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Compressible effects in solar wind turbulence

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In December 2024, Parker Solar Probe (PSP) reached its closest approach to the sun, providing a wealth of data from previously unexplored regions of the inner heliosphere. PSP has provided evidence that Alfvénic fluctuations are ubiquitous in the solar wind [1], reinforcing the theory that they can contribute to solar wind heating and acceleration in the context of wave-driven winds [2]. These large-amplitude Alfvén waves can induce magnetic field reversals, known as switchbacks, and predominantly propagate away from the Sun. Additionally, despite such large amplitudes, the strength of the total magnetic field remains constant, implying that Alfvén waves are in general spherically polarized. These observations pose challenges to current turbulence models, particularly those based on incompressible assumptions. In this talk, we discuss how the observed properties of Alfvénic fluctuations—the building blocks of wave-driven wind models—may necessitate the inclusion of compressible effects in nonlinear wave dynamics [3, 4].
We begin with a review of parametric instabilities of nonlinear Alfvén waves in fluid and kinetic models, emphasizing effects of expansion, wave spectrum and solar wind conditions on the development of these instabilities [5, 6]. Next, we discuss the kinetic aspects of these processes and associated wave-particle interactions, highlighting how Alfvén waves can nonlinearly lead to proton beam formation, in agreement with in-situ measurements [7, 8]. We conclude by highlighting how compressibility-driven nonlinear mechanisms influence the turbulent energy cascade and determine the kinetic properties of solar wind protons, advancing our understanding of fundamental plasma physics processes at play in the solar wind.

References

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