Jeffrey L. Linsky, Seth Redfield, and Max Schwarz

1. JILA, University of Colorado and NIST, Boulder CO, USA 80309-0440
2. Astronomy Department and Van Vleck Observatory, Wesleyan University, Middletown CT, USA 06459-0001
3. APS Department, University of Colorado, Boulder CO, USA 80309-0391

E-mail: jlinsky@jila.colorado.edu

Abstract. Analysis of high-resolution interstellar absorption lines observed in the ultraviolet spectra of nearby stars provides the basis for identifying 15 partially ionized warm “clouds” of interstellar gas located within a few parsecs of the Sun. We show visualizations of these clouds as seen from different directions. The presence of discrete clouds implies one or more physical processes that establish these structures and the presence of gas with very different properties between these clouds. While classical models of the interstellar medium based on the assumptions of pressure and ionization equilibrium in a nonmagnetic medium are not consistent with observations, dynamical simulations without these assumptions are likely more realistic. Possible physical processes that could structure the clouds include ram pressure, magnetic fields, and photoionization by extreme-ultraviolet radiation. We describe the available evidence concerning these three processes.

1. The many connections between the LISM, the heliosphere, and the Galactic interstellar medium

The local interstellar medium (LISM) is a collection of partially ionized gas clouds located within a few parsecs of the Sun. Each of these clouds is identified by a common velocity vector inferred from interstellar absorption-line radial velocities measured in high-resolution spectra towards stars covering a broad region of the sky. Redfield & Linsky (2008) [1] used HST ultraviolet spectra of 157 stars to identify 15 such clouds, each located within 0–15 pc of the Sun. Each cloud is located either in front of or surrounding the nearest star that shows interstellar absorption lines with a radial velocity consistent with the cloud’s vector velocity. Observations of interstellar absorption towards 40 additional stars [2] confirmed the existence and location of these clouds. Gry and Jenkins (2014) [3] subsequently proposed that these 15 clouds are actually a single cloud with a complex velocity structure. However, Redfield et al. (2015) [4] made the case for discrete clouds on the basis of a better fit to the observed radial velocities for the new data set of 40 observed stars and the presence of quasar-scattering sites at the edges of the clouds [5]. For comprehensive reviews of LISM science and the interaction between the solar wind and the LISM, see [6,7].
Understanding the structure and properties of the LISM clouds is important, because the LISM serves as an interface between the heliosphere and the Galactic interstellar medium, providing physical insights concerning both. The Sun is located barely inside the Local Interstellar Cloud (LIC) (see Figure 1), and the motion of the Sun through space will take the heliosphere outside of the LIC and into either: (a) the adjacent G cloud, (b) an interface between the LIC and G clouds, or (c) the highly ionized gas that may lie between the LISM clouds. This transition will occur in less than 4000 years [8], perhaps far less. Müller et al. (2006) [8] calculated the location of the termination shock, heliopause, and bow shock for a wide range of interstellar densities, temperatures, and flow velocities that the heliosphere would see during its past and future trajectory through the inhomogeneous LISM. For example, the passage of the heliosphere through a cloud with a neutral hydrogen density of \(11 \text{ cm}^{-3}\) rather than the present value of about \(0.2 \text{ cm}^{-3}\) would shrink the termination shock from about 90 AU in the upwind direction to only 14 AU. Since the LISM clouds are located nearby, our understanding of their properties will provide insight into the properties of partially ionized gas in more distant regions of the Galaxy. The ISM plays a critical role in the chemical evolution of the Galaxy with enrichment from supernova explosions and stellar mass loss and the subsequent formation of a new stars from the chemically enriched interstellar gas.

The physical properties and evolution of interstellar gas have been the subject of numerous theoretical and simulation studies. The now classic theoretical models [9], [10], and [11] postulate a steady-state interstellar medium in pressure and thermal equilibrium. These models predict that the ISM includes two or three thermal components, including a warm component with a temperature of about 8,000 K and density about \(0.1 \text{ cm}^{-3}\) that is similar to the properties of the LIC [6]. De Avillez & Breitschwerdt (2005) [12] proposed a very different model for the ISM on the basis of their three-dimensional MHD simulations. In these simulations, the energy source is random supernova events resulting in an ISM that is highly turbulent with no stable thermal phases and a wide range of plasma temperatures, densities, pressures, and magnetic field strengths. They find that, on average, magnetic pressure dominates for low temperature gas (\(T < 200 \text{ K}\)), ram pressure dominates for plasma at temperatures \(200-10^6 \text{ K}\), and thermal pressure dominates at \(T > 10^6 \text{ K}\). Do the observed physical properties of the LISM support the theoretical or simulations models? Which of these pressure terms dominates in the LISM, or is there another process that controls the properties, in particular the structure, of the LISM clouds?

2. Visualizing the LISM in three dimensions

Our analysis of interstellar absorption lines [1] provided neutral hydrogen column densities \(N(\text{H I})\) and cloud identifications along the lines of sight to many nearby stars with known distances.
To visualize the spatial layout of the clouds in three dimensions requires several assumptions. First, we assume that the neutral hydrogen density in all of the clouds is the same as for the LIC, \( n(\text{HI}) = 0.20 \, \text{cm}^{-3} \) [6]. Second, we assume that along each line of sight the cloud is centered at the midpoint to the star, and its thickness is \( \Delta d = N(\text{H I})/n(\text{H I}) \). We require that stars with observed astrospheres are located within one of the partially ionized clouds and that clouds do not overlap. Finally, we smooth the cloud surfaces.

Our simplifying assumptions should be tested when sufficient data become available. A major concern is that the neutral hydrogen number density could vary considerably from cloud to cloud. There is no obvious way of measuring the neutral hydrogen number density directly. Density-sensitive line ratios can measure electron densities, but these are a function of the total hydrogen number density and the ionization state in the clouds. The placement of clouds along each line of sight and the fuzziness of the cloud surfaces are interesting but not critical to LISM morphology. Progress in understanding cloud morphology would benefit from analysis of many more lines of sight and the inclusion of physical constraints such as the location of ionization zones (e.g., Stromgren spheres) set by the EUV radiation field and the locations of interstellar shock fronts and strong magnetic fields.

The video clip located at http://jila.colorado.edu/~jlinsky/Interstellar_Clouds.mp4 (or .wmv) shows the clouds in three dimensions as seen from various directions in the Galactic plane.

3. Potential causes for the structure of partially ionized clouds

We now consider three physical mechanisms that could shape the clouds in the LISM.

3.1. Ram pressure and intercloud collisions

![Figure 2. Zones of LISM cloud interactions. Colored regions indicate directions in which multiple LISM clouds are detected along the line of sight. Figure from [5].](image-url)
The simulations [12] predict that ram pressure should be the dominant pressure term that controls the structures of warm interstellar gas such as the LISM clouds. Figure 2 shows the velocity differences between two or more clouds along the same line of sight. The velocity differences are supersonic for many lines of sight, but we do not know whether the clouds along a given line of sight are in contact, in which case velocity differences greater than about 8 km/s would indicate shocks, or whether the clouds are not in contact, and there are no shocks. In either case, the figure provides support for the presence of large velocity differences in the ISM and thus potentially large ram pressures. A second argument for the importance of ram pressure in the LISM is shown in Figure 1. A considerable portion of the filamentary Mic cloud lies in the line of sight between the LIC and G clouds. Since the LIC and G clouds are approaching each other at a speed of 5.5 km s\(^{-1}\) and the LIC has the hottest gas (\(T = 9900\) K) of the 15 clouds [1], the LIC and G clouds may be compressing and thus heating the Mic cloud between them. This possible interaction supports the hypothesis that ram pressure or intercloud collisions structure the LISM clouds. However, we have no independent evidence that the Mic cloud actually lies between the LIC and G clouds rather than being simply more distant. The Mic cloud could be anywhere along the 5.1 pc line of sight to the nearest star \(\alpha\) Aql behind the cloud.

As a test of whether ram pressure controls the structure of the LISM clouds, we computed the cloud shapes as seen from the upwind direction of the interstellar flow vector (\(l=155^\circ\), \(b=7^\circ\)). Figure 3 shows no evidence for cloud elongations along the flow direction. We then plotted the cloud shapes perpendicular to the flow to search for elongations produced by the flow. None of the clouds showed thin structures aligned perpendicular to the flow.

![Figure 3](image1.png) **Figure 3.** The LISM clouds as viewed from the upwind direction of the interstellar flow.

![Figure 4](image2.png) **Figure 4.** The LISM clouds as viewed from the magnetic field direction.

### 3.2. Magnetic fields

The Voyager 1 spacecraft has been measuring magnetic fields in the heliopause, and the IBEX spacecraft has observed energetic neutral atoms (ENAs) with higher fluxes along a ribbon now referred to as the “IBEX ribbon”. Heerikhuisen et al. (2010) [13] proposed and Zirnstein et al. (2016) [14] refined a model for the ribbon in which the ribbon’s shape as a function of ENA energy is produced by the interstellar magnetic field draped around the heliopause. In their model...
the extrapolated-interstellar magnetic field away from the heliosphere is $2.93 \pm 0.08 \ \mu\text{Gauss}$. This magnetic field strength is consistent with Voyager 1 observations [15] and evidence from interstellar polarization [6]. For this value of the interstellar magnetic field, the magnetic pressure, $P_{\text{mag}}/k = 2480 \pm 130$. This pressure can be compared with the LISM cloud thermal pressures, $P_{\text{th}}/k = 2050 - 5030$ [6]. The plasma $\beta = P_{\text{th}}/P_{\text{mag}} = 0.5 - 1.2$, which suggests that magnetic fields may play a role in shaping the LISM clouds.

As a test of whether magnetic pressure is the pressure term controlling the structure of the LISM clouds, we computed the cloud shapes as seen from the direction of the interstellar magnetic field ($l=206^\circ$, $b=-50^\circ$) [14]. Figure 4 shows no evidence for cloud elongations along the magnetic field direction. We then plotted the cloud shapes perpendicular to the magnetic field vector to search for elongations produced by the magnetic field, but none of the clouds showed thin structures perpendicular to the magnetic field.

Figure 5. Distances from the geometric center of the LIC to its edge and the line of sight directions to three strong EUV radiation sources: $\epsilon$ CMa (E), $\beta$ CMa (B), and Sirius B (S).

3.3. Photoionization by EUV radiation
The Extreme Ultraviolet Explorer (EUVE) spacecraft, which observed the sky in the 70–730 Å EUV spectral range, detected many stars as sources of EUV radiation. In particular, the B1 V star $\epsilon$ CMa is by far the brightest nonsolar EUV source despite its distance of 124 pc. Besides $\epsilon$ CMa, there are four other important EUV sources [16], $\beta$ CMa and three hot white dwarfs.
(G191-B2B, HZ 43, and Feige 24). Figure 5 shows the distances from the geometric center of the LIC to its edge in Galactic coordinates. Centered near l=270°, b=-30° is a region of minimal distance from cloud center to edge with ε CMa, β CMa, and the nearby white dwarf Sirius B located in this region. The apparent depletion of neutral hydrogen suggests that EUV radiation from ε CMa and to a lesser extent the other sources are the photoionizing sources.

EUV photons penetrate to a 1/e depth $d = 1/n(H\ I)\sigma$, where $\sigma = 1 \times 10^{-17}$ cm$^2$. For a density of 0.2, hydrogen atoms per cm$^{-3}$, the 1/e penetration depth is $d = 0.2$ pc and essentially all of the EUV photons will be absorbed by 0.6 pc. Since the mean radius of the LIC is about 1.5 pc, the decrease in radius from the center of the LIC shown in Figure 5 is consistent with photoionization by EUV radiation from ε CMa.

As a test of whether EUV photons from ε CMa shape other LISM clouds, we computed the cloud shapes as seen from the direction of ε CMa (l=59°, b=11°). We note that no other clouds lie in the path from ε CMa to the LIC that could shield the LIC. This is consistent with the “interstellar tunnel” proposed by [17] and [18] to explain the strong flux measured by EUVE. Figure 6 shows no evidence for cloud elongations along the ε CMa direction. We then plotted the cloud shapes perpendicular to the line of sight from ε CMa to search for elongations produced by EUV photoionization. We found four clouds with alignments that are perpendicular to the line of sight from ε CMa. These are shown in Figures 7 and 8 (for the Aur and Hyades clouds) and Figures 9 and 10 (for the NGP and Cet clouds).

4. Conclusions and perspectives
We have presented a three dimensional model for the location and structure of the 15 partially ionized LISM clouds [1]. Using this model, we have tested whether ram pressure, magnetic fields, or EUV radiation are the most likely physical process that shapes these clouds. We find that EUV radiation from the brightest nonsolar source, ε CMa, is the most likely source for shaping the LIC and four other LISM clouds.
**Figure 7.** Boundary of the Auriga cloud (solid line) and 90° from the εCMa line of sight (dashed line).

**Figure 8.** Boundary of the Hyades cloud (solid line) and 90° from the εCMa line of sight (dashed line).

**Figure 9.** Boundary of the NGP cloud (solid line) and 90° from the εCMa line of sight (dashed line).

**Figure 10.** Boundary of the Cet cloud (solid line) and 90° from the εCMa line of sight (dashed line).

5. Acknowledgements
We acknowledge support through the NASA HST Grant GO-11568 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. for NASA, under contract NAS 5-26555. We thank Steven Burrows (JILA) for creating the visual clip and Figures 3, 4, and 6. We also thank the referee for helpful suggestions.

6. References

[1] Redfield S and Linsky J L 2008 *Astrophys. J.* 673 283
[2] Malamut C, Redfield S, Linsky, J L, Wood B E and Ayres T R 2014 *Astrophys. J.* 787 75
[3] Gry C and Jenkins E B 2014 *Astron. Astrophys.* 567 A58
[4] Redfield S and Linsky J L 2015 *Astrophys. J.* 822 125
[5] Linsky J L, Rickett, B J and Redfield S 2008 *Astrophys. J.* 675 413
[6] Frisch P C, Redfield S and Shaviv J D 2011 *Ann. Rev. Astron. Astrophys.* 49 237
[7] Zank G P 2015 *Ann. Rev. Astron. Astrophys.* 53 449
[8] Müller H-R, Frisch P C, Florinski V, and Zank G P 2006 *Astrophys. J.* 647 1491
[9] Field G B, Goldsmith D W and Habing H J 1969 *Astrophys. J.* 155 L149
[10] McKee C F and Ostriker J P 1977 *Astrophys. J.* 218 148
[11] Wolfire M, McKee C, Hollenbach D and Tielens A 1995 *Astrophys. J.* 453 673
[12] de Avillez, M A and Breitschwerdt, D 2005 *Astron. Astrophys.* 436 585
[13] Heerikhuisen J, Pogorelov N V, Zank G P, et al. 2010 *Astrophys. J. Letters* 708 L126
[14] Zirnstein E J, Heerikhuisen J, Funstein, H O, Livadiotis, G. McComas, D J, and Pogorelov N V 2016 *Astrophys. J.* 818 L18
[15] Zank G P, Heerikhuisen J., Wood B E, et al. 2013 *Astrophys. J.* 763 20
[16] Vallerga J V 1998 *Astrophys. J.* 497 921
[17] Welsh B Y 1991 *Astrophys. J.* **373** 556
[18] Welsh B Y, Wheatley J, Dickinson N J and Barstow M A 2013 *Pub. Astron. Soc. Pacific* **125** 644