1.3 What are the sources of solar wind turbulence and how does it evolve?

Present state of knowledge:

The solar wind is filled with turbulence and instabilities. At large scales, the fast solar wind is dominated by anti-sunward propagating Alfvén waves thought to be generated by photospheric motions. At smaller scales, these waves decay and generate an active turbulent cascade, with a spectrum similar to the Kolmogorov hydrodynamic scaling of f^-5/3. In the slow solar wind, turbulence does not have a dominant Alfvénic component, and it is fully developed over all measured scales. There is strong evidence that the cascade to smaller scales is anisotropic, but it is not known how the anisotropy is generated or driven (Horbury et al. 2008). What do the differences between the turbulence observed in the fast wind and that observed in the slow wind reveal about the sources of the turbulence and of the wind itself?

Little is known about what drives the evolution of solar wind turbulence. Slow-fast wind shears, fine-scale structures, and gradients are all candidate mechanisms (Tu and Marsch 1990; Breech et al. 2008). To determine how the plasma environment affects the dynamical evolution of solar wind turbulence it is essential to measure the plasma and magnetic field fluctuations in the solar wind as close to the Sun as possible, before the effects of mechanisms such as velocity shear become significant, and then to observe how the turbulence evolves with heliocentric distance.

The dissipation of energy in a turbulent cascade contributes to the heating of the solar wind plasma. However, while measurements of the properties of solar wind turbulence in near-Earth orbit largely agree with observed heating rates (Smith et al. 2001; Marino et al. 2008), the details are controversial and dependent on precise models of turbulent dynamics. In order to establish a full energy budget for the solar wind, the heating rates as a function of distance and stream properties must be determined, including turbulence levels before the cascade develops significantly.

The statistical analysis of the fluctuating fields also reveals pervasive fine-scale structure (e.g., discontinuities and pressure balanced structures). The origin of these structures is uncertain: are they the remnant of complex coronal structuring in the form of strands of small-scale flux tubes advected by the solar wind flow (Borovsky 2008; Bruno et al. 2001), or are they generated locally by turbulent fluctuations?

At scales around the proton gyroradius and below, turbulent fluctuations interact directly with the solar wind ions. The precise nature of the turbulent cascade below the proton gyroradius is poorly understood and might even vary depending on local plasma conditions. Below the electron gyroradius, conditions are even less certain and the partitioning of turbulent energy into electron or ion heating is unknown at this time. In addition, solar wind expansion constantly drives distribution functions toward kinetic instabilities, where fluctuations with characteristic signatures are generated (e.g., Marsch 2006). What physical role do kinetic effects play with distance from the Sun? What role do wave-particle interactions play in accelerating the fast solar wind? What contribution do minor ions make to the turbulent energy density in near-Sun space?

How Solar Orbiter will address this question:

Solar Orbiter will measure waves and turbulence in the solar corona and solar wind over a wide range of latitudes and distances, including closer to the Sun than ever before, making it possible to study turbulence before it is significantly affected by stream-stream interactions. By traveling over a range of distances, the spacecraft will determine how the turbulence evolves and is driven as it is carried anti-sunward by the solar wind flow.

Detailed in-situ data will make it possible to distinguish between competing theories of turbulent dissipation and heating mechanisms in a range of plasma environments and are thus of critical importance for advancing our understanding of coronal heating and of the role of turbulence in stellar winds.

By entering near-corotation close to the Sun, Solar Orbiter will be able to distinguish between the radial, longitudinal, and temporal scales of small-scale structures, determining whether they are the signatures of embedded flux tubes or are generated by local turbulence.

Solar Orbiter's magnetic and electric field measurements, combined with measurement of the full distribution functions of the protons and electrons will fully characterize plasma turbulence over all physically relevant time scales from very low frequencies to above the electron gyrofrequency. Because Solar Orbiter is a three-axis stabilized spacecraft, it can continuously view the solar wind beam with its proton instrument, measuring proton distributions at the gyroperiod and hence making it possible directly to diagnose wave-particle interactions in ways that are not possible on spinning spacecraft. By traveling closer to the Sun than ever before, it will measure wave-particle interactions before the particle distributions have fully thermalized, studying the same processes that occur in the corona. By measuring how the distributions and waves change with solar distance and between solar wind streams with different plasma properties, Solar Orbiter will make it possible to determine the relative effects of instabilities and turbulence in heating the plasma.

The solar wind is the only available plasma laboratory where detailed studies of magnetohydrodynamic (MHD) turbulence can be carried out free from interference with spatial boundaries and in the important domain of very large magnetic Reynolds numbers. A detailed comparison between experimental in-situ data and theoretical concepts will provide a more solid physical foundation for MHD turbulence theory, which will be of critical importance for understanding the solar coronal heating mechanism and the role or turbulence in the solar wind.