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What is the morphology of the local interstellar medium and its importance in the GAIA era?

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Abstract. High-resolution studies of interstellar absorption lines that appear in the spectra of nearby stars provide essential information on the physical properties and inhomogeneous structure of interstellar gas along short lines of sight. These absorption lines are primarily in the ultraviolet as observed with the *Space Telescope Imaging Spectrograph (STIS)* and *Cosmic Origins Spectrograph (COS)* instruments on the *Hubble Space Telescope (HST)*, but very sensitive ground-based spectra also are important. The local interstellar medium (LISM) within a few pc of the Sun provides a basis for testing the assumptions underlying theoretical models before these models can be applied reliably to understanding interstellar gas in more distant regions of the Galaxy where *GAIA* will be providing information on the stellar structure. We address here the critical question of whether the inhomogeneous properties of the LISM are more realistically characterized by a morphology consisting of many distinct structures, each with their own physical and kinematic properties, or by a continuous medium with nonrigid flows and spatially variable properties. We test these two models using a new data set with lines of sight randomly distributed in the sky. An expanded version of this paper is available (Redfield & Linsky 2015).

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

The gas and dust in the interstellar medium of our Galaxy is an inhomogeneous mixture of primordial material, chemically enriched gas ejected by stellar winds and catastropic explosions, and matter accreted from nearby low-mass galaxies. The study of the interstellar medium (ISM) is important because it provides information on the evolution of the Galaxy and is the raw material out of which new generations of stars are formed. The combination of Galactic stellar structure and evolution information provided by *GAIA* and the chemical and kinematic information provided by studies of the interstellar medium (ISM) will likely stimulate new understanding of the properties and evolution of our Galaxy.

High-resolution ultraviolet (UV) spectroscopy is a powerful technique for measuring the physical, chemical and kinematic properties of interstellar gas. One reason is that most absorption lines from the highly populated ground states of neutral and singly ionized atoms occur in the UV spectral region, especially at $\lambda < 200$ nm. Another reason is that interstellar absorption lines are generally narrow and typically have many velocity components produced by inhomogeneous flows along even short lines of sight. Thus high spectral resolution at < 3 km/s ($\lambda/\Delta\lambda \geq 100,000$) is highly desirable. The workhorse instrument for such studies is the *STIS* instrument on *HST*, but unfortunately there is no successor instrument ready to continue such observations after *HST*.

UV spectroscopy of nearby stars takes advantage of the relative brightness of the observed star, the accurately known distance to the star, and most important, the relatively small number of interstellar absorption velocity components compared to long lines of sight. The possible confusion of overlapping velocity components located at unknown locations along the line of sight makes it difficult to unravel the morphology and kinematic structure of the ISM in long lines of sight.

Since the pioneering early theoretical model of McKee & Ostriker (1977), there have been increasingly sophisticated models of the ISM that include energy input and loss terms, kinetic and thermal disequilibrium, dust, cosmic rays, and magnetic fields. There are also computer simulations describing the response of interstellar gas to supernova explosions. It is essential to test these theoretical models and simulations against high quality data for relatively simple short sightlines. Observations of the local ISM can provide an important test bed for these models even though the local region of space does not contain the full range of phenomenology that occurs in the Galaxy.

2. The development of different morphological models of the LISM

In the first survey of interstellar gas flows near the Sun, Crutcher (1982) called attention to the bulk flow of warm gas streaming from the direction of the Sco-Cen Association as seen in Ti II 338.4 nm absorption features in the spectra of stars within 100 pc of the Sun. He noted that this flow is consistent with an expanding shell of gas accelerated by the hot stars and supernovae in the Sco-Cen Association. Subsequent studies using UV spectrographs on the *Copernicus*, *International Ultraviolet Explorer (IUE)*, and the *Goddard High Resolution Spectrograph (GHRS)* on the *HST* satellites analyzed absorption lines of H I, D I, O I, C II, Fe II, and Mg II along many lines of sight toward nearby stars (e.g., McClintock et al. 1978; Frisch & York 1983; Lallement et al. 1994; Linsky & Wood 1996).

The accumulating UV and ground-based Ca II line spectra led Lallement et al. (1995) to identify two regions of space with different bulk flow patterns: one region in the Galactic Center direction, now called the G cloud, and another region in the opposite direction, now called the Local Interstellar Cloud (LIC) because the Sun appeared to lie inside of the LIC.

The installation of the *STIS* instrument on *HST* provided 3 km/s spectral resolution with wide spectral coverage to study many new lines of sight and identify additional regions in Galactic coordinates (new clouds) with distinct kinematic patterns (e.g., Frisch, Grodnicki, & Welty 2002; Redfield & Linsky 2002; Redfield & Linsky 2004). As shown in Figure 1, the measured radial velocity components cluster about the mean bulk flow but with statistically large deviations indicating that the flow pattern is far from homogeneous.

Redfield & Linsky (2008) [hereafter RL08] developed a 15 cloud model to characterize the 270 UV and Ca II radial velocity measurements toward 157 stars located within 100 pc of the Sun. All of these warm partially ionized clouds, now called the complex of local interstellar clouds (CLIC), must lie entirely or in part within 15 pc of the Sun, because the nearest stars showing absorption by the gas at each cloud's velocity lie within this distance. Since all of these lines of sight show absorption by partially ionized gas in these clouds or in not yet identified clouds, there is presently no direction in space where the neutral hydrogen column density log N(H I) < 17.4. Comparison of the widths of absorption lines of a low mass element (D) with high-mass elements (e.g., Fe and Mg) allowed Redfield & Linsky (2008) to infer the gas temperature of the LIC to be $T = 7500 \pm 1300$ K and the temperatures of

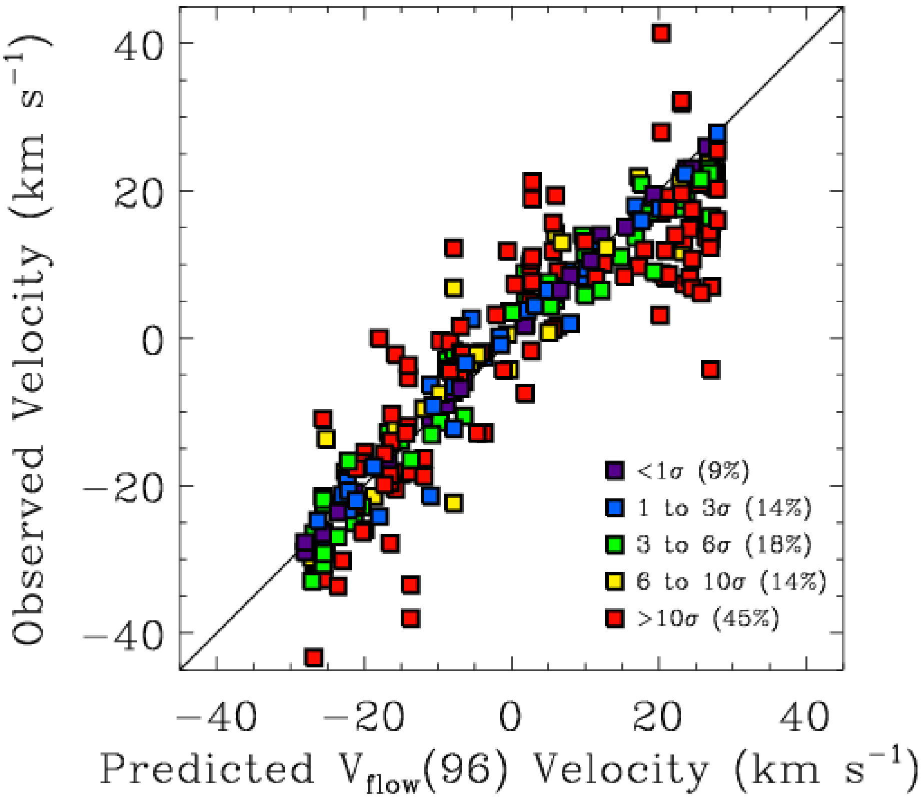

Fig. 1. A plot of the measured radial velocities for 96 interstellar velocity components vs. the best-fitting velocity vector for bulk motion. The data points are coded according to the ratio σ=deviation from the mean bulk motion velocity/velocity measurement error. Note that 45% of the data points lie more than 10σ away from the mean bulk motion, indicating the significant inhomogenity of velocity flows in the LISM. Figure from Redfield (2009).

the other clouds to lie in the range 3900 K (Blue cloud) to 9900 K (Mic cloud). This same method indicated that the nonthermal broadening of absorption lines viewed through the LIC is 1.62 ± 0.75 km s^{-1}, and the nonthermal broadening through the other clouds is in the range 1.2–3.6 km s^{-1}. The measured nonthermal broadening values are all well below the sound speed. Although Redfield & Linsky (2008) found no evidence for a cold gas cloud in their data set, Meyer et al. (2006) did find a cold cloud, now known as the Local Leo Cold Cloud, that lies somewhere between 11.3 and 24.3 pc from the Sun with a temperature of 15–30 K (Heiles & Troland 2003; Peek et al. 2011).

Frisch (2009) and Frisch, Redfield, & Slavin (2011) noted that the inferred temperatures and nonthermal broadening parameters assume a Maxwell-Boltzman distribution of velocities and mass-independent turbulence, which may not be valid for low density clouds. Frisch (2009) concluded that the physical properties of the CLIC clouds are typical of warm partially ionized gas observed elsewhere in the solar neighborhood on the basis of tem-

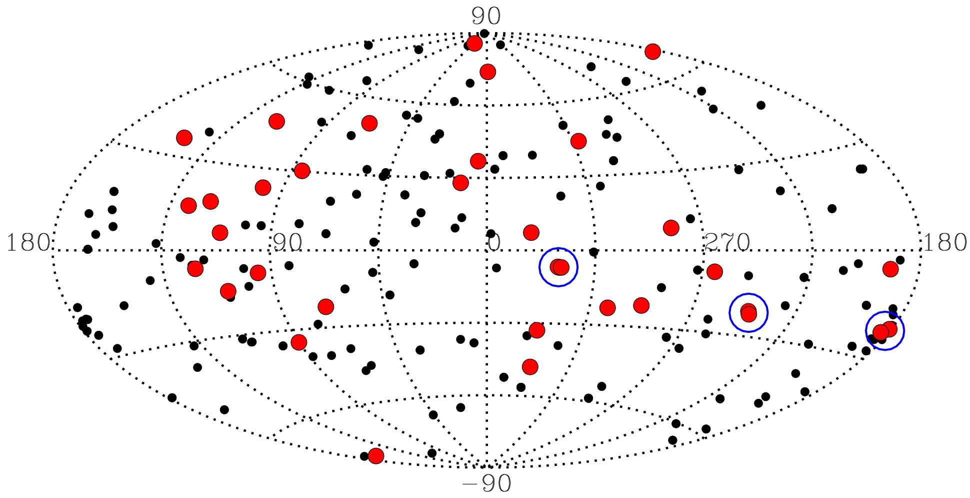

Fig. 2. Galactic coordinates of interstellar lines of sight. The small dots indicate sight lines observed by Redfield & Linsky (2002) that were the data set that Redfield & Linsky (2008) used in constructing their morphological model of the LISM consisting of 15 warm, partially ionized clouds. The large dots indicate the lines of sight obtained with the STIS SNAPshot program (Malamut et al. 2014). Large circles identify two or more sightlines in close proximity. Figure from Malamut et al. (2014).

perature, velocity, composition, ionization, and magnetic field properties. In particular, the ionization equilibrium of the CLIC gas is consistent with the local EUV radiation field (Slavin & Frisch 2008). The recent comprehensive review of the interstellar medium surrounding the Sun (Frisch, Redfield, & Slavin 2011) describes the Galactic environment of the LISM, the role of outflowing gas from the Sco-Cen association as a driver for the CLIC kinematics, the interstellar radiation field, ionization, metal depletions, gas kinematics, and the interstellar magnetic field.

Gry & Jenkins (2014) [hereafter GJ14] have proposed a fundamentally different morphology for the warm interstellar gas located near the Sun. In their model, all of the space within about 9 parsecs of the Sun is filled by a single continuous cloud with a nonridgid flow and a gradient in metal depletion properties. They fit the Redfield & Linsky (2002) Mg II and Fe II radial velocity data set with a nonrigid flow that is differentially decelerated in the direction of motion and expanding in directions perpendicular to the flow. In their model, which they call the Single Local Cloud (SLC), the flow speed and direction near the Sun is consistent with the speed and direction of interstellar helium flowing into the heliosphere as measured by the Interstellar Boundary Explorer (IBEX) and Ulysses satellites. They found that the SLC model fits nearly all of the MgII and FeII velocity components that RL08 assigned to the LIC, G, NGP, Blue and Aur clouds. If the mean neutral hydrogen density in the SLC is 0.055 cm^{-3}, as inferred from the hydrogen column densities and distances to nearby stars, then the SLC fills all of space out to roughly 9 parsecs from the Sun. GJ14 also found that another set of velocity components that RL08 had assigned to the Hyades and Mic clouds and including many of the previously unassigned velocity components, could be fit by another vector that they called the Cetus Ripple, which may be a signature of a shock front inside of the SLC. They speculated that the remaining unassigned velocity components are also perturbations located inside of the SLC.

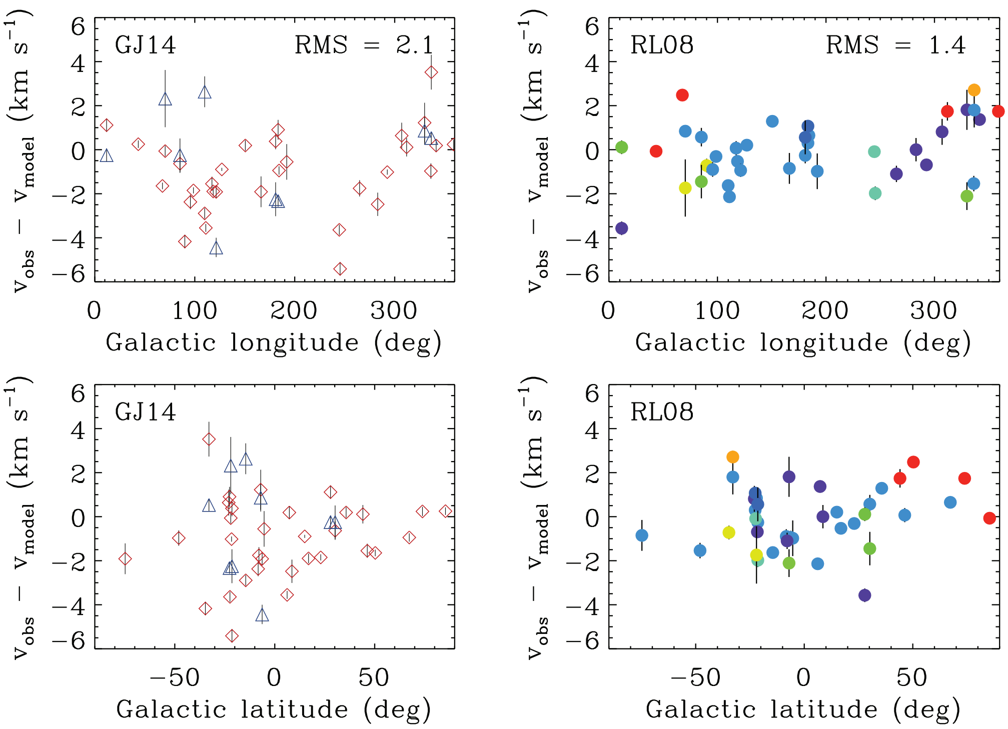

Fig. 3. Testing the accuracy with which the two morphological models of the LISM can predict the radial velocities measured in the SNAPshot program (Malamut et al. 2014). The two figures on the left show the differences between the observed and the GJ14 model prediction of radial velocities as a function of Galactic longitude and latitude. Diamond symbols represent the GJ14 single cloud model and the triangles represent the Cetus Ripple component. The two figures on the right use the RL08 model to predict radial velocities for the same data. The root mean square (RMS) values for the dispersion in each comparison are 2.1 for the GJ14 model and 1.4 for the RL08 model. Figure from Redfield & Linsky (2015).

3. Critical tests of the two morphological models

3.1. Which model best fits the Malamut et al. (2014) data set?

Both the GJ14 and RL08 models were constructed to fit the Mg II and Fe II absorption line radial velocities obtained by Redfield & Linsky (2002), although the RL08 model was constructed to also fit radial velocities for other lines of sight measured from Ca II absorption lines. A critical test of the viability of both models is, therefore, to determine how accurately each model predicts the observed radial velocities in a new data set with targets randomly distributed in Galactic coordinates.

Malamut et al. (2014) [hereafter M14] obtained high-resolution STIS E230H spectra of the Mg II, Fe II, and Mn II lines in the 258–280.5 nm spectral region for stars that previously had only 120–170 nm spectra (typically obtained at medium spectral resolution that is inadequate for resolving the velocity structure). This data set includes 76 velocity components measured in the lines of sight toward 34 stars. The data were obtained in the SNAPshot observing mode—designed to provide short (much less than one spacecraft orbit) observations to fill gaps in the *HST* schedule. Since the observed targets were selected by the *HST* schedulers from a large list of stars distributed across the sky, the observed targets are, in effect, randomly distributed in Galactic coordinates as shown in Figure 2. This data set, therefore, provides an excellent opportunity for testing the two models.

Figure 3 compares the differences between the observed and predicted radial velocities for the two models using the M14 observed data set with the differences plotted as a function of Galactic longitude and latitude. The left panels show the differences using the GJ14 model to predict radial velocities, and the right panels show the differences using the RL08 model to predict radial velocities. The RL08 model clearly provides a much tighter fit to the M14 data that is quantified by the root mean square (RMS) scatter of 1.4 km/s for the RL08 model compared to 2.1 km/s for the GJ14 model. An RMS scatter of about 1.5 km/s is expected on the basis of *STIS* measurement errors. Redfield & Linsky (2015) describe several statistical tests for comparing the predictions of the two models that take into account the many more free parameters in the RL08 model. They conclude that the quality of fit is significantly better for the RL08 model than for the GJ14 model and that the RL08 model is statistically preferred. The robustness of the RL08 model is confirmed by its sucessful prediction of the radial velocity of at least one velocity component observed toward all of the stars observed by M14.

3.2. Additional considerations for evaluating the two morphological models

- Spectra of many nearby stars have three or more distinct velocity components along their lines of sight. In the Redfield & Linsky (2002) and Malamut et al. (2014) surveys, there are 20 lines of sight to stars closer 100 pc that show 3 velocity components: 4 of these stars lie within 10 pc, and 2 of these stars (70 Oph and α Aql) are only 5.1 pc distant, well inside the CLIC. Also τ^6 Eri (d=17.6 pc) shows 4 velocity components and ϵ Gru (d = 39.5 pc) shows 6 components. This complex velocity structure is difficult to explain with a single nonridgid interstellar cloud, but can be simply explained with a model consisting of many distinct clouds each with its own kinematics.
- Frisch, Redfield, & Slavin (2011) have summarized the evidence that the interstellar magnetic field strength is between 2.7 and 5 μG immediately surrounding the heliosphere. For example, the Voyager 1 spacecraft has been making *in situ* measurements of the interstellar magnetic field strength with a mean value of 4.64 ± 0.09 μG and nearly constant orientation very different from that of the solar magnetic field inside of the heliosheath (Gurnett et al. 2013; Burlaga & Ness 2014a,b). Although the measured magnetic field likely refers to the field draped around the heliopause, which may be compressed relative to the undisturbed field further away from the Sun, Voyager 1 has provided us with the best available estimate of the interstellar magnetic field strength near the Sun. Since equipartition between magnetic and thermal energy is about 2.7 μG in the LIC, the Voyager 1 magnetic-field-strength measurement suggests that strong interstellar magnetic fields are present near the Sun and thus could control the structure of discrete clouds. The thin-elongated structures of several clouds identified by RL08 (Aur, Cet, Mic, Local Leo Cold Cloud, and perhaps others) suggest that they are confined by elongated parsec-scale magnetic fields.
- Large-amplitude intraday and annual scintillations of some quasars at radio wavelengths indicate turbulent-scattering screens in the CLIC. Linsky, Rickett, & Redfield (2008) showed that the variability of three well-studied quasars (B1257-326, B1519-273, and J1819+385) can be understood as produced by the Earth's orbital motion through the diffraction pattern of screens located within 7 parsecs of the Sun. The directions to these quasars pass close to the outer edges of two or more adjacent or perhaps colliding clouds, as shown in

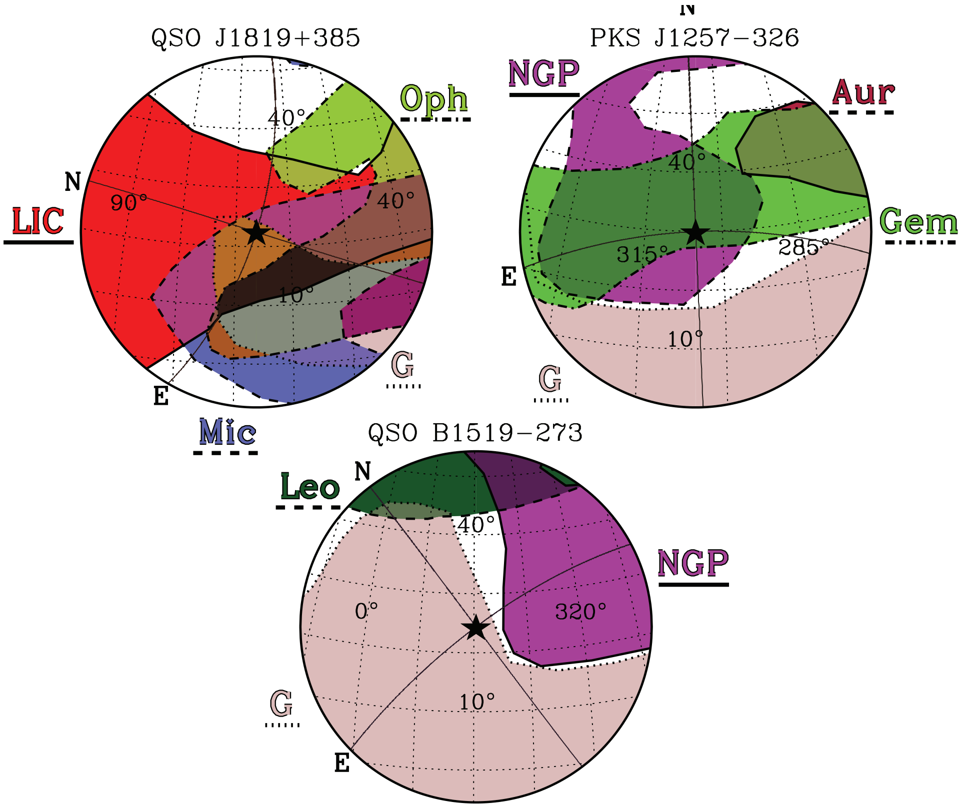

Fig. 4. The location of interstellar clouds identified by Redfield & Linsky (2008) relative to the lines of sight to three unresolved quasars with large-amplitude intraday and annular scintillations. The lines of sight to the quasars in Galactic coordinates are indicated by star symbols and the approximate cloud boundaries are drawn by lines. In all cases, the quasar lines of sight pass through or very near the edges of several clouds. Figure from Linsky, Rickett, & Redfield (2008).

Figure 4. The inhomogeneous index of refraction of turbulent ionized plasma in scattering screens at cloud edges could be produced by shear between interacting clouds or higher ionization of the gas at the cloud edges resulting from external ionizing radiation or thermal conduction from hot surrounding gas.

- All observed lines of sight even to the nearest stars show interstellar Lyman-α absorption with log N(H I)≥ 17.4. Gry & Jenkins (2014) have argued that the absence of gaps in interstellar H I absorption to the nearest stars favors a single cloud surrounding the Sun rather than individual clouds that do not completely fill the local volume. Assuming that all of the clouds in the RL08 model are randomly distributed within 7 pc of the Sun, our simulations show that there is a 99.6% probability that all sight lines will traverse at least one of the clouds to satisfy the log N(H I)≥ 17.4 observational constraint.

4. What physical processes control the morphology of the LISM?

If the CLIC does consist of a number of distinct clouds, either isolated or in close contact, each with its own physical properties and gas flow

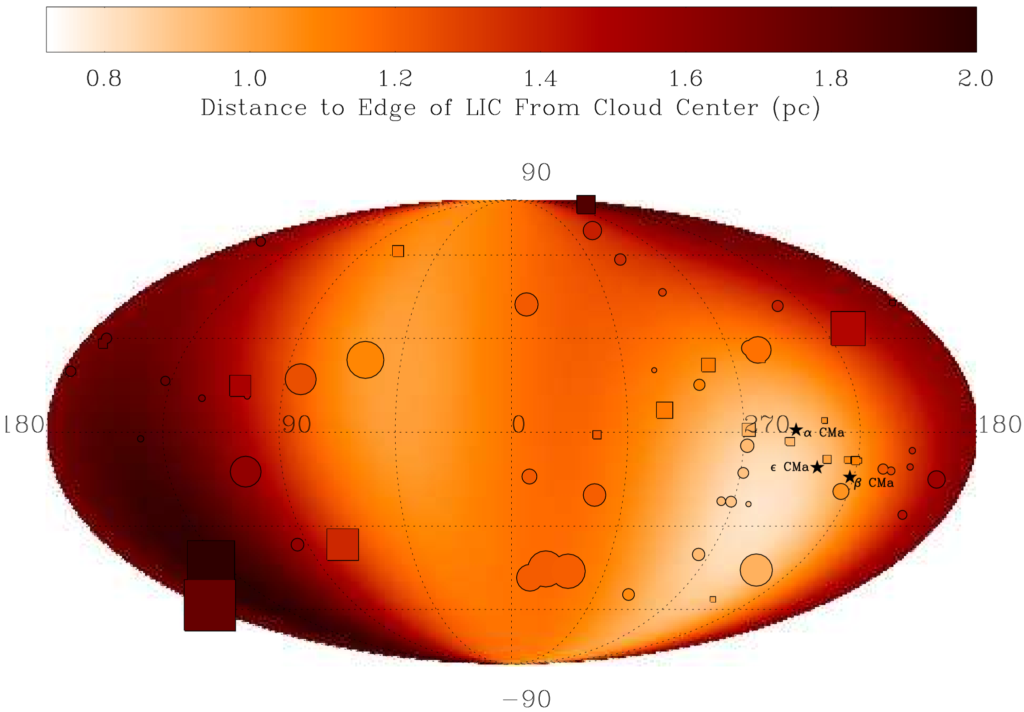

Fig. 5. View from the center of mass of the LIC in Galactic coordinates. Increasing darkness indicates higher neutral hydrogen column density N(HI) from the center of the LIC to its boundary. In the quadrant with the lowest N(HI) values are the lines of sight from the center of the LIC to the hot white dwarf Sirius B (α CMa B), the strongest EUV source ϵ CMa found by the *EUVE* satellite, and the second brightest source β CMa. Star symbols identify the location of these three stars.

vector, then what physical processes could be responsible for this morphological structure? There are several possibilities.

Photoionization: The 15 clouds are filled with warm partially ionized gas. For example, the hydrogen in the LIC is about 30% ionized. The *Extreme Ultraviolet Explorer (EUVE)* satellite found that the dominant sources of ionizing radiation in the local neighborhood are hot stars, in particular ϵ CMa and β CMa, and hot white dwarfs, in particular G191-B2B, HZ 43, Feige 24, and Sirius B, which is only 2.6 pc from the Sun (Vallerga 1998; Slavin & Frisch 2008; Frisch, Redfield, & Slavin 2011; Welsh et al. 2013). The LISM likely has a honeycomb structure of Stromgren spheres surrounding these and other hot stars (Tat & Terzian 1999). Figure 5 shows the neutral hydrogen column density of the LIC as seen from its center of mass. It is noteworthy that the strongest ionizing source (ϵ CMa) and two other strong ionizing sources (β CMa and Sirius B) are in lines of sight that pass through the region of lowest neutral hydrogen coumn density, a clear indication of the importance of ionizing radiation in shaping partially ionized warm clouds.

Magnetic fields: In the previous section we mentioned that if magnetic field strengths are as large in the CLIC as the measured fields immediately surrounding the heliosphere, then magnetic pressure will likely be larger than gas pressure in the partially ionized clouds. The effect will be to shape the cloud morphologies. The long filamentary shapes of the Aur, Cet, Mic, and Local Leo Cold clouds suggest confinement by magnetic fields that are roughly linear on parsec scales. Since disk-like thin clouds would have a one-dimensional linear structure when viewed along the disk axis, but a two-dimensional structure when viewed from other angles, many more of the 15 clouds identified by RL08 may actually be disk-like then appear from our perspective.

Shock waves: In many lines of sight, the velocity difference between two or more clouds exceeds the thermal speed of roughly 8 km/s (Linsky, Rickett, & Redfield 2008). If these clouds are in contact, then there will be a shock, either acoustic or MHD depending on the magnetic field strength, at their interface. Supernovae are known to produce strong shocks in the ISM. GJ14 identify the Cetus Ripple as an interstellar shock. Since shocks can ionize hydrogen and metals, they can shape clouds that are identified on the basis of absorption by H I, Mg II, Fe II, Ca II.

Evaporative boundary layers: Frisch, Redfield, & Slavin (2011) summarize the evidence for and uncertainties concerning evaporation at cloud boundaries. This evaporation could result from thermal conductive heating from surrounding hot gas or a turbulent mixing layer at the cloud boundary. In either case, the cloud shape and evolution could be controlled by physical processes at the cloud boundary.

5. Conclusions

The SNAPshot observations of interstellar absorption line radial velocities obtained by M14 provide an excellent data set with which to test the predictive power of two very different models for the partially ionized interstellar gas within a few parsecs of the Sun. One type of model describes this gas as a complex of local interstellar clouds, exemplified by the 15 cloud model proposed by RL08. The other type, proposed by GJ14, envisions a single cloud with a nonridged velocity structure. Our test of the accuracy with which each model can predict the radial velocities along the 34 lines of sight observed by M14 shows that the RL08 model predicts these velocities with significantly higher accuracy than the GJ14 model. Also, the RL08 model is statistically preferred even though it has many more free parameters than the GJ14 model. We also identify four other reasons for concluding that the local interstellar gas is better described as a complex of distinct clouds each with its own physical properties and kinematics rather than a single nonridgid cloud. However, both models are idealized, and it is likely that a more realistic description of the CLIC kinematics lies somewhere between these two extreme morphologies.

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