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What Lies Outside of the Heliopause: Connecting the Outer Heliosphere with the Interstellar Medium

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ABSTRACT

Our understanding of the outer heliosphere is becoming clearer from direct measurements by the Voyager spacecraft and theoretical models, but what lies beyond the heliopause in the Very Local Interstellar Medium (VLISM) and beyond in the pristine Local Interstellar Medium (LISM) is a new frontier of heliospheric research. This white paper for the Heliophysics 2050 Workshop describes critical questions concerning the plasma and magnetic field and physical processes in the VLISM and LISM.

1. THE PRESENT PICTURE

The heliosphere is the interface between our solar system and the rest of the galaxy. Measurements using both heliospheric and astronomical techniques are required to fully understand the physical interactions and morphology of this interface. Measurements from both perspectives are needed to apply out knowledge of the heliosphere to analogous structures around other nearby stars, many of which host habitable planets, and to evaluate how the heliosphere has evolved and influenced the habitability of solar system planets.

The Voyagers passed the termnation shock (TS) at 94 AU (V1) and 84 AU (V2) and traversed the heliopause (HP) at 122 AU (V1) and 119 AU (V2). Beyond the HP, interstellar plasma is modified by the inclusion of pickup ions and anomalous cosmic rays created in the TS and heliosheath that leak into the VLISM through the HP. This region was called the Very Local Interstellar Medium (VLISM) by Zank (2015). Inside the VLISM, charge exchange reactions between inflowing hydrogen atoms and energetic solar wind protons create the “hydrogen wall” (HW) where hydrogen atoms are piled up (increased density), heated, and slowed down relative to the inflow speed of neutral hydrogen from the pristine LISM. Hydrogen wall absorption in the Lyman-α line measures solar or stellar mass-loss rates. Figure 1 shows a heliosphere model where the HW is seen as a neutral hydrogen density enhancement outside of the HP. In models by Zank et al. (2013), the maximum density in the HW occurs near 300 AU and extends outward to 400–600 AU depending on the local magnetic field strength. The only direct measurements of the inflowing VLISM gas are the neutral helium atoms that penetrate the heliosphere relatively unscathed by charge exchange reactions and neutral hydrogen atoms modified by charge exchange reactions and identified by backscattered Lyman-α radiation.

Beyond the VLISM, perhaps 500–700 AU from the Sun, is the pristine Local Interstellar Medium (LISM) for which there are no direct measurements. We have only a crude understanding of the LISM based only on theory and remote measurements.

2. VLISM SCIENCE QUESTIONS

Models of the HW and VLISM computed with a MHD plasma – kinetic hydrogen code by

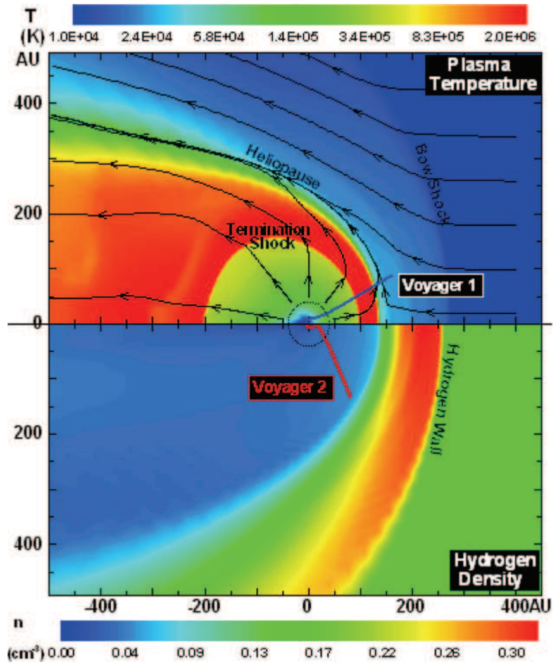

Figure 1. The heliosphere model computed by Richardson & Stone (2009). The top half shows the temperature structure. The bottom half shows the neutral hydrogen density. The HW is between 200 and 250 AU in the upwind direction.

Zank et al. (2013) show that the VLISM magnetic field plays a critical role in determining (i) whether the decelerating LISM plasma has a bow shock or a bow wave, (ii) the amount of heating in the VLISM, and (iii) the neutral H column density density in the HW. Absorption in the Lyman-α line is best described by their model with a VLISM magnetic field of 3 μG, the same value inferred from observations of the IBEX ribbon (Zirnstein et al 2016).

Other processes, known and unknown, shape the VLISM plasma. For example, pickup ions produced near the TS and accelerated ions (anomalous cosmic rays) dominate the heliosheath pressure. Gloeckler & Fisk (2016) estimate the total pressure just beyond the HP by balancing the total pressure on both sides of the HP. They estimate that the total gas pressure pressure just beyond the HP as $P(\mathrm{tot})/k = 25,855$ Kcm^{-3}, whereas the total gas and magnetic pressure in the inner LISM is only 5,565 Kcm^{-3} (Frisch et al. 2011), a factor of 4–5 times smaller. To balance the total pressure, the magnetic field just outside of the HP should be about 8 μG, which is far larger than measured by V1 and somewhat larger than measured by V2. On this basis V1 and V2 have not yet have crossed the HP.

Direct measurements of the thermal and non-thermal plasma and magnetic fields are needed to understand the VLISM and test the models. In particular, we need to know how far out solar energetic neutrals and ions extend and the length scales for charge exchange and thermalization processes in order to determine where the VLISM ends and the pristine LISM begins.

3. LISM SCIENCE QUESTIONS

Absorption line measurements of interstellar gas in the sightlines to nearby stars are the primary data set used to construct models of the LISM. Analysis of HST ultraviolet spectra yield line of sight average measurements of elemental abundances, ionization states, and velocity structure between the Sun and stars.

Redfield & Linsky identified 15 clouds in the LISM by common velocity vectors towards stars. Each of these clouds has a mean temperature of 5,000–10,000 K. Linsky et al. (2019) showed that four clouds (see Figure 2) are very near the outer heliosphere. Local Interstellar Cloud (LIC) absorption covers less than half the sky, indicating that the gas entering the VLISM and heliosphere may be at the edge LIC with somewhat different properties than in the LIC center. The neutral hydrogen density in the LIC had been estimated to be 0.195 cm^{-3} (Slavin & Frisch 2008) or about 0.12 cm^{-3} on the basis V2 and Cassini/INCA measurements (Dialynas et al. 2019). However, these are rough estimates of the mean hydrogen density in only one of the LISM clouds. Direct measurements of neutrals, electrons, and ions are needed to study the properties of the LISM.

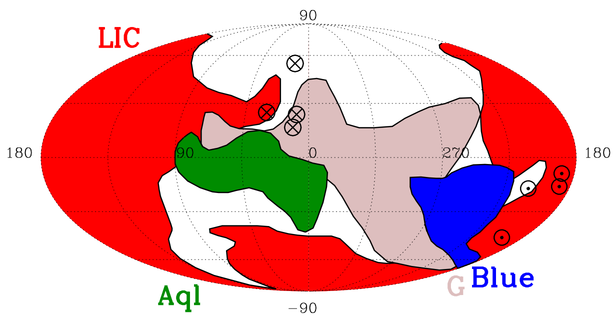

Figure 2. Morphologies of the four partially ionized LISM clouds that are near the outer heliosphere: the LIC (red), which lies in front of ϵ Eri (3.2 pc), the G cloud (brown), which lies in front of α Cen (1.32 pc), the Blue cloud (dark blue), which lies in front of Sirius (2.64 pc), and the Aql cloud (green), which lies in front of 61 Cyg (3.5 pc). The plot is in Galactic coordinates with the Galactic Center direction in the center. The LIC upwind direction is indicated by the circled-cross symbol near $l = 15°$ and $b = +20°$, and the upwind directions of the other clouds have similar marks.

The heliosphere is now exiting the LIC in the direction of the neighboring G cloud. Upper limits on the amount of interstellar Mg II absorption in this direction predict that the heliosphere will leave the LIC in less than 1900 years and perhaps this year. **This would be a major event.** Will the heliosphere directly enter the G cloud or a photoionized boundary layer with little neutral hydrogen? The size of the heliosphere and the composition of its plasma will change in either scenario.

The EUVE satellite discovered that the star ϵ CMa (ecliptic coordinates $\lambda = 111°$, $\beta = -51°$ and distance 124 pc) is the the brightest source of extreme-UV radiation. EUV photons from ϵ CMa produce a very large photoionized region (called a Strömgren sphere) that surrounds the LISM warm clouds and the partially ionized Strömgren shells on the outer regions of the LISM clouds. EUV radiation from ϵ CMa photoionizes neutral hydrogen producing very low neutral hydrogen column density in this direction called the "hydrogen hole". The role of photoionization must be tested.

Magnetic fields will be important in shaping the morphology of clouds if the magnetic pressure exceeds the gas pressure, which would occur if $B_{\rm LISM} > 3\mu$G. Stronger magnetic fields just beyond the HP observed by V2 (Dialynas et al.(2019) suggest that magnetic fields may dominate the pressure in the LISM clouds.

The very low density plasma in the LISM may include non-thermal particles that dominate the total pressure. Supernovae in the nearby Scorpio-Centaurus Association have occured as recently as a few million years ago and their shock waves produced high ionization in the LISM that may still be recombining. The ram pressure of supernovae shocks can dominate other sources of pressure in the simulations of Berghofer & Breitschwerdt (2002). Recent models of the velocity distribution of plasma in the outer heliosphere include non-thermal components (Swaczya et al. 2019). Future analysis of LISM absorption line profiles should test for high velocity tails using kappa distributions.

The relative importance of these and potentially other sources of ionization and morphology in the LISM need to be understood. Direct measurements of thermal and non-thermal plasma and magnetic fields can accomplish this.

References:

Berghofer & Breitschwerdt (2002) Astron. Astrphys. 390, 299. Dialynas et al. (2019) Geophys. Res. Let. 46, 7911. Frisch et al. (2011) ARAA 49, 237. Gloeckler & Fisk (2016) ApJ 833, 290. Linsky et al. (2019) ApJ 886, 41. Redfield & Linsky (2008) ApJ 673, 283. Richardson & Stone (2009) Space Sci. Rev 143, 7. Swaczyna et al. (2019) ApJ 871, 254. Zank et al. (2013) ApJ 763, 20. Zirnstein et al. (2016) ApJ 818, L18.