Cross-scale turbulence in space plasmas: old concepts, recent findings, and future challenges

T. Alberti

Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

Turbulence, a fascinating and intricate phenomenon, has captivated researchers across diverse scientific domains. Demonstrating a complex cross-scale behavior, turbulence spans a wide range of temporal and spatial scales. Despite decades of investigations, turbulence remains a perplexing enigma, motivating continuous endeavors to unveil its underlying physical mechanisms and refine mathematical theories along with numerical models.

This plenary talk explores recent findings from the Parker Solar Probe mission, providing a distinctive opportunity to characterize solar wind features at varying heliocentric distances. Analyzing the radial evolution of magnetic and velocity field fluctuations across the inertial range, a transition has been evidenced from local to global self-similarity as proximity to the Sun increases. This behavior has been reconciled with magnetohydrodynamic theory revising an old concept by emphasizing the evolving nature of the coupling between fields. This has profound implications for turbulence studies, inspiring novel modeling approaches aligned with Kraichnan and Kolmogorov perspectives. Indeed, our findings either point towards turbulence with regular statistics or the presence of intense stochastic fluctuations near the Sun, challenging conventional understanding of interplanetary plasma physics.

Similar deviations in the self-similar character emerge when approaching sub-ion scales. Revisiting concepts from dynamical system theory, an increased number of degrees of freedom at sub-ion scales is observed, suggesting externally induced dynamics associated with the direct cascade mechanism. At inertial scales, a low-dimensional phase-space is discerned, pointing to a quasi-2D nature of fluctuations featuring an inverse enstrophy cascade. Furthermore, large-scale intermittency-like variations are linked with unstable fixed points at sub-ion scales, potentially claiming for a stochastic strange attractor. Encompassing multi-stable and multi-scale fixed points, a novel approach to describing space plasma dynamics through low-order models with varying degrees of freedom and featuring stochasticity is required.

References

Alberti, T., Benzi, R., Carbone, V. (2023) Why (Still) Studying Turbulence in Fluids and Plasmas?, *Perspectives of Earth and Space Scientists*, **4**, e2023CN000215, doi:10.1029/2023CN000215.

Alberti, T., et al. (2022) Reconciling Parker Solar Probe Observations and Magnetohydrodynamic Theory, *The Astrophysical Journal Letters*, **940**, L13, doi:10.3847/2041-8213/aca075.

Alberti, T., et al. (2021) Small-scale induced large-scale transitions in solar wind magnetic field, *The Astrophysical Journal Letters*, **914**, L6, doi:10.3847/2041-8213/ac0148.

Alberti, T., et al. (2020) On the Scaling Properties of Magnetic-field Fluctuations through the Inner Heliosphere, *The Astrophysical Journal*, **902**, 84, doi:10.3847/1538-4357/abb3d2.