Local Interstellar Matter: The view from Paris

Priscilla C. Frisch

1 Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

Abstract. Observations of interstellar gas and dust towards nearby stars and within the solar system show that the Sun is embedded in a warm diffuse partially-ionized cloud. This cloud is the leading edge of a flow of interstellar matter (ISM) through our Galactic neighborhood. Interstellar matter sets the boundary conditions of the heliosphere and astrospheres of extra-solar planetary systems. Moreover, the interplanetary regions in these systems are sensitive to infalling ISM.

1 Introduction

What better place to review the Local Interstellar Medium (LISM) than in Paris – which has nurtured creative thinking in the sciences, mathematics and arts for many centuries?

The launch of the Copernicus satellite in 1972 provided UV spectrometers capable of observing dominant trace ions in the low density intercloud medium (as it was then called) around the Sun. York, Jenkins, Spitzer and colleagues discovered that gas towards α Leo (24 pc) is ∼50% ionized since N(N\textsc{i}) ∼ N(N\textsc{ii}) [28], while observations of nearby cool stars demonstrated the low mean densities of the closest ISM (n ≤ 0.1 cm$^{-3}$, e.g. [27]). Copernicus yielded the first spectral observations of interstellar H\textsc{i} inside of the solar system, showing that this material has a velocity several km s$^{-1}$ different from the velocities of nearby interstellar clouds located in the upwind direction [1]. Vidal-Madjar and colleagues used Copernicus data to evaluate the inhomogeneity of ISM within a few parsecs, based on a possible gradient in radiation pressure [34]. The fact that the interstellar cloud seen inside of the solar system (now called the Local Interstellar Cloud, LIC) does not extend to α Cen, the nearest star, was originally discovered with Copernicus [22] and remains a puzzle. During the last decade of the 20th century, observations by GHRS and STIS on HST, and high-resolution optical data, provided the basic properties, composition, and kinematics of individual cloudlets close to the Sun. Ulysses and Galileo have now made in situ observations of interstellar gas and dust inside of the solar system, and the pickup ions and anomalous cosmic ray populations which result from the interaction of ISM with the solar wind.

These data, together with heliosphere\textsuperscript{1} models, show that the physical properties of the ISM influence the heliosphere configuration, the astrospheres

\textsuperscript{1}The heliosphere is the region of space containing the solar wind plasma.
of external cool stars, and the interplanetary environment of both our own solar system and extra-solar planetary systems [7, 37].

2 LISM Gas towards Nearby Stars

The relative absence of O/B stars nearby the Sun (there are no O stars and four B-stars within 30 pc) means that the LISM properties are pieced together from observations of several types of target objects, each with limitations, including A, F, G, K stars (there are 57 A stars within 30 pc) and white dwarf stars (118 are within 20 pc [18]).

Optical Ca II and UV absorption lines show that the Sun is embedded in a flow of interstellar cloudlets with a bulk velocity of $-28.2 \text{ km s}^{-1}$, and approaching the Sun from the upstream direction $l=12.6^\circ$, $b=11.7^\circ$ [12]. This corresponds to an upwind direction in the local standard of rest of $l=3^\circ$, $b=-5^\circ$, and flow velocity $-17.0 \text{ km s}^{-1}$ [3]. The distribution of absorption components about the best-fit velocity is consistent with a Gaussian $(e^{-(V-V_o)^2/2\sigma^2})$ with a dispersion $\sigma \sim 4.5 \text{ km s}^{-1}$. The strongest Ca II absorption lines within 30 pc are found towards $\alpha$ Oph (14 pc), but the properties of the cloud forming these features are virtually known. Three Ca II components are seen towards $\alpha$ Aql (5 pc), showing the complex LISM structure [4]. Based on cloud radial velocities (V), the next interstellar cloud to be encountered by the Sun as it traverses interstellar space is likely to be either the cloud in front of $\alpha$ Cen ($V \sim -18 \text{ km s}^{-1}$) or one of the clouds towards $\alpha$ Aql (e.g. $V \sim -27 \text{ km s}^{-1}$) located near the direction of solar apex motion.

The ionization of the LISM has been found from observations of Mg I/Mg II and C II*/C II towards nearby stars. The C II* fine-structure lines are insensitive to the radiation field since they are collisionally populated, while in warm gas Mg I is dominated by photoionization, and radiative and dielectronic recombination. Values range from $n(e)=0.12 \text{ cm}^{-3}$ (C II* data) to $n(e)=0.35 \text{ cm}^{-3}$ (Mg I data), based on observations of $\alpha$ CMa [21], $\epsilon$ CMa [14], REJ 1032+532 [17], $\delta$ Cas [22], $\eta$ UMa [11], and including unpublished values for two components towards $\alpha$ Aql ($n(e)=0.35\pm0.16 \text{ cm}^{-3}$ and $0.15\pm0.10 \text{ cm}^{-3}$). The difference between C II* and Mg I results may indicate that Mg I and Mg II do not sample identical portions of the clouds.

A self-consistent photoionization model of interstellar matter within $\sim 5$ pc of the Sun yields $n(e)\sim0.13 \text{ cm}^{-3}$, $n(\text{H i})\sim0.24 \text{ cm}^{-3}$, $T \sim 7200 \text{ K}$, and fractional ionization $X(\text{H})\sim0.3$ and $X(\text{He})\sim0.4$ at the solar location, in good agreement with observations (Model 17 in [3], hereafter SF17). This model, constrained both by in situ particle data and absorption line data, includes radiation from nearby hot stars, diffuse emission from the soft X-ray background, and unobserved EUV emission from a possible evaporative boundary between the local ISM and hot gas (also see Slavin’s talk in this volume). In low column-density gas N I equilibrium depends partly on photoionization,
while at higher column densities N and H ionization are coupled by charge exchange. In contrast, O and H ionization are tightly coupled by charge exchange. At lower column densities, SF17 predict an inverse relation between N(O I)/N(N I) and N(H I) (Figure 1), and this same behavior is observed for Log N(H I)>17.8 cm$^{-2}$ (Figure 2).

The LISM shows enhanced abundances for refractory elements typical of warm disk gas which has been processed by shock front activity [10]. The photoionization model (above) compares abundances to the total of H i and H ii. Resulting abundances for C, N, O within 5 pc are, respectively, 427, 81, and 630 parts-per-million by number (SF17).

Observations towards local white dwarfs (d<100 pc) at wavelengths <912 Å show that the interstellar H i/He i ratio varies by a factor of ∼2 between sightlines (e.g. [32]), indicating the ionization of LISM is inhomogeneous.

ISM within 30 pc is distributed asymmetrically around the Sun, and the Sun is located in the leading edge of an outflow from Loop I and the Sco-Cen Association [9].

3 Observations of LISM Gas inside of the Heliosphere

ISM inside of the heliosphere provides a unique window on the LIC. Interstellar neutrals flow into the heliosphere and are ionized near ∼5 AU for H i (mainly by charge exchange with the solar wind) and ∼0.5 AU for He i (by photoioniza-
The detection by *Ulysses* of interstellar He I provides a direct measure of the heliocentric velocity of the LIC, which agrees with values found from the FUV fluorescent scattering of solar 584 Å emission. The LIC He I density, temperature and heliocentric velocity are *n*(He I)=0.017 cm⁻³, *T*=6700±900, and *v*=−25.5 km s⁻¹, and this “local interstellar wind” arrives from the upstream direction of *l=2.7°, b=15.6°*. Absorption components near the LIC velocity are identified towards 30 nearby stars, but surprisingly not towards the nearest star α Cen.

Neutral ISM flows into the heliosphere, interacts with the solar wind plasma, and forms the pickup ion (PUI) and anomalous cosmic ray populations. The PUIs give the composition of the parent population of interstellar O I, N I, Ne I, and He I atoms, and seed the anomalous cosmic rays population observed in the inner solar system (e.g. *2*). The PUIs yield *O I/N I=7.0±1.5* inside of the heliosheath, or *8.8±1.5* after correcting for 25% heliosphere filtration of O I. Abundance ratios in both PUIs and the anomalous cosmic-rays can be used to constrain LIC ionization [*8, 30*], and observations of nearby stars show that results from observations inside and outside of the heliosphere are consistent (Figure *2*).

*Ulysses* and *Galileo* have observed interstellar dust grains with masses 10⁻¹⁵ to 10⁻¹⁰ g, flowing through the solar system at the LIC velocity (Figure *3, 10*). The gas-to-dust mass ratio for the measured grain population is consistent with values for the general ISM. For *n*_total=0.37 cm⁻³ (SF17), the observed grains correspond to a gas-to-dust mass ratio of 116⁺⁴⁶⁻³⁸. However ∼40% of the grain mass is removed by heliosheath and heliospheric filtration of small charged grains interacting with the solar wind, indicating a lower value (*R*_g/d~70) for the LIC (assuming H/He=10).

### 4 Conclusions

ISM sets the boundary conditions of the heliosphere and the astrospheres of extra-solar planetary systems. In the low density environment of the Sun today, interstellar gas surprisingly comprises ∼98% of the diffuse material within the heliosphere. An increase in the LIC density from the current value to *n*(H I)=10 cm⁻³ would cause the heliosphere to contract to a radius of ∼10–15 AU in the upstream direction (from the current value of ∼100 AU), dramatically alter the interplanetary environments of the inner planets, and expose outer planets to “raw” ISM [*37*]. Although the consequences of modifying the heliosphere configuration are unknown (despite “black cloud” scenarios), speculations about climate modifications from such an encounter have long intrigued scientists [*29*] and challenged our understanding of the Galactic environment of the Sun.

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*The heliopause is the contact discontinuity between the solar wind and interstellar plasmas. The deflected plasmas on either side of the heliopause form the inner and outer heliosheath regions.*
Figure 2: Log $N(\text{O I})/N(\text{N I})$ versus Log $N(\text{H I})$ for stars sampling nearby ISM. Data points are for G191-B2B, HZ 43, WD 0621-376, WD 2211-495, BD +28D 421, WD 1634-573, Feige 24, GD 394, WD 2331-475, Sirius, REJ 1032+532, $\epsilon$ CMa, and $\eta$ UMa, based on FUSE, HST (GHRS and STIS), and IUE data [17, 16, 33, 6, 25, 24, 20, 15, 31, 36, 19, 14, 11]. The points at (x,y)=(18.6,0.6), (17.8,1.2), and (18.5,1.5) are, respectively, REJ 1032+532, Sirius, and Feige 24. The ratio N/O for pickup ions (the box) is plotted at Log $N(\text{H I})$=17.8 cm$^{-2}$ (SF17).

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Figure 3: The observed mass-density distribution for interstellar dust grains observed within the solar system ([10]). The dashed lines show the MRN distribution [26] for three normalizations of the total mass density in the LIC. The vertical line gives the upper limit cutoff of the MRN distribution (see [10] for additional information).

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