Exploring Turbulence from the Sun to the Local Interstellar Medium using Interstellar Probe

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Turbulence is one of the most important processes in heliosphere and astrophysical plasmas, routing energy from the largest to the smallest scales and mediating the transport of energetic particles. The properties of plasma and magnetic field (\(B\)) turbulence in the outermost regions of the heliosphere and beyond are poorly understood. Interstellar Probe (IP) will explore four distinct regions (see Figure 1): the supersonic solar wind (SW), the inner heliosheath (IHS), the very local interstellar medium (VLISM), and the local interstellar medium (LISM). The term VLISM identifies the part of the LISM affected by physical processes associated with the heliosphere [Zank, 2015]. At the termination shock (TS), about 80-90 AU from the Sun, the SW transitions to a subsonic flow. The heliopause (HP) separates solar wind from the interstellar medium. A possible heliospheric boundary layer (HBL) with decreased plasma density and draped \(B\) is adjacent to the HP on the VLISM side [Pogorelov et al., 2017, Kim et al., 2017]. The boundary between the VLISM and LISM is unlikely to be distinct, but IP will certainly be able to observe a more pristine state of the LISM than any previous missions.

The global and adjacent fine-scale properties of these regions are significantly affected by the presence of interstellar pickup ions (PUIs), i.e., interstellar neutrals that were ionized as they flow into the heliosphere or neutrals of heliospheric origin that were deposited in the VLISM [Zank 1999]. They are thermally dominant in the outer supersonic solar wind as they carry a significant amount of the SW thermal energy flux beyond about 10 au from the Sun [Zank et al. 2018; Zhao et al. 2019a]. Much of our current understanding of the outer heliosphere and VLISM relies on previous missions, including the Voyagers (V1, V2), IBEX, and New Horizons. However, the instrumentation on the in-situ measurement missions was not specifically designed for an interstellar mission, nor for turbulence analysis. Major limitations to the study of turbulence are related to (i) the 1-D nature of the heliospheric measurements, (ii) the lack of high-resolution imaging, and (iii) the limited time coverage of the measurements.

Figure 1 (a,b) Illustration of the four regions that will be sampled by IP. Regions 1a and 1b represent the LISM and VLISM, respectively. Region 2 represents the IHS. Region 3 represents the supersonic SW. Panel (b) shows a simulation of these different regions [Zank 2015]. (c) Transition to chaotic behavior in the IHS. The magnetic field strength distribution (in μG) is shown in the meridional plane [Pogorelov et al., 2013].
of single-spacecraft in situ measurements; (ii) the cadence of measurements; (iii) instrumental issues such as noise, limited telemetry coverage, failure or shutdown of subsystems and (iv) unavailability of PUI measurements, and (v) resolving numerically turbulence over the whole range of scales is infeasible. For turbulence studies, IP should be equipped with a high-cadence magnetometer and a plasma instrument with the capability to distinguish PUIs from thermal plasma. We summarize some specific science objectives as follows.

**Scientific objectives**

**Interplanetary SW turbulence.** High-resolution plasma and magnetic field measurements in the distant SW will be critical for understanding turbulence in an environment where observations and models suggest that PUIs play a dominant thermodynamical role. PUIs act as a source of in situ turbulence, and possibly offer an alternate dissipation route [Zank 2016, Zank et al. 2018]. Previous missions to the outer heliosphere have been limited in their ability to collect data. Voyager magnetic field measurements are not continuously available at high cadence nor can they measure the energy range of PUIs. New Horizons measures PUIs but unfortunately cannot make magnetic field measurements. Specific challenges to be addressed are: (i) the three-dimensional properties of interplanetary turbulence from 1 au to the TS; (ii) turbulence produced by PUIs; (iii) turbulent energy dissipation processes and related SW heating via analysis of the kinetic regime. IP will investigate interplanetary shock waves, and related fluctuations generated in front of and behind shocks by the streaming of energetic particles. It will be possible to derive energetic particles diffusion coefficients throughout the heliosphere and the VLISM [Zhao et al., 2017, 2018]. Since IP will likely use gravity assists (at Jupiter or Saturn), there will be an opportunity to study magnetospheric turbulence.

**Turbulence at the termination shock.** IP can study the largest and perhaps most complicated multi-ion shock in the distant heliosphere. The question of if and how the TS might accelerate anomalous cosmic rays [Pesses et al. 1981, Zank et al. 2015, Zhao et al. 2019b] remains open. Central to understanding particle acceleration at shocks is the presence of turbulence responsible for scattering energetic particles. The structure of the termination shock is mediated by both PUIs [Mostafavi et al., 2018, Zank et al. 2018] and energetic particles accelerated near the shock [Decker et al. 2008, Florinski et al., 2009]. To date, the TS has only been observed by the Voyagers. Since New Horizons does not have a magnetic field instrument, it is very limited in studying shock structure, turbulence, and PUI and ACR transport via pitch-angle scattering in the vicinity of the TS.

**Turbulence in the inner heliosheath.** Fluctuations of B in the IHS are observed over a broad range of scales with very complex profiles. This “turbulence” [Burlaga et al., 2006] appears to be fundamentally different than that in the SW. Its nature and origin are not fully understood and certainly there is no single physical mechanism that describes the observed turbulence characteristics. Turbulence in the IHS is critically controlled by processes occurring at the TS, including the generation of weak shocks reflected at the HP [Washimi et al., 2011] and magnetic reconnection [Pogorelov et al., 2013, 2017] (see panel c in Figure 1). Data gaps of several hours per day in Voyager data, the high level of noise, and lack of plasma data on V1 make turbulence analysis challenging. Our current understanding of IHS turbulence includes: differences in sector and unipolar regions [Burlaga et al., 2009]; multifractal, intermittent, and compressible fluctuations [e.g. Burlaga & Ness, 2010]; different power-law spectral regimes Fraternale et al., 2019a,b); coherent structures and current sheets [Burlaga & Ness, 2011; Zhao et al., 2019]. IP will investigate the existence, turbulence, and formation of flux ropes and current sheets in sector and unipolar regions [Burlaga & Ness, 2010, Richardson et al., 2016], the role of magnetic reconnection at the heliospheric current sheet (HCS) in generating turbulence in the outer heliosphere. The role of PUIs in both energy release and mediation can be addressed by IP. In the IHS, suprathermal ions contribute ~90% to the total plasma pressure. The kinetic regime of turbulence is still entirely unexplored. IP will provide the first analysis of the dissipation regime of IHS turbulence and will explore the structure and stability of the HP [e.g. Florinski et al. 2005, Pogorelov et al., 2017].
Turbulence in the HBL, VLISM, and LISM. Observations by Voyagers indicate the presence of compressible turbulence in the VLISM [Burlaga et al., 2015], which is likely generated across and by the HP and superimposed on the pristine interstellar turbulence [Zank et al., 2017, Matsukiyo et al., 2019]. Alfvénic fluctuations have been recently detected [Burlaga et al., 2018, Zank et al., 2019]. Traveling shock/compression waves, plasma wave events and cosmic ray anisotropy characterize the HBL [e.g. Gurnett et al., 2015]. Microscale, shock-related turbulence has been observed [Fraternale et al., 2020]. However, the low fluctuation level of interstellar turbulence is close to the Voyager uncertainties (~0.02 nT), and thus limits the accuracy and reliability of the observations. IP will shed light into (i) the nature of compressible and Alfvénic turbulence in the VLISM by high resolution plasma and magnetic field measurements; (ii) collisionality of plasma in the partially ionized medium and the possibility that the VLISM is collisional on larger scales and collisionless on smaller scales; (iii) self-generated turbulence due to the instability of PUI distributions [Florinski et al., 2016, Roytershteyn et al., 2019]; (iv) contribution to VLISM turbulence by weak shocks likely due to major solar eruptive events. Specifically, IP can investigate interstellar shock structure [Mostafavi & Zank, 2018], and the acceleration of electrons and ions in foreshocks and the associated generation of plasma waves and related turbulence. Finally, being about 150 au away from the Sun, the Voyagers are still within the HBL. An exciting task of IP will be to measure the properties of pristine LISM, since IP is expected to reach about 500 au by the end of the mission. Traversing such immense distances will offer critical insights into one of the dominant phases of the ISM.

References