Radial Evolution of Turbulent Fluctuations Near Sun Using Parker Solar Probe and Solar Orbiter Measurements

Monika Karki[1], Gary P. Zank[1], Ben Altermann[2] and Laxman Adhikari[1]

[1]*Department of Space Science and CSPAR, University of Alabama in Huntsville, Huntsville, AL, 35899, USA*

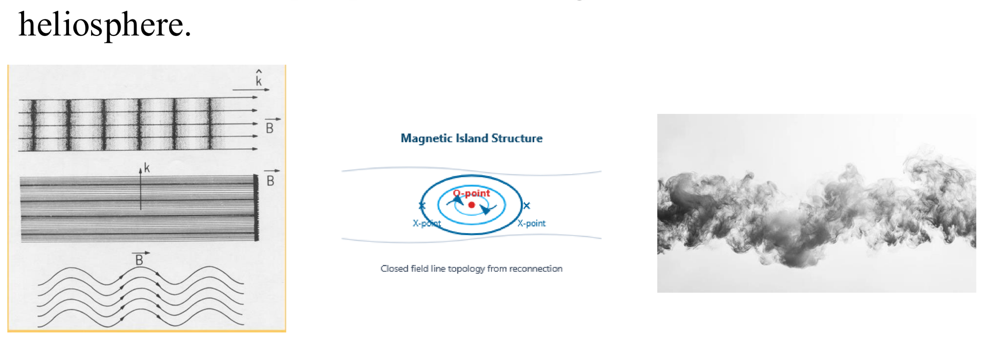
[2]*NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

Abstract

We investigate the radial evolution of the turbulent fluctuations in the inner heliosphere using Parker Solar Probe and Solar Orbiter observations over heliocentric distances of ~ 32 to 90 solar radii. We decomposed the measured fluctuations of density, velocity, and magnetic field into eight fundamental magnetohydrodynamic modes using the linear mode decomposition technique. The mode-resolved energy result shows that the fluctuation energy is highly field-dependent: velocity fluctuations are primarily Alfvénic, with both forward and backward Alfvén modes exhibiting relatively shallow radial decay, whereas magnetic fluctuations are dominated by transverse nonpropagating incompressible/magnetic-island-like components. In contrast, density fluctuations are mainly governed by fast magnetosonic modes, while entropy and slow magnetosonic contributions remain comparatively weaker and decay more rapidly with heliocentric distance. We find that the variance anisotropy of the transverse magnetic-island mode and the Alfvén modes increases slightly with heliocentric distance.

Introduction

Understanding the composition and propagation characteristics of magnetohydrodynamic (MHD) field changes in solar wind plasmas is essential to improving our knowledge of the solar wind's heating and acceleration [1-3] and assessing radiation hazards in the heliosphere.



Research Objectives

To understand the physical nature and detail composition of turbulent fluctuations in the solar wind.

1. How do the individual linear modes evolve with heliocentric distance?
2. Do fast, slow, entropy-like, and coherent magnetic-structure modes become more significant as the solar wind increases, or is the turbulent energy mostly conveyed by outward and inward Alfvénic modes?
3. How does the relative power contribution of each mode change as the solar wind expands away from the Sun?

Data Overview

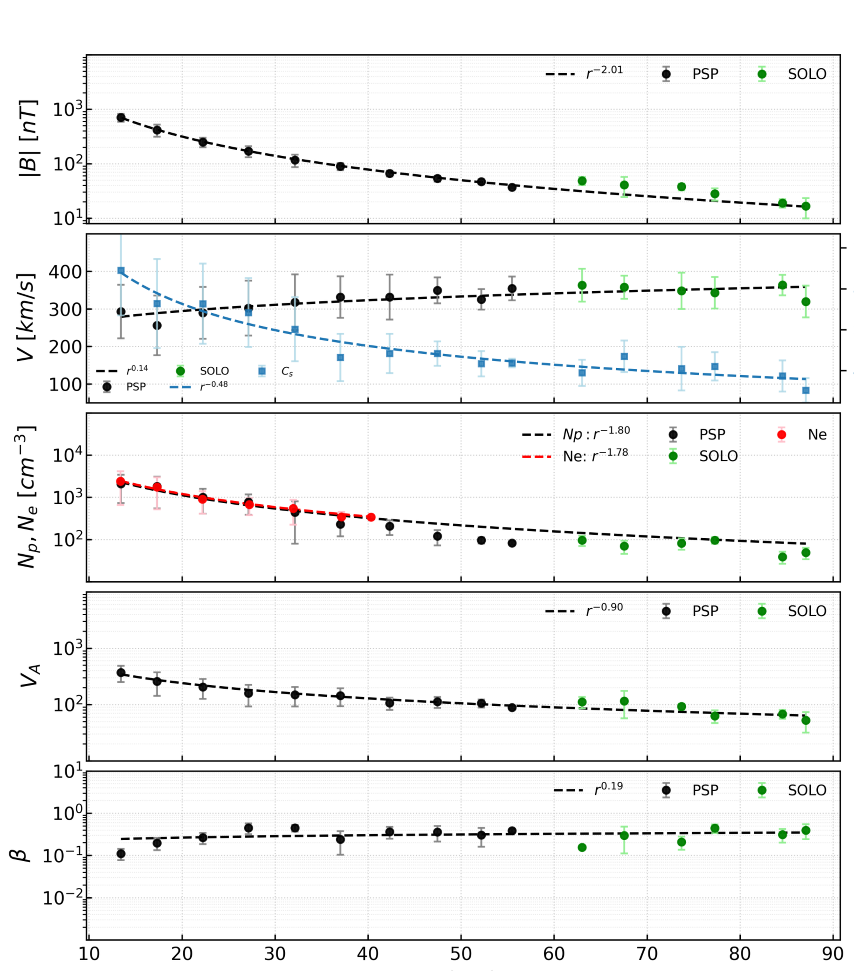
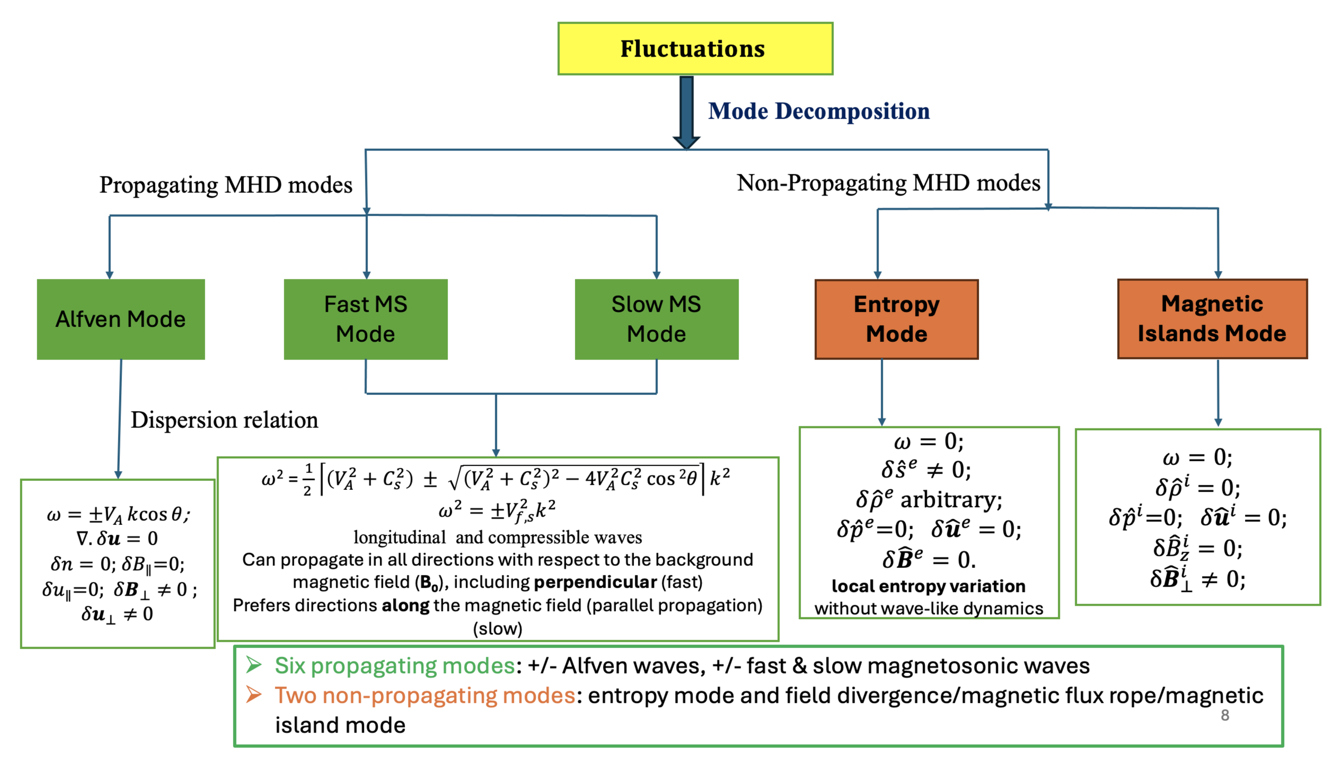


Figure: Overview of the field and plasma measurements from Parker Solar Probe and Solar Orbiter over heliocentric distances of ~ 10 – 90 solar radii. Slow solar wind: V <= 450 km/s

Key Assumptions

- Fluctuations are locally linear perturbations
- The selected interval is locally homogeneous and stationary
- Fluctuations remain coherent within the selection period
- The measured fluctuations can be represented as a superposition of MHD eigenmodes
- The wave propagation direction is estimated using Minimum Variance Analysis

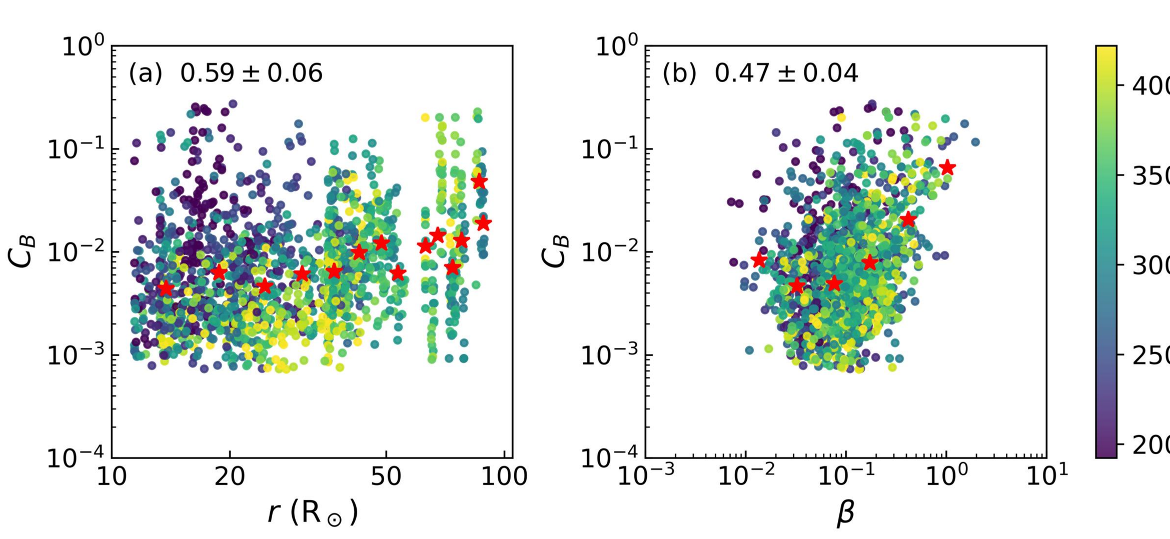
Method



Mode abbreviations: +/- forward/backward; f = fast MS; s = slow MS; e = entropy and i = magnetic island mode

$$C_B = \frac{\delta|B|^2}{\delta B^2}$$

$$\delta\rho_m = \delta\rho^e + \delta\rho^{f+} + \delta\rho^{f-} + \delta\rho^{s+} + \delta\rho^{s+}$$



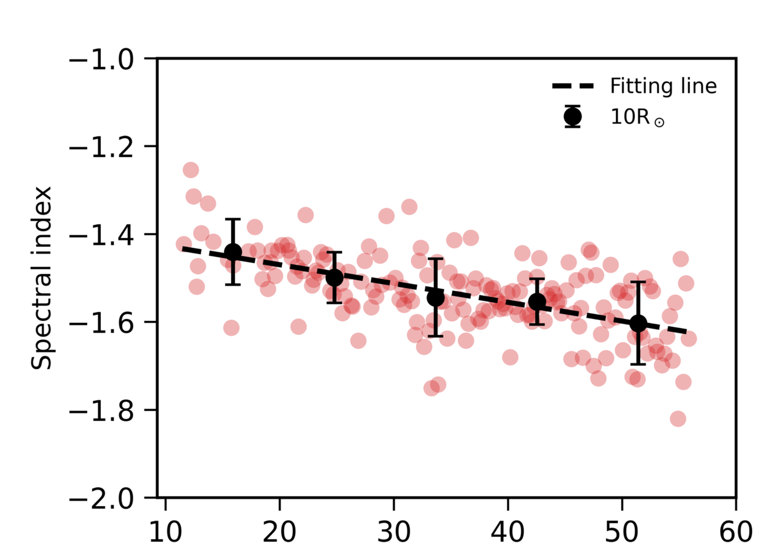


Figure: Magnetic compressibility, C_B as a function of r (top left) and beta (top right), with the color scale representing the solar-wind speed and spectral index as a function of r (bottom).

Results

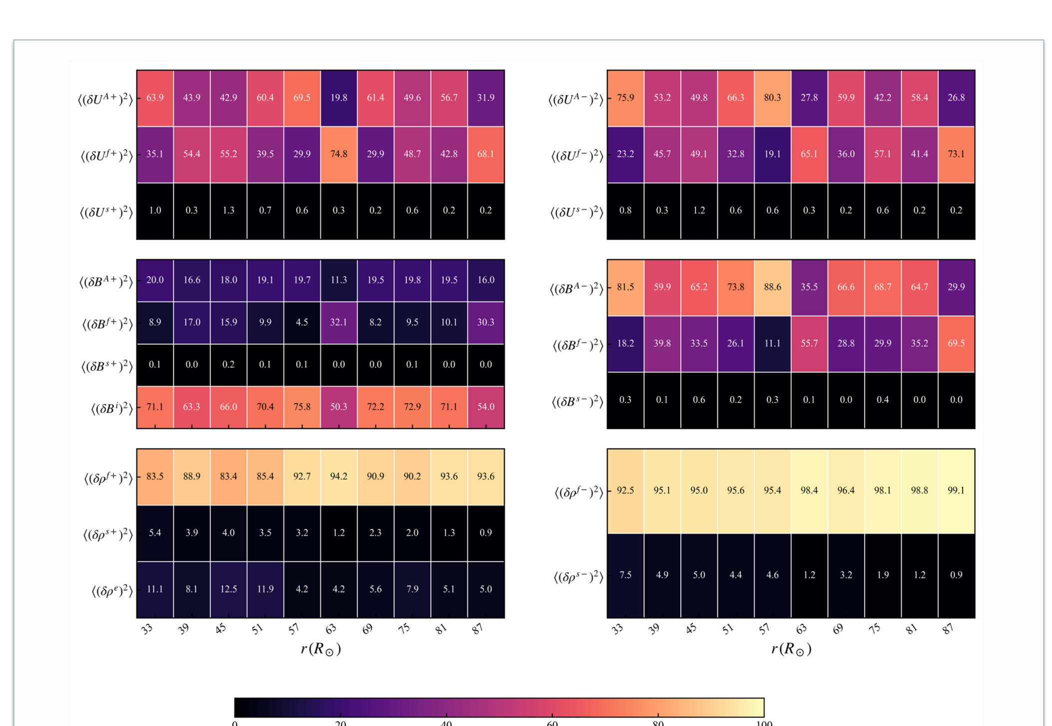


Figure: Radial variation of the fractional mode variance power contribution for the velocity, magnetic-field, and density fluctuations over the selected intervals.

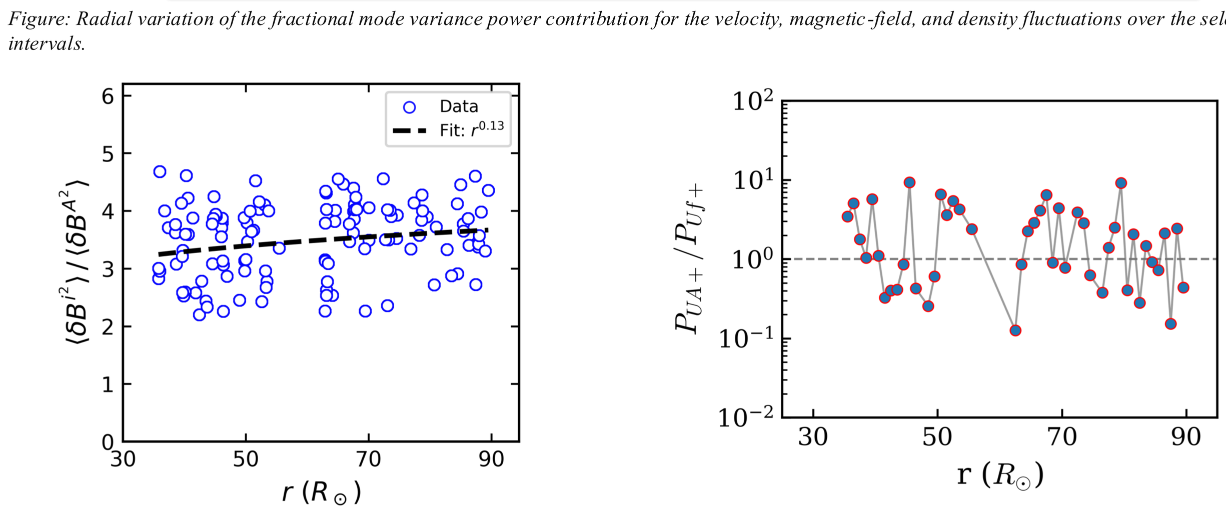


Figure: Scatter plot of computed magnetic variance anisotropy (left) and ratio of the power in velocity-field fluctuations between forward Alfvén and fast magnetosonic modes (right) versus r.

Results

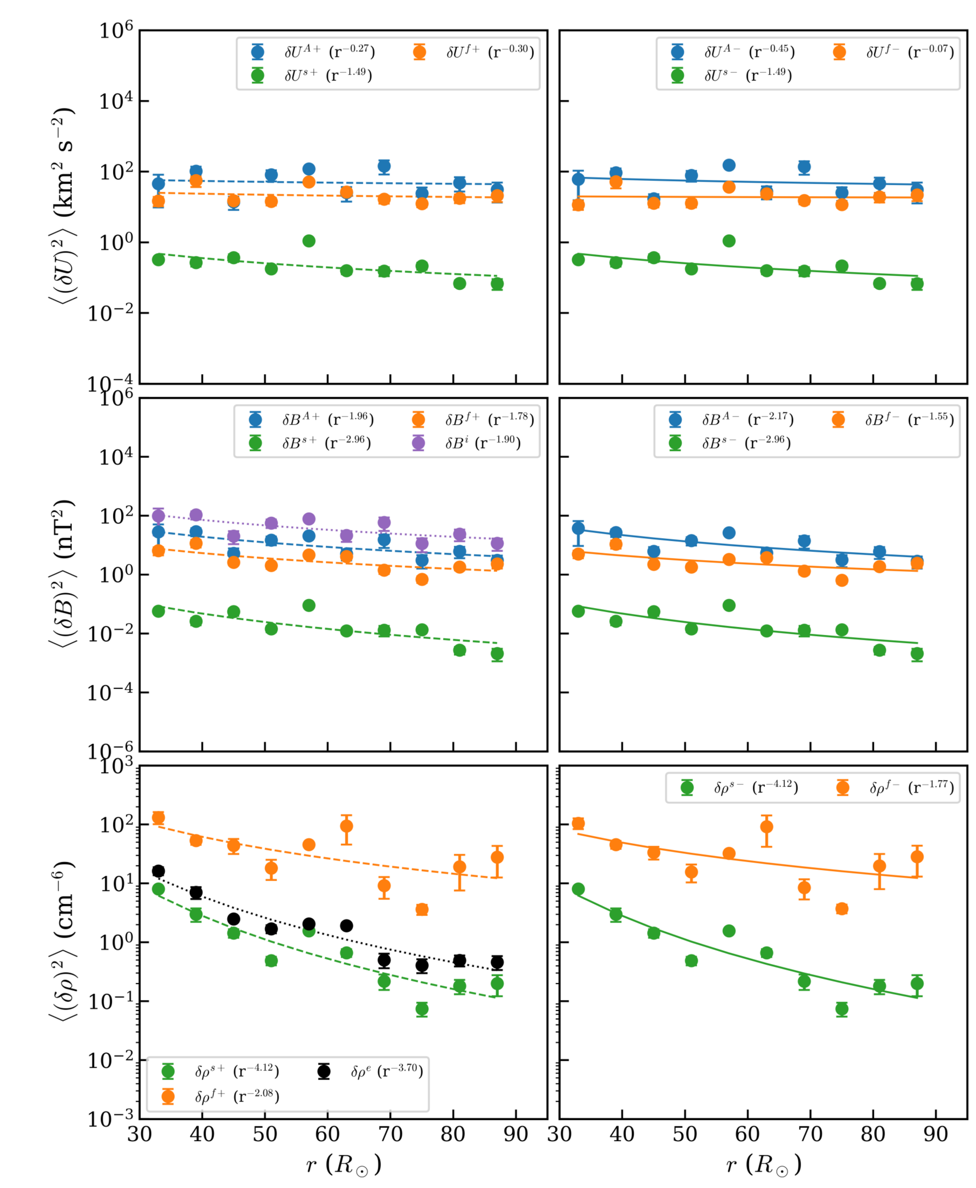


Figure: Mean energies of the velocity, magnetic field, and density fluctuations over the selected intervals as a function of heliocentric distance.

Summary

- We find that the mean energies associated with velocity fluctuations are dominated by the Alfvénic modes, with the forward Alfvénic component δU^{A+} showing the largest amplitude and the shallowest radial decay, $r^{0.27}$, while the backward Alfvénic component δU^{A-} also remains significant with $r^{0.45}$.
- In terms of magnetic fluctuations energy, the dominant mode observed across all identified fluctuations is associated with the transverse nonpropagating incompressible modes i.e., magnetic islands δB^i, with radial profile of $r^{1.90}$.
- The density fluctuations are dominated by the fast magnetosonic modes, with the forward fast mode $\delta\rho^{f+}$ being the strongest component and scaling as $r^{2.08}$.
- The observed increase of variance anisotropy with heliocentric distance suggests that transverse incompressible turbulence becomes progressively more dominated by magnetic-island or quasi-2D structure-like fluctuations than by Alfvénic fluctuations consistent with [2,3].

Future Work

The limited number of suitable intervals remains a constraint, as the LMD analysis is highly sensitive to data quality and selection criteria, restricting the available events for robust statistical characterization.

- Study larger heliocentric distances and systematically distinguishing between slow and fast solar wind streams will help clarify the evolution of turbulence properties under different source conditions.
- Study these variations across different phases of the solar cycle as well as heliographic latitude.

References

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Contact: mk0160@uah.edu