New results concerning the environment of the heliosphere, nearby interstellar clouds, and physical processes in the inter–cloud medium

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Abstract.
We present our new results concerning the interface between the outer heliosphere and the local interstellar medium (LISM). The three dimensional shape of the Local Interstellar Cloud (LIC) based on 62 sightlines to nearby stars shows a region of very low neutral hydrogen density in the direction of the star ε CMa, the brightest source of extreme-UV (EUV) radiation. This “hydrogen hole” with very weak neutral hydrogen absorption by the LIC and Blue clouds results from photoionization by the EUV radiation from ε CMa. The LIC likely surrounds the heliosphere, but in the direction of the hydrogen hole its neutral hydrogen column density is too low to be measured. Upper limits to this column density and the direction of the Sun’s motion through space indicate that the Sun will leave the outer edge of the LIC in less than 1,900 years. The measured difference between the speed and direction of incoming neutral hydrogen atoms (measured by IBEX and Ulysses) and the flow vector of the LIC indicate that the plasma at the edge of the LIC has a different flow vector than the LIC core. The inter-cloud plasma and much of the Local Cavity are inside the Strömgren sphere (also called an H II region) surrounding ε CMa. The outer edges of the LIC and other clouds are Strömgren shells that are partially ionized by the EUV radiation from ε CMa and white dwarfs. The Local Cavity could be a Strömgren sphere plasma photoionized by ε CMa and hot white dwarfs that contains low density ionized gas that is not hot. An interstellar probe should measure magnetic field and plasma properties in the VLISM between the heliopause and ~600–700 au from the Sun and then enter what is likely the Strömgren shell outer edge of the LIC. When the Sun leaves the LIC, it will either enter the G cloud, a transition region between the LIC and the G cloud, or ionized Strömgren sphere plasma.

1. Unfortunate barriers between heliophysics and interstellar medium research
Within the broad domain of astrophysics, studies of the heliosphere and the interstellar medium are often pursued in isolation with little cross-fertilization despite the reliance of both fields on a common set of physical principles and observed interactions between the solar wind and the interstellar plasma. Figure 1 illustrates many of the barriers that have hindered interactions between researchers in these two fields. The causes include different terminologies, coordinate systems, and literatures. Equally as important are the different perspectives introduced by the different distance scales of the subjects of research, different kinds of measurements (in situ
vs remote sensing), and the different drivers of the physical phenomena (solar radiation and particles vs. EUV radiation from an external source - the star \( \epsilon \) CMa.)

Nevertheless, there is considerable value in studying the region where the solar wind and interstellar plasma interact guided by insights obtained from both heliospheric and interstellar medium studies. The intrepid Voyager space probes obtained the first direct measurements of plasmas and magnetic fields in the interaction regions when they transversed the termination shock, heliosheath, and more recently the heliopause where inflowing interstellar plasma is moderated by the solar wind. While Voyager-1 is now about 149 au distant and Voyager-2 is not far behind, their useful remaining lifetimes of roughly 5 years means that they will tell us plasma and magnetic field properties only out to about 167 au. They will not sample the physical properties in the hydrogen wall at roughly 300 au [36], the bow shock/wave, or the pristine interstellar plasma beyond the influence of the solar wind beginning at about 600 au. Future missions such as the proposed Interstellar Probe are needed for such direct measurements. In the next 15-30 years remote sensing, theory, and simulations will be the only available tools.

In the oral presentation at Santa Fe in March 2020 and in this written version, we summarize our recent research concerning the LISM and speculate on what lies just outside of the heliosphere that future missions such as Interstellar Probe may encounter. For more details see our recent paper [13], which is the basis for this presentation. For completeness, we include a portion of the our presentation at the previous International Astrophysics Conference.

2. How ultraviolet spectroscopy can provide information about the kinematic and morphological properties of the LISM gas

For nearly 20 years, we have been acquiring a large spectroscopic database of interstellar gas absorption properties within 100 pc of the Sun, the region of space that we call the local interstellar medium (LISM). The observations with several ultraviolet spectrographs on the Hubble Space Telescope (HST) consist of stellar emission line spectra with superimposed narrow absorption lines produced by neutral and ionized gas in the lines of sight to these stars. We now have acquired spectra of more than 200 stars that are distributed across the sky sampling nearly all Galactic coordinates. The HST spectra were obtained mostly with the Space Telescope Imaging Spectrograph (STIS) instrument with resolutions of 3.0–6.5 km s\(^{-1}\), but we also use some ground based spectra of the Ca II H and K lines. The STIS spectra include interstellar absorption lines of H I (121.6 nm Lyman-\( \alpha \)), O I (130.2, 130.5, 130.6 nm), C II (133.4, 133.5 nm), Mg II (279.5, 280.3 nm), and Fe II (258.6, 260.0 nm) superimposed on emission lines formed in stellar chromospheres.

The high-resolution spectra of these lines allow us to measure the radial velocities (\( v_r \)) and line widths (\( b \)) of each interstellar velocity component detected against the background of a stellar emission line or continuum. For every sightline, we detect at least one velocity component and often two to six components even for stars located within 5 pc. Our detection of multiple velocity components along the same short sightline indicates that the LISM gas has velocity structure with scales of order one pc (206,265 au) or smaller. With this large data set, Redfield & Linsky (hereafter RL08) [23] developed a model of the partially ionized LISM gas consisting of many discrete components, which we call clouds, for which we assume that the gas moves coherently with the same velocity vector and physical properties (temperature and turbulence). While this model is likely too simple, it fits the data quite well [24], but we intend to test this model when there is sufficient data to see whether the clouds have inhomogeneous properties, as proposed by Gry & Jenkins [6], or may have nonthermal velocity distributions.

With spectra for 160 sightlines, RL08 identified 15 interstellar clouds located within 15 pc of the Sun and derived temperatures and turbulence values for many of the velocity components identified in each sightline. The technique for inferring these results is described schematically in Figure 2. While the observed profile of a single ion in a single sightline provides only radial
Figure 1. A partial listing of the barriers to interactions between heliophysics and interstellar medium researchers. Studies of the local interstellar medium (LISM) will need insights from both of these fields.

| Heliosphere                        | Interstellar Medium                      |
|------------------------------------|------------------------------------------|
| • Heliophysics terminology         | • Astrophysics terminology               |
| • Ecliptic coordinates             | • Galactic coordinates                   |
| • In situ satellite measurements   | • Remote satellite measurements          |
| • <AU distance scale               | • <pc (<200,000 AU) distance scale       |
| • Internal driver (Sun)            | • External driver (e CMA)                |
| • Heliophysics literature          | • Astrophysics literature                |

Flow from the VLISM → the heliosphere: gas (identified by He°), dust, supernova isotopes (e.g., 60Fe).

Flow from the heliosphere → the VLISM: solar wind tail.

velocity $v_r$ and column density of that ion $N_{ion}$, the observation of multiple ions in the same sightline provides a wealth of information. Comparison of the line widths of different ions or neutrals with different atomic masses ($m$) allowed us to determine the temperature ($T$) and turbulent velocity ($\xi$) of the gas. The best leverage for this measurement comes from the comparison of the widths of lines of D I ($m=2$) with Fe II ($m=26$). The difference in the column density of element X relative to hydrogen, $\log (X/H)$, compared to the solar ratio is the depletion of the element that probably results from atoms being absorbed onto the surfaces of dust grains and thus removed from the interstellar gas. Accurate depletions require measurements of the important ionization stages of an element in order to obtain the total abundance of the element in the LISM gas. Finally, there are line ratios that are sensitive to electron density because the radiative de-excitation of one of the lines is very small such that de-excitation from the upper level is by electron collisions rather than radiative de-excitation [20]. The ratio of Mg I/Mg II is also sensitive to electron density [6], Slavin & Frisch [25], and Frisch et al. [5] obtained the neutral hydrogen number density in the LIC.

The morphological structure of interstellar clouds requires a determination of the velocity vector for each cloud from the radial velocity data. We started this iterative process by asking how accurately a single velocity vector fits all of the radial velocity data. The differences of
Figure 2. Observational diagnostics — the interstellar gas properties that can be obtained from high-resolution spectra of one ion or multiple ions in a single sightline showing the equations used to infer temperature, turbulence, element depletion, and electron density.

individual radial velocities relative to the projected radial velocities computed from the best fit vector are very large: the ratios of these differences divided by the velocity measurement errors are more than 10σ away from the predicted values for 45% of the data points [19]. The velocity structure of the LISM is therefore very clumpy. We then deleted data points one by one starting with the most discrepant data point until the remaining discrepancies were consistent with the velocity measurement errors (about 1.5 km s$^{-1}$ for the STIS data). The velocity vector for these 79 sightlines define a two-dimensional region in space roughly centered opposite from the Galactic Center and covering about 45% of the sky. This cloud called the Local Interstellar Cloud (LIC) has a mean temperature $T = 7500 \pm 1300$ K, mean turbulence (non-thermal broadening component) $\xi = 1.62 \pm 0.75$ km s$^{-1}$, and logarithmic depletions of Fe and Mg ($-1.12 \pm 0.10$ and $-0.97 \pm 0.23$, respectively). A similar analysis of the data for the remaining sightlines led to the identification of 14 other clouds. The nearest four clouds to the Sun are the LIC, the G cloud in the direction of α Cen (1.3 pc) toward the Galactic center, the Blue cloud in the direction of Sirius (2.6 pc), and the Aql cloud in the direction of 61 Cyg (3.5 pc). The G cloud covering about 20% of the sky has a mean temperature $T = 5500 \pm 400$ K, while the Blue cloud covering about 6% of the sky may have even cooler gas ($T = 3900 \pm 2300$ K). Figure 3 shows the location of the four clouds closest to the Sun in Galactic coordinates. These clouds are partially ionized with hydrogen about 26% ionized if the LIC is representative [25]. A figure showing all 15 clouds included in Redfield & Linsky [23].

After this 15 cloud model was constructed, we obtained observations of 34 stars randomly selected from a much larger list in an HST SNAP program. Malamut et al. [15] found that every radial velocity predicted by the 15 velocity vectors is consistent with the observed radial velocities of these stars, thereby confirming the 15-cloud model. A calculator for the radial and tangential velocities predicted by each cloud’s velocity vector for all directions is available at
Figure 3. Morphologies of the four partially ionized LISM clouds that are closest to the outer heliosphere. They are 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 upwind direction of the LIC velocity vector is indicated by the circled-cross symbol near $l = 15^\circ$ and $b = +20^\circ$, and the upwind directions of the other clouds have similar marks. The downwind directions are indicated by the circled-dot symbols. A full map of all 15 LISM clouds is given by Redfield & Linsky [23].

http://sredfield.web.wesleyan.edu.

An important question is whether the Sun lies inside or outside of the LIC, because the properties of the LISM gas immediately outside of the heliosphere set the outer boundary condition for heliosphere models. Since the LIC covers about 45% of the sky, the Sun could lie either just inside or just outside of the LIC. The absence of interstellar absorption at the velocity predicted by the LIC vector in the direction of α Cen (1.32 pc) suggests that the Sun lies outside of the LIC or barely inside with insufficient optical depth to detect absorption by Mg II or other lines. If the Sun is located inside of the LIC, then the Mg II absorption upper limits and the Sun’s motion with respect to the LIC indicate that the Sun will leave the LIC in less than 1900 years [19], perhaps very soon.
3. The flow vectors of the Local Interstellar Cloud and the neutral helium flowing into the heliosphere do not agree and possible explanations for the disagreement

The flow of interstellar helium atoms into the heliosphere is the best test of the inflow vector of interstellar gas, because charge exchange and ionization by solar extreme ultraviolet radiation should have only small effects on helium atoms and thus may not substantially change their inflow direction and speed until very close to the Sun. Wood et al. [34] reanalyzed the Ulysses spacecraft observations of neutral helium, and Möbius et al. [16], Leonard et al. [12], and Bzowski et al. [4] analyzed the Interstellar Boundary Explorer (IBEX) observations of neutral helium. Table 1 summarizes Ulysses and IBEX results and compares them to the predicted inflow properties of gas in the LIC and nearby G clouds (RL08). For comparison with the helium inflow measurements, we include in the table the velocity amplitudes and inflow directions of the LIC, G, and Blue clouds and the inflow vectors of neutral hydrogen and interstellar dust in ecliptic coordinates.

| Source     | Specie | $v$ (km s$^{-1}$) | $T$ (K) | $\lambda$ (ecliptic) | $\beta$ (ecliptic) | Ref. |
|------------|--------|------------------|---------|----------------------|-------------------|-----|
| EUVE       | He$^0$ | $24.5 \pm 2$    | $6500 \pm 2000$ | $74.7 \pm 0.5$ | $-5.7 \pm 0.5$ | [31] |
| IBEX       | He$^0$ | $26^{+440}_{-680}$ | $75.75 \pm 0.92$ | $-5.29 \pm 0.05$ | [16] |
| IBEX       | He$^0$ | $27.0 \pm 1.3$  | $74.5 \pm 1.7$ | $-5.2 \pm 0.3$ | [12] |
| IBEX       | He$^0$ | $25.76 \pm 0.4$ | $7440 \pm 260$ | $75.75 \pm 0.5$ | $-5.16 \pm 0.10$ | [4] |
| IBEX       | He$^0$ | $26.21 \pm 0.37$ | $7691 \pm 230$ | $75.41 \pm 0.40$ | $-5.03 \pm 0.07$ | [28] |
| Ulysses    | He$^0$ | $26.08 \pm 0.21$ | $7260 \pm 270$ | $75.54 \pm 0.19$ | $-5.44 \pm 0.24$ | [34] |
| STEREO     | He$^+$ PUI | $26.08 \pm 0.21$ | $7260 \pm 270$ | $75.21 \pm 0.04$ | [17] |
| STEREO     | He$^+$ PUI | $26.08 \pm 0.21$ | $7260 \pm 270$ | $75.41 \pm 0.34$ | [29] |
| LIC cloud  | H$^0$  | $23.84 \pm 0.90$ | $7500 \pm 1300$ | $78.53 \pm 3.4$ | $-7.20 \pm 3.3$ | [23] |
| LIC cloud  | H$^0$  | $23.9$           | $78.6$ | $-7.0$ | [13] |
| G cloud    | H$^0$  | $29.6 \pm 1.1$  | $5500 \pm 400$ | $71.11 \pm 1.9$ | $-8.52 \pm 3.6$ | [23] |
| Blue cloud | H$^0$  | $13.89 \pm 0.89$| $3900 \pm 2300$| $79.09$ | $-26.60$ | [23] |
| SWAN       | H$^0$  | $22 \pm 1$     | $11500 \pm 1000$ | $72.5$ | $-8.8$ | [11] |
| Ulysses    | dust   | $26$           | $75 \pm 30$ | $-13 \pm 4$ | [27] |

The speed and direction of the interstellar neutral helium gas flowing into the heliosphere do not agree with the mean properties of the LIC and G clouds, although the LIC cloud properties are closer to the helium inflow values. The disagreement between the helium inflow velocity and the LIC velocity is about 2 km s$^{-1}$ in speed and 2–3 degrees in direction. There are several possible explanations for these differences. (1) The non-thermal broadening component of the measured spectral line widths is $\pm 1.6$ km s$^{-1}$, implying variations in the flow speed within the LIC comparable to the disagreement in speed. (2) The neutral helium flow has secondary component called the “helium warm breeze” [10,3] and may have additional components that result in the measured inflow vector being slightly different from the vector far from the influence of the solar wind and charge-exchange reactions. (3) Measurements of the helium inflow vector assume that the atoms have a Maxwell-Boltzmann velocity distribution, but the Voyagers measure plasma beyond the termination shock that is better fitted by kappa functions (e.g., [41]) that could be anisotropic. (4) The helium inflow parameters obtained from analysis of the IBEX data have tightly correlated parameters [4] in which a 2 km s$^{-1}$ and an increase 3 degrees in ecliptic longitude $\lambda$ equally can fit the data within errors.

Until these possible causes for the disagreement between the helium inflow and LIC vectors...
are better understood, the simplest explanation is that the disagreement results from a real difference between the helium inflow vector and the LIC vector. The morphology of the LIC (see next section) and the less than 50% sky coverage both indicate that the Sun is far from the core of the LIC and likely at its edge. The 2 km s$^{-1}$ difference in the flow speed could be simply explained by the flow speed at the edge of the LIC being slightly different than in its core with a difference similar to the measured non-thermal broadening of the spectral lines.

4. A three dimensional model for the LIC

We have constructed a three dimensional model of the LIC using 62 sight lines with radial velocities consistent with the LIC velocity vector [13] Figure 4 shows this model in Galactic coordinates as viewed from the North Galactic Pole. Located at coordinates (0,0) in this figure, the Sun is at the edge of the LIC or perhaps just beyond the edge. The slightly less than half sky coverage of the LIC shown in Figure 3 is consistent with the Sun being at or just beyond the edge of the LIC. The geometric size of the LIC is inversely proportional to the neutral hydrogen number density, which we assume is 0.2 cm$^{-3}$, and its mass is about 0.32 $M_\odot$ [5].

5. Inverting the model of the LIC and the hydrogen hole

The three dimensional model of the LIC allowed us to compute the neutral hydrogen column density $N(\text{H I})$ from the geometric center of the LIC outwards in all directions. Fig 5 shows the distance from the geometric center of the LIC outwards computed from $d=N(\text{H I})/n(\text{H I})$, where the neutral hydrogen density is $n(\text{H I})=0.2$ cm$^{-3}$ [25]. A large part of the lower right portion of this figure is white indicating very short distances from the center to the edge of the LIC. Linsky et al. [13] called this region the “hydrogen hole”. The lines of sight to three important stars traverse the hydrogen hole: Sirius B, $\epsilon$ CMa, and $\beta$ CMa. These three stars are all sources of EUV radiation with $\epsilon$ CMa the brightest source of 50.4–91.2 nm radiation observed during an all-sky survey by the Extreme Ultraviolet Explorer (EUVE) satellite [32,30]. $\beta$ CMa is the second brightest EUV source, and Sirius B is the nearest EUV emitting white dwarf. The identification of these strong EUV sources and especially $\epsilon$ CMa in the direction of the hydrogen hole is strong evidence that photoionization of neutral hydrogen by $\epsilon$ CMa produces the hydrogen hole. Welsh et al. [33] identified an interstellar tunnel in the direction of the CMa stars with very little neutral hydrogen. The hydrogen hole is likely the local portion of the interstellar tunnel.

As described by Strömgren [26], a star emitting EUV radiation will be surrounded by a region of ionized hydrogen out to a distance called the Strömgren radius where the EUV radiation becomes so dilute that recombinations exceed photo-ionizations. The volume of ionized hydrogen around the star is called a Strömgren sphere or an H II region. At the edge of the Strömgren sphere is a shell of partially ionized hydrogen with a thickness given by $\delta = 1.0/[n(\text{H I}) \times \sigma]$. For a density $n(\text{H I})=0.2$ cm$^{-3}$ and photoionization cross-section $\sigma \approx 10^{-17}$ cm$^2$, the thickness of a Strömgren shell is about 0.2 pc (40,000 au).

Figure 6 shows the hydrogen hole, three clouds (Blue, LIC, and G), and the directions to $\epsilon$ CMa, $\beta$ CMa, Sirius, and a few other stars. Although the exact shape of the hydrogen hole is not yet determined, it is roughly overlaid by the Blue cloud, which adds a small amount of $N(\text{H I})$ outside of the hydrogen hole. $\epsilon$ CMa is observed through the edges of the Blue and LIC clouds [7] with log($N(\text{H I})$) equal to 16.76 and 17.34 corresponding to cloud thicknesses of 0.12 and 0.35 pc, respectively. Sirius is observed through the Blue and LIC clouds with log($N(\text{H I})$) equal to 17.2 for each cloud [23] corresponding to cloud thicknesses of 0.25 pc. These thickness for the partially ionized clouds edges are consistent with their edges being Strömgren shells. Figure 7 shows the orientation of the local clouds relative to $\epsilon$ CMa as seen from the North Galactic Pole. The edges of the LIC, Blue, and G clouds illuminated by the EUV radiation from $\epsilon$ CMa are Strömgren shells.
Figure 4. Contour map of LIC as viewed from North Galactic Pole. The Sun is located at the origin (0,0). Red contours are cuts below the LIC center parallel to the Galactic plane, and the blue contours are cuts above. The two x symbols indicate the locations where the edge of the LIC is furthest above and below the plane of the figure.
Figure 5. Distances to the edge of the LIC from its geometric center computed from \(N(H\,I)\) along lines of sight to 62 nearby stars. The symbols are S for the Galactic coordinates of the hot white dwarf Sirius B, E for \(\epsilon\) CMa, and B for \(\beta\) CMa. Faint circles indicate the locations of stars near the hydrogen hole.

6. The photo-ionizing radiation field in the LISM and the Local Cavity

We now ask how \(\epsilon\) CMa, a star 124 pc distant, can dominate the local EUV radiation field. EUVE found that \(\epsilon\) CMa is by far the brightest radiation source in the 50.2-91.2 nm wavelength band [30]. Because interstellar hydrogen opacity is significant at these wavelengths, they estimated the unabsorbed stellar ionizing flux in this band to be \(2.7 \times 10^{46}\) photons s\(^{-1}\) assuming absorption by \(N(H\,I) = 9 \times 10^{17}\) cm\(^2\) along the line of sight. Since Gry et al. [7] found that \(N(H\,I) \leq 5 \times 10^{17}\) cm\(^2\) and could be as low as \(3 \times 10^{17}\) cm\(^2\), the intrinsic ionizing photon flux will be larger than that proposed by Vallerga [30].

The radius of a simple Strömgren sphere is,

\[
R^3 = \frac{3(dN_i/dt)}{4\pi\alpha n_i n_e}.
\]

Here \(dN_i/dt\) is the number of ionizing photons per second, which we assume to be \(\geq 2.7 \times 10^{46}\), \(\alpha\) is the hydrogen recombination factor \(4 \times 10^{-13}\), and \(n_i\) and \(n_e\) are the number densities of protons and electrons in the sphere. For simplicity we assume a pure hydrogen medium with \(n_i = n_e\). Overlapping Strömgren spheres produced by several hot stars will increase the size of the ionized region. There are no direct measurements of the electron density in the line of sight to \(\epsilon\) CMa, but dispersion measures of radio signal time delays from pulsars provide a good
estimate. The mean electron density in the lines of sight to the nearest six pulsars at distances of 156–361 pc is $0.0121 \text{ cm}^{-3}$. This is likely an upper limit to the electron density in the Local Cavity as densities are higher outside. With this value of $n_e$, the radius of the Str"omgren sphere surrounding $\epsilon$ CMa is $R \geq 160$ pc. Thus the local warm clouds are inside of the Str"omgren sphere of $\epsilon$ CMa, and the star photo-ionizes the outer edges (Str"omgren shells) of the LIC and other warm clouds. Also, $\epsilon$ CMa could be the main ionizing source in the Local Cavity.

7. What should an interstellar probe search for in the VLISM beyond the heliopause?

Zank [35] redefined the term very local interstellar medium (VLISM) to describe the region upwind of the heliopause and extending outward to 600–700 au where inflowing gas from the LISM is mediated by the deposition of heliospheric material. Gas in the LISM further from the heliosphere is considered pristine as heliospheric mediation does not extend this far. As described by Zank et al. [37] and Zank [35], hot neutral hydrogen atoms created by change exchange reactions inside the heliopause propagate outward into the VLISM where secondary charge exchanges produce hot or super-thermal protons referred to as pickup ions (PUI) that heat the VLISM gas. The 50–100 au mean free path of the hot neutral hydrogen atoms and the several hundred au equilibration length of the hot protons with interstellar gas result in the heated VLISM extending to 600–700 au [8]. Another source of heat in the VLISM immediately outside
Figure 7. The local ISM region within 3 pc of the Sun as viewed from the North Galactic pole showing the location of the four partially ionized clouds that are in contact with the outer heliosphere. Not shown are other clouds lying outside of the four clouds. Shown are the Sun (point), an exaggerated representation of the heliopause (circle around the Sun) and the LIC, G, Aql, and Blue clouds. Lines of sight projected on to the Galactic equator are shown for 5 stars. Red shading shows the Strömgren shells produced by EUV radiation from ε CMa. Also shown are the direction of inflowing interstellar gas as seen from the Sun and the direction to the Upper Scorpius region of the Scorpius-Centauri Association where the most recent supernovae likely occurred.
of the heliopause is compressible turbulence [1] that is subsequently converted into incompressible turbulence [2]. The propagation of shocks through the heliopause into the VLISM may also be important (e.g., [18]). Zirnstein et al. [40] predicted that a significant fraction of the energetic neutral atoms (ENAs) observed at 1 au results from charge-exchange reactions in the VLISM. The broad width of the Lyman-α absorption feature produced in the hydrogen wall (peak neutral hydrogen number density at 200–300 au) is consistent with temperatures of 20,000–30,000 K in the heated VLISM [14,9,36]. In situ measurements of temperature, turbulence, and super-thermal particle populations in the VLISM, which will test theoretical models (e.g., [38]), will be a major task for the proposed Interstellar Probe (ISP).

Immediately upwind of the heliopause, Voyager-2 measured a magnetic field strength $|B| = 7 \mu G$ with strength decreasing outward [2] and surprisingly little change in direction from the field inward of the heliopause. Further out in the VLISM, the magnetic field strength has been estimated to be about $3 \mu G$ on the basis that the hydrogen wall almost disappears if $|B| > 4 \mu G$ [36,8]. The existence of intense ENA emission in a circle projected on the celestial sphere and a model for the formation of this IBEX ribbon allowed Zirnstein et al. [39] to infer that the magnetic field strength just outside of the VLISM is $|B| = 2.93 \pm 0.8 \mu G$ and its direction in ecliptic coordinates. In situ measurements of magnetic field strength, orientation, turbulence, and possible heating processes beyond the heliopause and through the VLISM will be another major task for a future ISP.

After passing through the VLISM, a future interstellar spacecraft will enter the pristine LISM, which will likely be in the partially ionized Strömgren shell at the edge of the LIC. At a spacecraft speed of roughly 8 au per year, the motion of the spacecraft through the LISM will be only a small difference from the 24 km s$^{-1}$ speed of the Sun relative to the LISM flow. As shown in Figure 7, the Sun is traveling through space in the direction the G cloud (the opposite of the LISM inflow direction). When the Sun leaves the edge of the LIC (in $\leq 1,900$ yr) it could enter the G cloud, which has slightly different temperature than the LIC but unknown density and pressure. It could instead enter a transition region between the LIC and G clouds with unknown properties, or it could enter the Strömgren sphere gas with very low density, high ionization, and 10,000-20,000 K temperature. New studies are needed to determine which is the most likely scenario.

8. Takeaway points

**Understanding the Heliosphere-ISM interface:** Despite the many differences between the terminology and perspectives of heliospheric and interstellar medium research, the common physical processes occurring at the interface between the outer heliopause and the very local interstellar medium (VLISM) will facilitate the development of this new emerging research topic.

**UV spectroscopy measures the kinematics and physical properties of the LISM:** The prime observational method for determining the kinematics and physical properties of the VLISM is the measurement of spectral line profiles for interstellar neutral and ionized atoms observed in absorption against the bright emission lines and continua of nearby stars. The high resolution spectrographs on HST provide the data needed to infer velocity vectors, gas temperatures, and non-thermal broadening parameters for the warm partially ionized interstellar clouds within 15 pc of the Sun.

**The heliosphere is at the edge of the LIC:** The three dimensional morphological model of the Local Interstellar Cloud (LIC) shows that the Sun is likely at the edge of the LIC. The different speed and directions of the the inflowing neutral helium measured by IBEX and Ulysses compared to the mean flow of LIC gas is consistent with the edge of the LIC having slightly different kinematical properties than the LIC core.
There is a hydrogen hole in the direction of $\epsilon$ CMa: Inversion of the three dimensional model of the LIC shows that as seen from the geometric center of the LIC there is a large region of negligible neutral hydrogen column density that we call the hydrogen hole. The strongest source of photo-ionizing EUV radiation is from the star $\epsilon$ CMa, which is in the direction of the hydrogen hole. The second brightest source of EUV radiation ($\beta$ CMa) and the nearest hot white dwarf (Sirius B) are also seen through the hydrogen hole.

The heliosphere and local warm clouds are inside of $\epsilon$ CMa’s Strömgren sphere: The ionizing radiation emitted by hot stars produces a surrounding region of ionized gas called a Strömgren sphere with an outer shell of partially ionized gas called a Strömgren shell. The very low electron density in the Local Cavity measured by pulsar dispersion measures predicts that the Strömgren sphere surrounding $\epsilon$ CMa has a radius of at least 160 pc. Since $\epsilon$ CMa is only 124 pc distant, the Strömgren sphere gas envelopes the local warm gas clouds ionizes their outer edges (Strömgren shells), and ionizes hydrogen in the direction of this star producing the hydrogen wall. We propose that the ionizing radiation from $\epsilon$ CMa and hot white dwarfs is responsible for the Local Cavity gas being ionized but not hot.

What should an interstellar probe search for in the VLISM and beyond in the LISM?
The decrease in the magnetic field strength with distance beyond the heliopause should be measured as well as changes in field direction, turbulence modes, and possible plasma heating from turbulence in the magnetic field. Also the thermal and super-thermal particle distributions and local heating rates should be measured to test theoretical models of the modulation of the inflowing LISM gas. The plasma and magnetic field properties of the hydrogen wall region at 200–300 au and the end of mediation predicted to be near 600–700 au are particularly interesting. An interstellar probe entering the pristine LISM will sample the properties of the Strömgren shell edge of the LIC. The speed of the interstellar probe of about 8 km s$^{-1}$ will be small compared to the 24 km s$^{-1}$ speed of the Sun through the LISM, and thus both will be heading in the direction of the G cloud. Whether they directly enter the G cloud, or a possible transition region between the LIC and the G cloud, or perhaps Strömgren sphere ionized plasma is presently speculation.

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