The Local Interstellar Medium: Comparison with IBEX Results, Sightlines to Exoplanet Host Stars, and Trajectories of the Voyager Spacecraft

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Abstract. We report on our recent studies of the local interstellar medium (LISM) using high-resolution ultraviolet spectra of nearby stars with the \textit{Space Telescope Imaging Spectrograph (STIS)} instrument on the \textit{Hubble Space Telescope (HST)}. Our objective is to measure the physical properties, kinematics, and morphology of the LISM near the Sun. After describing our techniques, we call attention to the different direction and speed of the gas in the Local Interstellar Cloud (LIC) surrounding the Sun compared to the infall vector of neutral helium entering the heliosphere as measured by the \textit{Interstellar Boundary Explorer (IBEX)} and \textit{Ulysses} spacecraft. We then suggest possible explanations for the differences. We describe the cloud structure and gas properties along the lines of sight to 3 nearby exoplanet host stars. Finally, we determine the cloud structure and properties of the interstellar gas in the directions that the \textit{Voyager} spacecraft are heading. In the trajectory of \textit{Voyager 2}, there is no absorption from the LIC or the very close G cloud suggesting that the Sun may lie very close to the outer edge of the LIC or perhaps even outside of the LIC.

1. Inferring kinematic and morphological properties of the LISM gas

For the last 16 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 \textit{Hubble Space Telescope (HST)} consist of stellar emission line spectra with narrow absorption lines produced by neutral and ionized gas in the lines of sight to these stars. We have now acquired spectra of more than 200 stars that are distributed across the sky sampling nearly all Galactic coordinates (see Figure 1). The \textit{HST} spectra were obtained mostly with the \textit{Space Telescope Imaging Spectrograph (STIS)} instrument with resolutions of 3.0–6.5 km/s, but we also use some ground based spectra of the Ca II H and K lines. The \textit{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 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 or smaller. With this large data set, Redfield & Linsky (2008) (hereafter RL08) 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 simple, it fits the data quite well (Redfield & Linsky 2015), 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 (2014), 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 $v_r$ and the column density of that ion $N_{\text{ion}}$, the observation of multiple ions in the same sightline provides a wealth of information. Comparison of the line widths ($b$) of different ions or neutrals with different atomic masses ($m$) allows one to determine the temperature ($T$) and turbulent velocity ($\xi$) of the gas (see Figure 3). 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 phase. Accurate depletions require measurements.
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.

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 (Redfield & Falcon 2008). The ratio of Mg I/Mg II is also sensitive to electron density (Gry & Jenkins 2014). An upper limit to the neutral hydrogen number density can be obtained from the hydrogen column density and sightline distance or from theoretical models (e.g., Slavin & Frisch 2008, Frisch et al. 2011).

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 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 (Redfield 2009). The velocity structure of the LISM is therefore very clumpy. We then deleted data points one by one starting with the most discrepant data 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 \(T = 7500\pm1300\) K, mean turbulence \(\xi = 1.62\pm0.75\) km s\(^{-1}\), and logarithmic depletions of Fe and Mg (\(-1.12\pm0.10\) and \(-0.97\pm0.23\), respectively). A similar analysis of the data for the remaining sightlines led to the identification of 14 other clouds. The nearest clouds to the Sun are the G cloud in the direction of \(\alpha\) Cen (1.3 pc) toward the Galactic center, and the Blue cloud in the direction of Sirius (2.6 pc). The G cloud covering about 20% of the sky has a mean temperature \(T = 5500\pm400\) K, while the Blue cloud covering about 6%
Figure 3. Determination of temperature \( T \) and turbulence \( \xi \) from the widths of spectral lines of many elements with different atomic weights. \textit{Left panels:} Plots of the range of parameter space \( (\xi \text{ and } T) \) consistent with the measured widths (solid lines) and their measurement errors (dashed lines) for different elements and ions. The symbol \( \times \) shows the best agreement and the solid lines around \( \times \) are 1\( \sigma \) and 2\( \sigma \) uncertainties in the best fit parameters. \textit{Right panels:} Plots of the Doppler width parameters \( b \) for each element and the least squares best fit for \( T \) and \( \xi \). For HZ 43 (top panels) deuterium is thermally broadened and the heavier elements are increasingly broadened by turbulence with increasing mass. For the sightline to \( \upsilon \text{ Peg} \), the inferred temperature is low and thermal broadening is very small for all elements. Figure from Redfield & Linsky (2004).

of the sky may have even cooler gas \( (T = 3900 \pm 2300 \text{ K}) \). Figure 4 shows the location of the four closest clouds in Galactic coordinates. These clouds are partially ionized with hydrogen about 26\% ionized if the LIC is representative (Slavin & Frisch 2008).

After this 15 cloud model was constructed, we obtained observations of 34 stars randomly selected from a much larger list in an \textit{HST SNAP} program. Malamut et al. (2014) 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 http://sredfield.web.wesleyan.edu. Figure 5 shows the complete 15 cloud model.

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
Figure 4. Location in Galactic coordinates of four nearby interstellar clouds: LIC, G, Blue, and Mic. The star symbols indicate the location of GJ 780 (lower symbol) and GJ 754 (upper symbol). Both stars are in directions outside of the four closest interstellar clouds. Original figure from RL08.

velocity predicted by the LIC vector in the direction of $\alpha$ Cen 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 3000 years (Redfield & Linsky 2000), perhaps very soon.

2. 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. (2015) reanalyzed the Ulysses spacecraft observations of neutral helium, and the Interstellar Boundary Explorer (IBEX) observations of helium have been analyzed by Möbius et al. (2015), Leonard et al. (2015), and Bzowski et al. (2015). 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).

The speed and direction of the interstellar 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 than the G cloud. The absence of agreement could be explained in several ways:

**Uncertain LIC mean properties:** RL08 obtained the mean kinematic and temperature parameters for the LIC from the analysis of data for 160 sightlines. Since then we have
Figure 5. Location in Galactic coordinates of the 15 interstellar clouds identified by RL08. The star symbols indicate the location of GJ 780 (lower symbol) and GJ 754 (upper symbol). Neither of the two sightlines shows absorption by the LIC or G clouds or spatial agreement with these clouds, but both show absorption likely produced by the Vel cloud. The ⊗ symbols indicate the upwind directions and the ⊙ symbols indicate the downwind directions of the cloud velocity vectors. Original figure from RL08.

Table 1. Comparison of heliospheric and astronomical measurements of inflowing LISM neutrals

| Source      | $v_r$ (km s$^{-1}$) | $T$ (K)     | $\lambda$ (ecliptic) | $\beta$ (ecliptic) | Reference          |
|-------------|---------------------|-------------|-----------------------|--------------------|--------------------|
| IBEX       | 26                  | 8710$^{+440}_{-680}$ | 75.75 ± 0.92          | −5.29 ± 0.05       | Möbius et al. (2015) |
| IBEX       | 27.0 ± 1.3          | 74.5 ± 1.7  | −5.2 ± 0.3            |                    | Leonard et al. (2015) |
| IBEX       | 25.8 ± 0.4          | 7440 ± 260 | 75.8 ± 0.5            | −5.16 ± 0.10       | Bzowski et al. (2015) |
| Ulysses    | 26.08 ± 0.21        | 7260 ± 270 | 75.54 ± 0.19          | −5.44 ± 0.24       | Wood et al. (2015)   |
| LIC cloud  | 23.84 ± 0.90        | 7500 ± 1300| 78.55 ± 3.4           | −7.19 ± 3.3        | RL08               |
| G cloud    | 29.6 ± 1.1          | 5500 ± 400 | 71.11 ± 1.9           | −8.52 ± 3.6        | RL08               |

increased the number of LIC sightlines by about 25%. The resulting change in the LIC parameters is very small with $\Delta v_r = 0.1$ km s$^{-1}$, $\Delta \lambda = +0.1$, and $\Delta \beta = +0.2$. As a result, we do not anticipate a major change in the mean LIC parameters with future analyses of larger data sets.

Turbulence near the heliosphere: The radial velocity dispersion of the LIC gas, which we have called turbulence, is $\pm 1.6$ km s$^{-1}$. If the gas speed in the LIC near the heliosphere is 1.6 km s$^{-1}$ larger than the mean speed for the LIC, then $v_r = 23.84 + 1.6 = 25.46$ km s$^{-1}$,
which is consistent with the *IBEX* and *Ulysses* measurements of the speed of inflowing helium atoms. The large uncertainty in the flow direction of the LIC gas is not inconsistent with the flow directions measured by *IBEX* and *Ulysses*, and the LIC gas temperature is in good agreement with their results. Thus a higher speed of the LIC gas close to the heliosphere is a viable explanation for the discrepancy as suggested by Bzowski et al. (2015).

**Helium Warm Breeze:** The derived speed and direction of the inflowing helium atoms observed by *IBEX* requires two components: the main component and a secondary component now called the “Helium Warm Breeze” discovered by Kubiak et al. (2014). According to Bzowski et al. (2015), the Warm Breeze component needed to be included when fitting the *IBEX* helium data is substantial (4–10% of the main component flux) but highly uncertain, leading to possible systematic errors in the inflow speed and direction of the main component. They argued that there may be an as yet unaccounted for additional component in the heliosphere. It is important to decrease the uncertainty in the helium flow parameters through more observations and more sophisticated data analysis. Simulations presented by Bzowski et al. (2017) show that the Warm Breeze can be explained by charge exchange reactions between neutral He and He$^+$ in the outer heliosphere that is distorted by the interstellar magnetic field.

**Non-Maxwellian velocity distribution:** Since densities in the LISM clouds are very low (about 0.2 cm$^{-3}$), the velocity distribution of atoms and ions in the LISM gas may differ substantially from a Maxwellian distribution. Space plasmas, such as those seen by Voyager beyond the termination shock, often have power-law tails that can be fitted with kappa functions (e.g., Zirnstein & McComas 2015). Whether the electron and proton energy distributions in partially ionized LISM clouds should be characterized by kappa functions is an open question.

**Helium inflow parameters are fitted inside of heliosphere:** The *IBEX* observations are fitted with helium inflow parameters extrapolated to a distance of 150 AU. However, the peak neutral hydrogen density in the solar hydrogen wall occurs near 300 AU and “pristine” interstellar densities occur beyond 600 AU in the plasma model of Zank et al. (2013). Thus the comparison of the helium inflow parameters and the LIC velocity vector refer to different locations. Just as the inflow speed of neutral hydrogen is decelerated by charge-exchange interactions, especially in the heliopause and hydrogen wall regions, neutral helium atoms may experience a much smaller but still significant deceleration by charge exchange or other collisional interactions between 150 and 600 AU.

**Helium inflow parameters are tightly correlated:** Bzowski et al. (2015) showed that $T$, $v_r$, and $\lambda$ are tightly correlated in the analysis of *IBEX* observations of inflowing helium. If for some reason the inflow speed of helium is 24 km s$^{-1}$ rather than 25.8 km s$^{-1}$, then the tight correlations among parameters require that $T = 6300$ K, $\lambda = 78.5$, and $\beta = -5$. These parameters would then all be consistent with the LIC parameters. This calculation highlights the need to better understand the Helium Warm Breeze and its effects on the determination of the helium inflow parameters from the *IBEX* observations. However, the analysis of the *Ulysses* data from all parts of its orbit does not involve any tight correlations among parameters and may, therefore, provide a more precise determination of the He flow vector.

At this point in time, we can likely rule out only the first possible explanation for the disagreement in flow parameters. The other possible explanations require further study or observations. It is important to understand the reason or reasons for the present disagreement, in particular whether the disagreement results from errors in the analysis of *IBEX* and *Ulysses* data or from departures from the mean flow of LIC gas near the heliosphere.
3. Properties of LISM gas along the sightlines to three exoplanet host stars

One objective of our study of LISM gas is to identify the interstellar gas properties along sightlines to nearby planet-hosting stars. This information is important for the analysis of Lyman-α and other stellar emission lines with interstellar absorption components during planetary transits in order to separate absorption by an exoplanet’s atmosphere from interstellar absorption. We are also looking for evidence of stellar winds that can be measured from Lyman-α absorption in the star’s astrosphere. Edelman et al. (2018) will be submitting a paper soon analyzing STIS spectra of the Mg II, Fe II, and Lyman-α lines for three planet-hosting stars: HD 192310 (K2 V), HD 9826 (F9 V), and HD 206860 (G0 V). We identify absorption by the LIC and two other clouds in the sightlines to each star, but none of the stars shows astrospheric absorption in the Lyman-α line. We also list the clouds in the sightlines to all planet-hosting stars within 20 pc of the Sun based either on measurements or from the kinematic calculator described above.

4. Properties of the LISM gas along the trajectories of the Voyager spacecraft

On April 16, 2018 Voyager 1 was at a distance of 141.84 AU from the Sun past the heliopause and heading toward the edge of the heliosphere at a speed of 3.6 AU/year. At this time Voyager 2 was at 117.27 AU in the heliosheath and in the process of leaving the heliosphere at a speed of 3.26 AU/year. What will be the interstellar environments that these spacecraft will encounter after leaving the heliosphere? Zachary et al. (2018) have investigated this question by analyzing STIS spectra of four stars located within 10 pc — two stars (GJ 678.1A and GJ 686) in the general direction that Voyager 1 is headed and two (GJ 780 and GJ 754) in the direction that Voyager 2 is headed (see Figure 6). The present positions of the Voyager spacecraft, coordinates (Galactic and ecliptic) of the four stars and the angular distances from the Voyager sightlines (Δθ) are listed in Table 2. Both GJ 678.1A and GJ 754 show absorption predicted by the LIC velocity vector and second components consistent with other clouds. We, therefore, predict that Voyager 1 will first pass through the peak of the hydrogen wall at 300 AU in 44 years and then in about 127 years enter the pristine LIC at 600 AU. These locations are from the plasma model of Zank et al. (2013). The RL08 LISM model predicts that Voyager 1 will leave the LIC in about 1,900 years. It may then enter the Oph, NGP, or Mic clouds.

| Spacecraft or Star | Distance | l (Galactic) | b (Galactic) | λ (Ecliptic) | β (Ecliptic) | Δθ (degrees) |
|--------------------|----------|--------------|--------------|--------------|--------------|--------------|
| Voyager 1           | 141.84 AU| 33.31        | +27.15       | 256.17       | +35.20       |              |
| GJ 678.1A           | 9.98 pc  | 28.57        | +20.54       | 261.84       | +28.76       | 8.1          |
| GJ 686              | 8.09 pc  | 42.24        | +24.30       | 263.20       | +41.89       | 9.0          |
| Voyager 2           | 117.27 AU| 340.03       | −32.73       | 290.63       | −36.36       |              |
| GJ 780              | 6.11 pc  | 329.77       | −32.42       | 287.87       | −44.70       | 9.2          |
| GJ 754              | 5.92 pc  | 352.36       | −23.90       | 285.50       | −23.18       | 13.1         |

The trajectory of Voyager 2 is very different from Voyager 1. The sightlines of GJ 780 and GJ 754 do not show absorption at the predicted LIC or G cloud velocities. Instead, both show absorption by the Vel cloud and other clouds (Dor, Mic, and Aql). The absence of absorption at the predicted LIC velocity indicates that the Sun is located either barely inside of the LIC.
Figure 6. Trajectories of the Voyager 1 (V1) and Voyager 2 (V2) spacecraft. Solid lines indicate their trajectories through the solar system, the termination shock, and the heliopause (for V1) and dashed lines indicate future paths above and below the ecliptic plane. Solid lines enclose the LISM that the Voyagers will encounter. The vertical dashed line is for the distance of 1 pc. KB refers to the location of the Kuiper belt and OC refers to the location of the Oort cloud.

with only an upper limit to the column density of LIC gas in the Voyager 2 sightline or perhaps just outside of the LIC. Figure 4 shows that GJ 780 and GJ 754 are located away from LIC and G clouds but near or perhaps inside of the Vel or other clouds (see Figure 5). We predict that Voyager 2 will enter the hydrogen wall peak in about 56 years and enter the pristine LISM in
about 148 years. Which LISM cloud it will enter, however, is uncertain. It may traverse a thin layer of the LIC for less than 2000 years or directly enter the Vel or another cloud.

5. Conclusions
The outer edge of the heliosphere can be studied from an external perspective by analyzing interstellar absorption line measurements and from an internal perspective by analyzing observations of inflowing helium atoms obtained by the IBEX and Ulysses satellites. At present these two techniques do not provide consistent results for the gas flowing into the heliosphere. Whether the different inferred properties of the inflowing gas result from (a) the LIC having inhomogeneous kinematics, with the gas flowing into the heliosphere moving slightly faster than the mean LIC flow, or (b) from inaccurate knowledge of the Helium Warm Breeze or another component of the helium flow is a challenge that must be resolved. It is essential that both techniques be studied in detail until we have a robust understanding of the interface between the outer heliosphere and the inner LISM.

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