Shock Waves Propagation Beyond the Heliosphere: How Far Does the Sun's Influence Extend into the Interstellar Medium?

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The heliosphere is controlled by the motion of the Sun through the interstellar space. Although humankind has explored the region of space about the Earth quite extensively, the distant heliosphere beyond the planets remains almost entirely unexplored with only the two Voyager spacecraft, New Horizons, and the early Pioneer 10 and 11 spacecraft returning the in-situ observations of this most distant region. Moreover, remote observations of energetic neutral atoms (ENAs) from the Interstellar Boundary Explorer (IBEX) at 1 au and Cassini/INCA at 10 au revealed bewildering structure related to the interstellar medium. Voyager 1 and 2 crossed the heliopause in 2012 and 2018, respectively, and are both continue to make in-situ measurements of the very local interstellar medium (VLISM; the nearby region of the LISM affected by physical processes associated with the heliosphere) for the first time. Voyager 1 and 2 have identified and partially answered many interesting questions about the outer heliosphere and the VLISM while raising numerous new questions, many of which have profound implications for the detailed structure and properties of the heliosphere and our place in the galaxy. One particularly interesting topic is the influence of the large-scale disturbances generated by the dynamical Sun on the VLISM. These disturbances form heliospheric shock waves that first propagate through and influence the boundaries of the heliosphere and then traverse and modify the VLISM.

New Horizons observations showed that energetic pickup ions (PUIs) dominate the internal pressure of the outer heliosphere, with PUI pressures larger than the thermal solar wind and magnetic pressures outside ~ 20 au (McComas et al. 2017). Although Voyager 1 and 2 are not instrumented to measure PUIs, the Voyager 2's crossing of the heliospheric termination shock (HTS) indicated that the primary dissipation mechanism at the HTS is not provided by thermal gas (Richardson et al. 2008) and thus it is completely **mediated by PUIs** (Mostafavi et al. 2018; Zank et al. 2018; Dialynas et al. white paper). Since the inner heliosheath (IHS) is thermally dominated by energetic particles such as anomalous cosmic rays (ACRs) and PUIs (Decker et al. 2015), shock waves in the IHS should be mediated by energetic particles. Models by Zank et al. (2018) and Opher et al. (2020) treat PUIs as a separate component along with the thermal gas. By 2050, models of the outer heliosphere should include multiple plasma components, such as thermal plasma, PUIs, and ACRs, ideally treating the last two kinetically. PUIs in the IHS and VLISM change the plasma properties, typically increasing the sound speed with a concomitant weakening or even elimination of the interstellar bow shock (McComas et al. 2012; Zank et al. 2013, but it does not represent a significant dissipation at weak interstellar shocks (Mostafavi & Zank 2018). The evolution of ribbon fluxes observed by IBEX is primarily driven by changes in the neutralized solar wind and not PUI interactions with shocks outside the heliopause (Zirnstein et al. 2020). To understand the basic physics of the VLISM, it is necessary to **directly measure PUIs** in the LISM and understand their basic properties as a function of distance from the HP.

Heliospheric shocks and pressure waves propagate into the heliosphere are partially transmitted and partially reflected at the HP, and are then observed in the VLISM (Gurnett et al. 2013). Figure 1 shows the Voyager 1 observations of the electron plasma oscillations and the magnetic field in the VLISM. Two shock waves have been observed by Voyager 1 in the VLISM by the magnetometer on Voyager 1 (Burlaga & Ness, 2016) in association with electron plasma oscillations (Gurnett et al 2013). The shock wave observed late in 2012 was **extremely broad,** exhibiting properties very different from those shocks in the heliosphere (Burlaga et al. 2013). Mostafavi & Zank (2018) showed that the VLISM is **collisional** with respect to the thermal plasma and determined that the weak VLISM shock structure is due to thermal particle collisions and is not mediated by wave-particle interactions. This was a surprise since our intuition and understanding of shocks in the heliosphere has been guided by collisionless processes. The **collisionality of the VLISM and the properties of shocks** need to be studied more extensively with regard to distance from the HP and orientation of the LISM magnetic field. This requires more sophisticated multi-component plasma physics model of the VLISM and the perspective of a **3-D global model**. Understanding the fundamental plasma physics from a global perspective will allow us to understand **the transition from the VLISM to the LISM.**

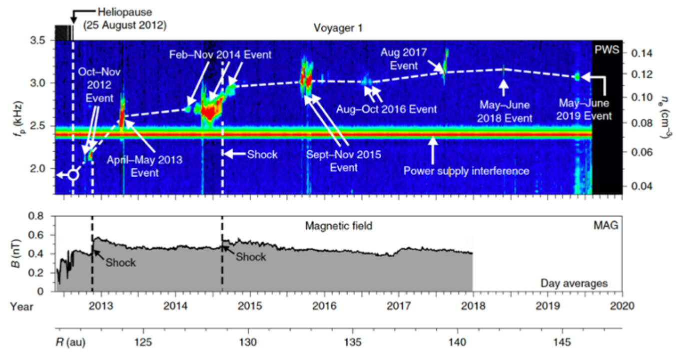

Figure 1: Frequency–time spectrogram of electron plasma oscillations detected by the V1, and the corresponding local magnetic field strength from the magnetometer. Two vertical dashed lines indicate two observed shocks in the VLISM. (from Gurnett & Kurth 2019).

Voyager 1 observed an increase in the magnetic field during an interval of ~ 40 days period at the end of 2016 (Burlaga et al. 2019), which is far too long to be a collisional shock wave. Burlaga et al. have concluded that the magnetic field enhancement was a pressure wave driven by the movement of the HP. The **origin and evolution of VLISM pressure waves** is not well understood via either theory and modeling. Voyager 2 observed electron plasma oscillations and an increase in currents in 2019 that might indicate a shock elsewhere in the VLISM (Gurnett and Kurth (2019); Richardson et al. (2019)). To confirm this idea requires an **ultra-high-resolution data-driven model** that lets us **explain model propagation effects associated with observed changes in electron quantities** throughout the VLISM.

Turbulence in the VLISM presents itself differently close to the HP than at greater distances (Burlaga et al. 2020, Zank et al. 2019) and is different than turbulence in the heliosphere. **Shocks** may be responsible in part for localized small-scale **turbulence and waves in the VLISM.** For example, Fraternale et al. (2020) found an increase in transverse magnetic field fluctuations a few days before Voyager 1 entered the electron foreshock of 2012 VLISM shock. Turbulence may be related to the observed anisotropy of galactic cosmic rays (GCRs), and this **anisotropy** may provide a remote-sensing diagnostic of VLISM shock waves (Gurnett & Kurth 2019). GCR streaming due to reflection at the shock front may be responsible for the observed turbulence.

By 2050, we need a spacecraft that could reach the ISM to make in situ measurements. Voyager 1 and 2 were designed as planetary missions and are not ideally instrumented to properly explore the VLISM and LISM. Unfortunately, they will cease returning data in ~ 2028, leaving humankind without **a spacecraft dedicated to the study of the outer heliosphere and the ISM.** The technology for an interstellar mission will be available by 2030; see http://interstellarprobe.jhuapl.edu/ for more details.

Prior to any launch of a mission, an ultra-high-resolution data-driven model that captures shock wave propagation from the inner heliosphere to the LISM is necessary. The grid sizes of current models cannot adequately resolve shock structures deep in the IHS (e.g., Kim et al. 2017) and VLISM. The proposed **ultra-high-resolution global model** would capture shock waves in the outer heliosphere, shock merging, and collisions between interplanetary shocks, the HTS, and the HP. It would quantify changes in the strength, thickness, and the speed of VLISM shocks with distance from the HP and provide crucial predictions to be tested by a future Interstellar Probe mission. The model is feasible given the growth of the expected computational power by 2050 (see Mostafavi et al. whitepaper for more details).

Summary and questions

Voyager 1 and 2 have identified many interesting questions about the outer heliosphere and the VLISM. The interstellar medium is a much colder and denser plasma than the heliosphere. The very different physics of the VLISM effects the properties of shocks and turbulence in this region. The Voyagers were not instrumented properly to fully elucidate the physics of this complex region, so the influence of the heliosphere on the VLISM is poorly understood. A better understanding of this region has astrophysical ramifications for the understanding of the interaction of the astrospheres of stars with their local ISM. A first important start is to significantly improve our **theoretical understanding and modeling of the heliosphere-VLISM-LISM interaction**. A **spacecraft** that explores the heliospheric boundary regions, the VLISM and the transition to the LISM is essential if we are to ultimately understand our place in the galaxy. Questions that need to be addressed by 2050 are:

- By performing a statistical analyses of interplanetary shock waves per solar cycle, can we quantify how many of these shocks enter the inner heliosheath and the VLISM? How does the strength, thickness, and speed of VLISM shocks change with distance from the HP?
- What are the properties of the heliospheric shocks that survive and reach the VLISM? What is the origin of pressure waves in the VLISM?
- What is the role of collisionality in the VLISM, and on what scales is the VLISM is collisional? For what physical processes is collisionality important and when do collisionless wave-particle effects become important or even dominant?
- Do shocks in the VLISM contribute to turbulence in the VLISM? The LISM?
- How does the global structure of VLISM shocks affect GCR anisotropies? How do heliospheric shocks alter the intensity of GCRs? Can GCR anisotropies act as a remote probe of VLISM shocks and their properties? Do shocks contribute at all to ACR acceleration processes?
- What are the properties of PUIs in the VLISM, based on their different origins? How far from the HP are energetic PUIs found in the VLISM? Does their presence change the physics of VLISM? Do VLISM PUIs affect shock properties? Is there a bow shock/wave in front of the HP?
- How far does the VLISM, being mediated by the heliosphere, extend, and where is the transition to the LISM or the pristine interstellar medium? What is the global distribution of the VLISM plasma parameters? What are the plasma quantities and magnetic field structures in the interstellar medium?

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