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Space-time structure of turbulent fields in the heliosphere

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Turbulence in the heliosphere plays an important role in non-adiabatic heating in interplanetary space, and serves as a natural and accessible laboratory for detailed studies on plasma nonlinearities and particle acceleration in the turbulent fields in the astrophysical context. Our picture of plasma turbulence is continuously being improved and revised thanks to various spacecraft observations in the heliosphere, covering a wide range of distance from the Sun and a wide range of spatial and temporal scales. In particular, multi-spacecraft observations turn out to be a powerful study method in understanding space-time structure of turbulent fields in the heliosphere and an impact of the large-scale magnetic field on the turbulence evolution. Turbulence in the heliosphere not only inherits fluid nonlinearities (e.g., eddies) but also evolves through plasma nonlinearities (e.g., wave-wave and wave-particle interactions). Different fluctuation types have been identified in the turbulent fields such as linear-mode waves from fluid scales to kinetic scales, nonlinear coherent structures, sideband waves, convection, and random sweeping. Each of these fluctuation types has a unique dispersion relation, and can be identified as a "fingerprint" in the wavenumber-frequency domain. The fluctuation types and the expected key control parameters in turbulence evolution are presented as lessons from the spacecraft observations as well as the theoretical studies in view of upcoming spacecraft observations in the heliosphere (Solar Orbiter, Parker Solar Probe, and BepiColombo cruise to Mercury).