three linear MHD modes and the total magnetic and velocity fields calculated from an isothermal 3D ideal MHD simulation. The left and right panels show the magnetic and kinetic energies respectively. The top row shows the 1D spectra.The middle and bottom rows show the spectra in the parallel and perpendicular direction with respect to the magnetic field.*

This project aims to conduct a detailed investigation of fast MHD mode properties, focusing on mode isotropy and the energy cascade through high-resolution numerical simulations. Fig. 1 shows an example spectrum of the three linear MHD modes calculated from an earlier simulation, showcasing curious spectrum slopes which require further investigation. Another key focus will be exploring the energy transfer between linear MHD modes within

3D MHD simulations. Turbulence in magnetized plasmas often involves nonlinear interactions among these modes, and prior simulations at lower resolutions have highlighted intriguing phenomena, including rapid energy transfer between modes during turbulence evolution and energy saturation. These preliminary results suggest that substantial energy exchanges may occur, potentially affecting plasma stability and dynamics. Fig. 2 shows the time evolution of the magnetic energies of linear MHD modes.

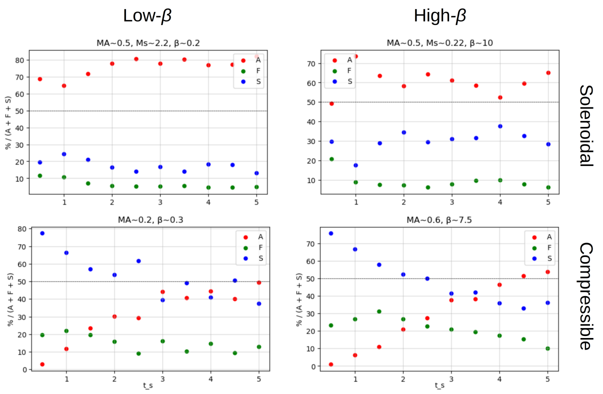

Figure 2: *The time evolution of the magnetic energies of the linear MHD modes from four isothermal 3D ideal MHD simulations with different driving mechanisms and plasma-β.*

In MHD turbulence, energy typically cascades from larger to smaller scales, where dissipation occurs. The specific nature of this cascade, as well as the roles played by different MHD modes, remains an active area of research. By utilizing high-resolution, higher-order simulations, this project seeks to examine these energy transfer mechanisms in greater depth. Gaining insights into these interactions is crucial for developing more accurate theoretical models of plasma turbulence, ultimately enhancing our understanding of fundamental plasma processes and improving predictive capabilities for plasma behavior.

We will divide our investigation into two parts. The primary goals of this project are to investigate the fast-mode energy spectrum, cascading behavior, and isotropy across various low-β environments. We plan to compute high-resolution compressible turbulence simulations. The goal is to investigate the fast mode energy spectrum and isotropy, as well as their dependence on plasma-β across various magnetized environments. Further, this project aims to extend the simulations of decaying fast-mode turbulence to three dimensions. Implementing higher-order spatial and temporal solvers will enhance simulation accuracy, allowing us to gain insights into the rate and properties of the fast-mode energy cascade. This extension will also provide a clearer understanding of the differences between balanced and imbalanced fast-mode cascades, with a specific focus on how these configurations affect turbulence dissipation and isotropy across the inertial range.

More Information

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Project Partners

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DFG Subject Area

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