Large-scale Interstellar Structure and the Heliosphere
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Abstract

The properties of interstellar clouds near the Sun are ordered by the Loop I superbubble and by the interstellar radiation field. Comparisons of the kinematics and magnetic field of the interstellar gas flowing past the Sun, including the Local Interstellar Cloud (LIC), indicate a geometric relation between Loop I as defined by radio synchrotron emission, and the interstellar magnetic field that polarizes nearby starlight. Depletion of Fe and Mg onto dust grains in the LIC shows a surprising relation to the far ultraviolet interstellar radiation field that is best explained by a scenario for the LIC to be extended, possibly filamentary, porous material drifting through space with the Loop I superbubble. The interstellar velocity and magnetic field measured by the Interstellar Boundary Explorer (IBEX) help anchor our understanding of the physical properties of the nearby interstellar medium.

1 Introduction

The first maps of the distribution of interstellar dust, obtained from starlight reddened in the interstellar medium (ISM), showed that the Sun is located in a void with a radius of \( \sim 75 \) pc (Fitzgerald, 1968). This void is now known as the “Local Bubble”. The dawn of the space age enabled the discovery that hydrogen and helium flow through the heliosphere with the velocity of nearby interstellar gas (Bertaux & Blamont, 1971; Thomas & Krassa, 1971; Weller & Meier, 1974; Adams & Frisch, 1977), and that low density partially ionized gas is seen toward the closest stars (Rogerson et al., 1973). These earliest data showed that the Sun is embedded in a low density partially ionized interstellar cloud, the Local Interstellar Cloud (LIC), with low volume densities (\(< < 1 \) cm\(^{-3}\)). Recent studies indicate that hydrogen is 23% ionized, and helium is \( \sim 39\% \) ionized in the LIC, and that refractory elements have relatively high gas-phase abundances (Frisch et al., 2011, FRS11). In the global ISM, clouds such as the LIC were first termed the “intercloud medium” because they are warm and optically thin and favor higher velocities, \( > 20 \) km s\(^{-1}\) (Welty et al., 1999), through the local standard of rest velocity frame (LSR); LIC-like clouds are not at risk of gravitational collapse, in contrast to the local cold, opaque, dense low velocity clouds that border the Local Bubble. Recent discoveries of tiny dense compact clouds through observations of the H\(^{\circ}\) 21-cm hyperfine transition (e.g. Saul et al., 2012), even within \( \sim 20 \) pc of the Sun (Meyer et al., 2012), and the relation between Loop I and the interstellar magnetic field (ISMF) and gas around the heliosphere (Frisch, 1981; Frisch et al., 2012), signals that the local environment is a complex interstellar region. The location of the Sun in the Local Bubble void allows the interstellar radiation field (ISRF) to affect the LIC.

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2 Cloud kinematics, Loop I and the local interstellar magnetic field

Local interstellar clouds are identified by absorption lines formed in the spectra of nearby stars by the foreground interstellar gas. High-spectral resolution spectra are interpreted using the assumption that the velocities of the atoms forming the absorption lines have Maxwellian velocity distributions in the cloud, with an additional “turbulent” broadening to explain mass-independent non-thermal motions. Ultimately, the detailed kinematical structure of the local interstellar medium that is derived from absorption line data depends on the spectral resolution of the measuring instrument, which is generally $>3$ km s$^{-1}$ for ultraviolet (UV) data and $>1$ km s$^{-1}$ for ground-based data. For optical Na$\dagger$, Ca$\dagger$, and K$\dagger$ lines, the frequency of adjacent components with small separations in velocity in a given sightline increases significantly as separations become smaller, but decreases near the limit of instrumental spectral resolutions (Welty & Hobbs, 2001). This indicates that the UV data that provide most of our information on local clouds under-samples the velocity structure of the local ISM.

The distribution of cloud velocities obtained from interstellar absorption components in the spectra of nearby stars indicate that the Sun is located in a decelerating flow of interstellar gas (Frisch et al., 2002). Converting the observed heliocentric velocities into the LSR gives a bulk flow velocity with an LSR flow speed of $-17$ km s$^{-1}$ from the “true” LSR upwind direction that is toward the direction $\ell, b \sim 335^\circ, -5^\circ$ (galactic coordinates, FRS11). The kinematic structure of the local ISM has been parsed by RL08 into fifteen nearby clouds (earlier studies had derived fewer clouds). Figure 1 shows the LSR velocities of the RL08 clouds that we have derived using the solar apex motion in Schönrich et al. (2010, see Table 1).

The deceleration of the bulk motion of nearby ISM produces regions of cloud collisions (e.g. Redfield & Linsky, 2008, RL08). The closest of those collisions is between the LIC and Blue Cloud (BC), which have LSR velocity vectors that are separated by an angle of $47^\circ$ (Table 1), and a relative speed between the two clouds of $|V| \sim$ 10.5 km s$^{-1}$. For a LIC density of 0.27 cm$^{-3}$ (model 26 in Slavin & Frisch, 2008, SF08), and reduced mass per
particle of $2.34 \times 10^{-24}$ gr, the ram pressure of the LIC on the BC is $P_{\text{ram}} = 1.28 \times 10^{12}$ dynes cm$^{-2}$. This is a factor of five larger than the LIC thermal pressure of $2.32 \times 10^{13}$ dynes cm$^{-2}$, using the LIC temperature 6300 K from McComas et al. (2012), indicating a supersonic interface between the LIC and BC. Nearby sources of intraday scintillation sources have been identified close to the direction of the LIC-BC collision (Linsky et al., 2008).

Loop I is an evolved superbubble originally identified by an extended arc of synchrotron emission (e.g. Haslam et al., 1971). Models of the Loop I shell, based on the hydrodynamic expansion of a superbubble into low density ISM, explain the large size and give an age of 4 Myrs, corresponding to the approximate age of the latest epoch of star-formation in the Scorpius-Centaurus Association that formed the Upper Scorpius subgroup (Frisch, 1995). Measurements of starlight polarized by interstellar dust show that the east and west sides of Loop I differ in the distance of polarizing grains (Santos et al., 2011). Wolleben (2007) has separated Loop I into two spherical shells; the Sun is located in the rim of the S1 component (gray arc in Figure 1) that is centered $78 \pm 10$ pc away at galactic coordinates of $\ell, b = 346^\circ \pm 5^\circ, 3^\circ \pm 5^\circ$.

The S1 shell has a notable relation to the properties of the very local ISM: (1) the bulk motion of nearby clouds in the LSR is directed away from a direction within $14^\circ \pm 8^\circ$ of the S1 shell center (thick gray arrow in Figure 1; the thin arrows originate at cloud centers and the distance of the nearest cloud star). (2) the local (< 40 pc) ISMF direction determined from weighted fits of starlight polarized by magnetically aligned dust, $\ell, b \sim 47^\circ \pm 20^\circ, 25^\circ \pm 20^\circ$, makes an angle of $\sim 76^\circ \pm 21^\circ$ with the bulk flow LSR velocity (Frisch et al., 2012). Both properties are expected for ISM associated with an expanding superbubble shell that has the ISMF perpendicular to a normal to the shell surface (e.g. aligned with that surface).

In addition to being the home of the heliosphere (for now at least), the LIC is special since the heliosphere itself probes the ISM. The Interstellar Boundary Explorer (IBEX) measured a Ribbon of energetic neutral atoms, with energies 0.2–6 keV, which appears to form in directions perpendicular to the ISMF as it drapes over the heliosphere (McComas et al., 2009; Schwadron et al., 2009). The Ribbon center at 2.73 keV is a proxy for the ISMF direction at the heliosphere, $\ell = 30.5^\circ \pm 2.6^\circ, b = 57.1^\circ \pm 1^\circ$ (with the uncertainties from the variation of the ribbon center with energy; Funsten et al., 2013). The angle of $33^\circ \pm 20^\circ$ between the very local ISMF obtained from the IBEX Ribbon and the ISMF determined over 8–40 parsec scales from polarized starlight suggests the two directions may be measuring different regions of the same ISMF. IBEX has also measured the velocity of interstellar He$^0$ in the inner heliosphere, finding a value that closely agrees with the LIC velocity obtained from spectroscopy (McComas et al., 2012, Table 1). The IBEX measurements of the ISM kinematics and ISMF at the heliosphere anchor our understanding of the LIC.

Photoionization models of the LIC give the LIC physical properties $n$(H$^0$) $\sim 0.19$ cm$^{-3}$ and $n$(H$^+$) $\sim 0.07$ cm$^{-3}$ (SF08); for equality of thermal and magnetic pressures, the magnetic field strength in the LIC would be $\sim 3 \mu$G. A similar estimate for the field strength arises from pressure balance based on the line-of-sight integrated pressure observed in energetic neutral atoms by IBEX (Schwadron et al., 2011). In global low electron density regions, Faraday
Rotation suggests that density fluctuations and magnetic field strength are uncorrelated (Wu et al., 2009), in agreement with the lack of evidence for flux freezing for clouds with densities $< 10^3 \text{ cm}^{-3}$ (Crutcher, 2007).

### 3 Abundances, depletions, and the interstellar radiation field

The gas-phase abundances of refractory elements such as Fe and Mg are a key diagnostic of the history of a cloud because grain erosion by sputtering and collisions with other grains in interstellar shocks return the refractory elements to the gas phase. It has long been known that the abundances of refractory elements in the gas of clouds with higher velocities are larger than those in cold slow dense clouds (e.g. Welty et al., 1999). The LIC provides the ISM sample that is most likely to be uniform for the purpose of understanding this effect. In the local ISM, the variations of the ratio Fe$^+/\text{Mg}^+$ in the gas within and between clouds suggest that interstellar shocks are presently active in destroying local dust grains (RL08, FRS11). This dust should consist of grains that were swept up and processed by the superbubbles that form the Loop I shell as it propagated through space (Frisch, 1995), but an admixture of evaporated dense cloud material is needed to explain the large micron-sized grains observed by Ulysses (FRS11).

Except for the LIC where photoionization corrections provide the amount of H$^+$ present, most local ISM abundances are found based only on H$^0$ column densities. This comparison yields erroneous abundances for the common species such as Fe$^+$ and Mg$^+$ that trace both the neutral and ionized components of warm partially ionized material (WPIM, SF08). Elemental gas-phase abundances are therefore overestimated in WPIM if ionization corrections are ignored, or equivalently the number of atoms in the grains are underestimated. Elemental "depletions" are given by $\delta_X = \log \left[ \frac{N(X)}{N(H)} |_{\text{is}}/N(X)/N(H)|_{\text{sun}} \right]$, where the first and second terms give the interstellar and solar abundances of X=Fe$^+$ or X=Mg$^+$ with respect to the column density N(H) (e.g. see Welty et al., 1999). If the neglect of H$^+$ biases abundances in the local ISM, these biases should be more prominent in regions of high than low radiation fluxes.

Figure 2, top panel, shows the Fe and Mg depletions for eight stars, d< 30 pc, with LIC components (from RL08), plotted against the far-ultraviolet (FUV) radiation flux at the position of each LIC star. The radiation field at 975Å is used for this comparison (Opal & Weller, 1984, Figure 12 of Frisch et al. 2012). The radiation field at 912Å, the wavelength corresponding to the first ionization potential of H$^+$, would be preferable to use but those data are not available; measurements of the brightest stars at 975Å are used as a proxy. The proxy stars include the brightest EUV sources $\epsilon$ CMa and $\beta$ CMa that dominate the LIC ionization at the Sun (SF08), and consist mainly of luminous B1 through O stars located where $\ell > 180^\circ$ and EUV interstellar opacities are very low due to the Local Bubble. HD 122451 is the brightest star at 975Å and it is located in the direction of the Loop I center. The 975Å radiation field at the Earth is useful as a proxy for the H-ionizing radiation (912Å).
at nearby stars if the LIC is porous so that cloud opacity does not decouple the 975Å and 912Å fluxes, and if the LIC is extended so that the inverse square dependence of the radiation field is significant over the length of the cloud. Local clouds typically fill less than 10%–30% of space (FRS11), so these assumptions are plausible. The radiation fluxes are calculated with the assumption of a transparent ISM at 975Å between the LIC star and each 975Å radiation source. Figure 2, top, shows a clear trend for the amount of Fe and Mg in dust grains in the LIC to decrease as the FUV radiation flux at the star increases, providing that the amount of ionized hydrogen present is insignificant.

The plotted depletions of Fe and Mg in the LIC show that the ISRF ($F_{975}$) is proportional to $\delta_{\text{Fe}}$ and $\delta_{\text{Mg}}$, so that abundances in the gas phase increase with the radiation flux. The black and blue dashed lines show linear fits to the Fe depletion-flux variation is better than found for Mg. Mg equilibrium in warm partially ionized gas is more complicated, since dielectric recombination of Mg$^+$ with an electron is significant, and Mg$^{++}$ forms in regions of high radiative flux (e.g. 15% of Mg is doubly ionized at the solar location, SF08). The dependence of the depletions on the

![Figure 2](image-url)
ISRF could result from an increase in gas ionization with increasing radiation flux, which when ignored would yield values of $\delta_{\text{Fe}}$ and $\delta_{\text{Mg}}$ that are too large. An alternative, that H$_2$ is present and increases with depth in the cloud, is unlikely because H$_2$ is easily photodissociated by UV radiation in environments such as the LIC. Another possible explanation for the depletion-radiation relation is that the collision between the LIC and BC, discussed above, creates shocks that preferentially destroy the grains in the region of the collision. Since the BC is located in the direction of the bright EUV sources $\epsilon$ CMa and $\beta$ CMa, this would resemble a dependence on radiation fluxes. The option that cloud opacity accounts for the depletion-radiation relation does not work if the LIC is a compact cloud restricted to being within a parsec of the heliosphere, since the depletion variation is plotted with respect to the distance between the LIC star and the radiation source.

A more interesting possibility that is consistent with Figure 2 is that the LIC gas consists of extended porous material, drifting through space at the same velocity, as part of the structure of the Loop I superbubble shell. For this configuration, the column of ISM between the star and radiation sources would see the largest gradient in flux. This scenario is consistent with the solar location at the upwind edge of the LIC (FRS11), and explains why the depletion-radiation effect is found at larger distances than is expected if the LIC were compact.

The middle panel in Figure 2 shows an example of the LIC fractional ionization, H$^+/(\text{H}^0+\text{H}^+)$, needed to explain the depletion variation with radiation flux. Ionization is calculated assuming an arbitrary constant value for the base-line depletion. The best fits through the ionization variation indicates variations larger than 50% in the LIC.

The bottom panel in Figure 2 plots the LIC temperature (from RL08) against radiation flux for these sightlines. At the Sun, $\sim 66\%$ of the cloud heating is caused by absorption of photons that can ionize H$^0$ and He$^0$ (SF08). Stars in the third and fourth galactic quadrants ($\ell > 180^\circ$, open circles) are clustered in high flux regions and tend to have higher temperatures than the remaining stars. The remaining stars appear to warm as the ISRF decreases, possibly due to decreased cooling by the collisionally excited fine-structure lines of heavy elements.

4 Summary

The Loop I evolved superbubble orders the kinematics of nearby interstellar clouds and the local magnetic field. The bulk flow LSR velocity of the local cloud system is perpendicular to the ISMF, making an angle of $76^\circ \pm 21^\circ$ with the field direction found from starlight polarized by the ISM. The LSR velocity is also aligned with the geometric center of Loop I, to within $14^\circ \pm 8^\circ$, as defined by the S1 shell seen in synchrotron emission. A surprising relation between the depletion of Fe and Mg onto dust grains in the LIC, and the far ultraviolet interstellar radiation field at 975Å, is best explained by a scenario for the LIC to be extended, possibly filamentary, porous material drifting through space with the near side of Loop I. The eastern arc of Loop I in galactic quadrant I ($\ell < 90^\circ$) appears to extend to the solar location, while the properties of the ISM in the opposite direction (quadrant III, $180^\circ < \ell < 270^\circ$) are
dominated by the FUV interstellar radiation field.

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A cloud heliocentric cloud velocities are from Redfield & Linsky (2008). These velocities are converted to the LSR using the solar apex motion in Schonrich, Binney and Dehnen (2010) of \( U = 11.1^{+0.69}_{-0.75} \), \( V = 12.24^{+0.47}_{-0.47} \), \( W = 7.25^{+0.37}_{-0.36} \), which gives a solar velocity of 18.0 ± 0.9 km s\(^{-1}\) towards the direction \( L = 47.9^\circ \pm 2.9^\circ \), \( B = 23.8^\circ \pm 2.0^\circ \). The cloud LSR uncertainties include the uncertainties on the solar apex motion.

### Table 1: Cloud velocity vectors\(^a\)

| Cloud | \( V_{\text{LSR}} \) (km s\(^{-1}\)) | \( L_{\text{LSR}} \) (deg.) | \( V_{\text{HC}} \) (km s\(^{-1}\)) | \( L_{\text{HC}} \) (deg.) |
|-------|-------------------------------------|-----------------------------|-----------------------------------|-----------------------------|
| LIC   | 15.3 ± 2.5                         | 141.9 ± 9.7                 | 23.8 ± 0.9                        | 187.0 ± 3.4                 |
|       | 6.4 ± 9.5                          | 152.9 ± 10.8                | 29.6 ± 1.1                        | 184.5 ± 1.9                 |
| G     | 19.6 ± 2.2                         | 148.8 ± 7.5                 | 29.6 ± 1.1                        | 184.5 ± 1.9                 |
| Blue  | 7.1 ± 2.3                          | 94.2 ± 22.0                 | 39.3 ± 0.9                        | 205.5 ± 4.3                 |
| Aql   | 46.6 ± 2.4                         | 163.4 ± 4.8                 | 58.6 ± 1.3                        | 187.0 ± 1.5                 |
| Eri   | 12.3 ± 2.2                         | 152.9 ± 10.8                | 24.1 ± 1.2                        | 196.7 ± 2.1                 |
| Aur   | 9.5 ± 2.3                          | 185.4 ± 13.6                | 25.2 ± 0.8                        | 212.0 ± 2.4                 |
| Hyades| 15.4 ± 2.9                         | 87.0 ± 10.5                 | 14.7 ± 0.8                        | 164.2 ± 9.4                 |
| Mic   | 16.3 ± 2.4                         | 174.2 ± 10.8                | 28.4 ± 0.9                        | 203.0 ± 3.4                 |
| Oph   | 18.0 ± 1.9                         | 207.8 ± 9.2                 | 32.2 ± 0.5                        | 217.7 ± 3.1                 |
| Gem   | 22.6 ± 2.3                         | 191.8 ± 5.8                 | 36.3 ± 1.1                        | 207.2 ± 1.6                 |
| NGP   | 26.2 ± 2.6                         | 166.8 ± 5.4                 | 37.0 ± 1.4                        | 189.8 ± 1.7                 |
| Leo   | 14.4 ± 2.6                         | 146.8 ± 11.8                | 23.5 ± 1.6                        | 191.3 ± 2.8                 |
| Dor   | 46.5 ± 2.0                         | 129.9 ± 3.4                 | 52.9 ± 0.9                        | 157.3 ± 1.5                 |
| Vel   | 30.6 ± 2.4                         | 176.6 ± 1.9                 | 45.2 ± 1.8                        | 195.4 ± 1.1                 |
| Cet   | 45.9 ± 3.1                         | 186.6 ± 2.5                 | 60.0 ± 2.0                        | 197.1 ± 0.6                 |

\(^a\)Cloud heliocentric cloud velocities are from Redfield & Linsky (2008). These velocities are converted to the LSR using the solar apex motion in Schonrich, Binney and Dehnen (2010) of \( U = 11.1^{+0.69}_{-0.75} \), \( V = 12.24^{+0.47}_{-0.47} \), \( W = 7.25^{+0.37}_{-0.36} \), which gives a solar velocity of 18.0 ± 0.9 km s\(^{-1}\) towards the direction \( L = 47.9^\circ \pm 2.9^\circ \), \( B = 23.8^\circ \pm 2.0^\circ \). The cloud LSR uncertainties include the uncertainties on the solar apex motion.