Energetic particles in compressible turbulence

Simulations of Compressible Intermittent Turbulence and Energetic Particle Transport

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In Short

- We aim to simulate compressible turbulence driven by fast waves and investigate its interaction with energetic particles.
- Understanding this turbulence and its impact on energetic particle transport will improve our knowledge of energy dissipation mechanisms and particle acceleration.
- Using VPIC simulations, we will analyze the energy cascade, dissipation rates, and the role of turbulence intermittency in scattering and transporting energetic particles.
- We will quantitatively assess particle transport in different turbulence conditions, compare our results with spacecraft measurements, and advance our understanding of energetic particle diffusion in the heliosphere and interstellar medium.

Since Victor Hess's pioneering work on cosmic rays in 1912, significant progress has been made in understanding their origins, acceleration mechanisms, and scattering processes (see, e.g. [1, 2]). Depending on their source, energetic particles could be classified into three parts. Outside our heliosphere, galactic cosmic rays source from the Galaxy with a energy range of $10^9 \sim 10^{20}\mathrm{eV}$. Within our heliosphere, solar energetic particles ($10^4 \sim 10^9\mathrm{eV}$) originate from the solar transient activities. At the heliosphere boundary, anomalous cosmic rays ($\sim 10^8\mathrm{eV}$) are thought to be the charged interstellar neutral atoms and accelerated at the heliosphere boundary.

Various spacecrafts, including Parker Solar Probe (PSP), Solar Orbiter, Cluster, and Voyagers, have provided in-situ measurements from regions close to the Sun (~ 10 solar radii) to the interstellar medium beyond the heliosphere. These observations consistently demonstrate the turbulent space plasma environment, particularly compressibility and intermittency. Such turbulent conditions significantly influence the propagation processes of energetic particles and cosmic rays[3, 4]. In particular, compressible turbulence significantly alters cosmic ray diffusion by modifying magnetic field topology [5] through mechanisms such as transit-time damping. As an essential component, fast wave modes could contribute more to scattering cosmic rays than Alfvén wave and slow modes [1]. Turbulence intermittency, being scale-dependent and characterized by spatially inhomogeneous energy distribution, further intensifies these effects due to the reason that intermittency can create low-magnetic-field regions that temporarily trap energetic particles and enhance local scattering rates. Therefore, a more quantitative properties of compressible turbulence will be the foundation for further study on energetic particle transport.

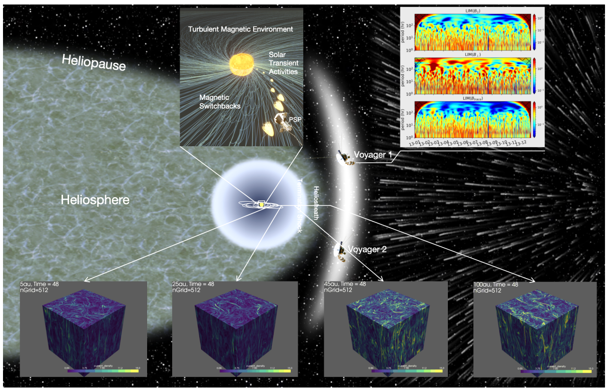

Figure 1: *Based on our previous works[6], a summary diagram integrating simulations and spacecraft measurements of turbulence in our heliosphere and the local interstellar medium to study the interaction with the energized particles. Turbulence simulation and Local Intermittency Measure (LIM) at different heliocentric distances are based on the measurements from Voyager spacecrafts. In this project, we aim to using VPIC simulations to further show the interaction between compressible turbulence and energetic particles.*

In this project, we have following goals:

The Impact of Compressible Turbulence on Energetic Particle Transport

Turbulence at the MHD scale is primarily dominated by three wave modes: Alfvén waves and fast and slow magnetosonic waves. The energy cascade of Alfvénic and slow-mode turbulence are similar, showing anisotropic cascades in weak turbulence environments that preferentially cascade along the perpendicular direction. In contrast, the cascade in fast-mode turbulence is nearly isotropic [7]. Therefore, fast mode can more effectively scatter energetic particles. In this project, we will exclude the influence of Alfvén waves and slow waves in turbulence, focusing solely on the turbulent energy cascade and dissipation caused by fast waves. To achieve this, we will first adjust the number of fast waves propagating in different directions in the initial state and compare the energy cascade rate and dissipation rate. The aim is to verify the turbulence power spectrum predicted by previous theories. Additionally, at the MHD scale, fast wave turbulence can excite shocks or accelerate particles through wave-particle resonance. Investigating which mechanism dominates under different initial conditions and turbulence states warrants further study.

The Impact of Turbulence Intermittency on Energetic Particle Transport

Turbulence intermittency, as an inevitable result of turbulent evolution, induces strong local magnetic fluctuations, leading to stronger scattering and lower streaming speeds for energetic particles. Therefore, inhomogeneous intermittency may enhance the local clustering of energetic particles, altering their energy spectra and spatial distribution. However, the specific contribution of different type of intermittent structures on energetic particle scattering has yet to be validated and improved through sufficient simulation. In this project, we plan to explore the key parameters controlling the types of intermittent structures (e.g., shocks, rotational discontinuities, current sheets, and vortex structures), their generation rates, and volume-filling factor of intermittent structures. Hence, we could quantitatively analyze the energetic particle transport, e.g. scattering rate, streaming speed, mean free path, spatial distribution, in intermittent turbulence.

Work package 1 To achieve the objectives of understanding the interaction between compressible turbulence and energetic particles, we plan to use the hybrid particle-in-cell (hybrid PIC) simulation code to perform three-dimensional simulations. In these simulations, electrons will be treated as fluid, while energetic ions will be treated as particles. The code is efficient in resolving particle dynamics while requiring relatively low computational resources. The grid is initially set to $1024 \times 1024 \times 1024$ cells and 300 particles per cell. We introduce initial magnetic field and electric field fluctuations that follow the polarization of fast wave modes. Periodic boundary conditions are applied to both fields and particles.

Work package 2 All numerical data will be post-processed and visualized using Python. Similar to the processing methods used for in-situ spacecraft measurements, we will sample the simulation data and apply spectrum-analysis techniques.

The power spectral density (PSD) will be calculated to reveal the turbulence energy distribution in wave-vector space. The time evolution of energy at each wave-vector will also be analyzed to determine the energy cascade rate and cascade time. A multi-dimensional wavelet transform will be used to investigate the dissipation properties of individual waves in the turbulence, enabling us to calculate the phase speed for each wave.

Additionally, we will visualize the 3D spatial distribution of energetic particles and calculate key parameters such as the mean free path and velocity. The velocity of energetic particles will be compared with the wave phase speed to evaluate whether they satisfy the wave-particle resonance condition. This analysis will help identify the dominant energy transfer mechanisms, including Landau resonance, transit-time damping, and shock acceleration.

WWW

http://www.unipotsdam.de/astroparticle/plasmaastrophysik.html

More Information

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Project Partners

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