The Local Interstellar Medium

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SUMMARY

Substantial progress in the field of the Local Interstellar Medium has been largely due to recent launches of space missions, mostly in the UV and X-ray domains, but also to ground-based observations, mainly in high resolution spectroscopy. However, a clear gap seems to remain between the wealth of new data and the theoretical understanding. This paper gives an overview of some observational aspects, with no attempt of completeness or doing justice to all the people involved in the field. As progress rarely evolves in straight paths, we can expect that our present picture of the solar system surroundings is not definitive.

KEY WORDS
Galaxy (the): solar neighbourhood (07.32.1)
Interstellar medium: clouds: individual: the Local Cloud (09.11.1)
Interstellar medium: bubbles (09.08.1)
Interstellar medium: kinematics (09.17.1)
Interplanetary medium (09.06.1)

INTRODUCTION

The Local Interstellar Medium (LISM) has been an active area of investigation since the very beginning of the seventies, but for quite long it was uncommon to appreciate what was being learned in this area by others. The story began as many widely dispersed rivulets which converged for an IAU Colloquium on Madison, Wisconsin in June 1984 dedicated to the LISM (Kondo et al. 1984). Since then, several LISM meetings took place, the last one (again IAU) in April 1997 in Garching, Germany (Breitschwerdt et al. 1998).
There is no exact definition of the LISM, neither in terms of column densities nor in terms of distances, since it comprises a number of components at very different densities and temperatures distributed in highly asymmetric ways. In fact, the study of the LISM is crucial because it offers two unique opportunities. First, the physical state and the multi-phase structure of the LISM bears important consequences for our picture of the more general ISM. Very little is yet known on how do coexist the hot, warm and cold phases, i.e. on the filling factors, the characteristics of the interfaces, the pressure balance between phases, the ionization degrees. Thanks to the low column densities encountered in the LISM, it should be possible to disentangle individual clouds (if they exist) and understand their subtle properties and relations. Obviously also, all the wavelengths reach our telescopes after passing through the LISM.

Second, we want to know about our environment. The physical state in the immediate interstellar vicinity of the Sun represents the boundary conditions for the expansion of the solar wind and constrains its confinement, i.e. the size of our heliosphere. While galactic tides equal the gravitational attraction of the Sun at distances of $\sim 150\,000$ AU in the galactic plane (the nearest star $\alpha$ Cen being at about $3 \times 10^5$ AU), it is surprising that the much closer location of the heliopause is still uncertain. More generally, the interpretation of heliospheric observations critically depends on the physical conditions that ions, dust grains and cosmic rays encounter on their way to the solar system.

Last but not least, the galactic environment of the Sun influences the one AU interplanetary volume around the Earth, including the Sun–Earth coupling mechanisms and the high energy radiation and particle fluxes at the top of the Earth’s atmosphere. The Sun moves through space (with respect to the Local Standard of Rest, LSR, defined by the velocity ellipsoid of nearby cool stars which have relaxed to dynamical equilibrium in the galactic gravitational field, Mihalas and Binney 1981) with a velocity of 16.5 pc per million years and encounters between the Sun and interstellar clouds do occur. Observations of ”dense” interstellar structures down to AU scales (Frail et al. 1994) show that environment variations are even possible on time scales down to years. Understanding the distribution, kinematics and properties of nearby interstellar clouds allows to evaluate such encounters which may perturb the terrestrial climate and eventually imprint anomalies in the geologic records. Extreme changes due to ”galactic weather” might not favor the emergence
GLOBAL MORPHOLOGY AND DISTRIBUTION

Within 500 pc of the Sun and 50 pc of the galactic plane, not less than about 15 molecular clouds are seen through the CO molecule which is a standard tracer for densities $10^3$–$10^6$ cm$^{-3}$ (Dame et al. 1987). They define the positions of spiral arms and the local warp of the galactic plane associated with the Gould’s Belt. They roughly represent about 50% of the mass of interstellar matter and their filling factor is estimated to be 0.16. They are basically at rest in the LSR. There is an overall pronounced deficiency of interstellar matter in the third Galactic quadrant between $l=220^\circ$ and $l=250^\circ$ which corresponds to the interarm region between the Local and Orion arms and merges with the interarm region between the ”grand design” Orion and Sagittarius spiral arms at about 1 kpc from the Sun. This deficiency is also shown by a lack of diffuse gamma-ray emission (Hunter et al. 1997) and of 21 cm emission (Stacy and Jackson, 1982). These last authors even identify an optically thin H I window out to the edge of the Galaxy near $l=245\pm5^\circ$ and $b=-3\pm3^\circ$. CO has also revealed a population of high-galactic latitude ($|b|\geq25^\circ$) molecular clouds with a mean distance of $\sim100$ pc (Magnani et al. 1985). One of these, MBM 12 at $l=159^\circ$, $b=-34^\circ$, has been proved to be located at $\sim65$ pc (Hobbs et al. 1986), making it the nearest known molecular cloud. There is another gap in the distribution of this population in the direction $180^\circ\leq l \leq 340^\circ$ which mimics the above one.

The distribution of diffuse dust and gas of densities 1–1000 cm$^{-3}$ can be traced by observing the reddening of starlight by interstellar dust (Lucke 1978). The minimum contour $E(B-V)=0.1$, which corresponds to a hydrogen column density of $\sim5.8\times10^{20}$ cm$^{-2}$, follows as expected the spiral arm molecular material. An abrupt increase in reddening at 200 pc is seen in directions $l=258.4^\circ$, $b=-11.1^\circ$ $l=271.3^\circ$, $b=+5.3^\circ$, which is attributed to the onset of reddening due to dust in the Gum nebula (Franco 1990). The Vela sheet ($l=272\cdash279^\circ$, $b=-3^\circ$) is embedded in the Gum nebula.

Interstellar absorption lines spectroscopy against stellar continua provide perhaps the most powerful tracer of diffuse clouds. For short path lengths column densities are small and resonance lines are the most opaque lines for each ion. Optical neutral sodium D lines and singly ionized calcium K lines are easily observed and sample densities 0.1 to 100 cm$^{-3}$ and thermal temperatures 50 to 8000 K. But most of the
resonance lines show up in the UV domain and allow to sample virtually all nearby interstellar media.

Already at the time of the Madison meeting, two characteristics of the interstellar matter distribution within $\sim 200$ pc were recognized thanks to absorption studies: inhomogeneity and asymmetry. Plots of column densities versus distances clearly show that the column density is not a strictly monotonic function of distance (see e.g. Frisch and York 1991). Early maps of contours of equal hydrogen column density (e.g. Frisch and York 1983; Paresce 1984) showed a noticeable rapid increase towards the Sco-Oph direction, more or less towards the Galactic center. Although these authors grossly disagreed about the distance to this increase, they however both also realized the lack of neutral gas towards the third quadrant, in particular in the Canis Majoris direction ($l \sim 240^\circ$) which was subsequently identified as a true "tunnel" nearly free of matter (Gry et al. 1985, 1995; Cassinelli et al. 1996).

In these early maps, $N(H_\text{I})$ was directly derived from Lyman $\alpha$ observations with the resolving power $R=\lambda/\Delta\lambda \sim 20000$ of the Copernicus satellite ($\sim 15$ km.s$^{-1}$) or even a factor of two lower of IUE, or indirectly inferred from other ions sensitive to both ionized and neutral material. Thereafter, NaI was sampled by Welsh et al. (1990, 1991) and CaII by Vallerga et al. (1993a) towards 45 early-type stars within 220 pc from the Sun with a resolving power $R=\sim 150000$. More specifically, the Sco-Cen association was extensively studied by Crawford (1991), in both NaI and CaII but at a slightly lower resolution, and Loop I near $l=320^\circ$, $b=20^\circ$ by Centurion and Vladilo (1991) and Fruscione et al. (1994). The overall distribution was confirmed, in particular: the abrupt increase in column densities towards Sco-Oph beyond roughly 130 pc, a $N(H_\text{I})$ rise near the distance of about 70 pc and the CMa tunnel.

For the over 80 absorption components detected in CaII (Vallerga et al. 1993a), the mean LSR velocity is $0.9$ km.s$^{-1}$ with an rms of $11.3$ km.s$^{-1}$. Identical results apply to NaI, but with a smaller rms of $3.6$ km.s$^{-1}$. The statistical analysis of a set of northern hemisphere neutral hydrogen clouds observed at 21 cm gives also an essentially zero LSR velocity with a dispersion of $6.9$ km.s$^{-1}$ (Belfort and Crovisier 1984). These clouds are therefore, in a global sense, associated with the general motion of the solar neighborhood and not of the Sun itself. Specifically from the Sco-Cen association, a general outflow is confirmed (Crawford 1991).

Moreover, when plotted against the LSR velocities, the $N(\text{NaI})/N(\text{CaII})$ ratios
for each identified absorption feature show the famous Routly–Spitzer (1952) effect in which higher velocity clouds have lower ratios. Since calcium is generally highly depleted in the interstellar medium, this effect is widely interpreted as due to a mechanism of desorption/destruction of grains efficient at returning calcium to the gas phase. According to Vallerga et al. (1993a), the effect seems evident down to ±10 km.s$^{-1}$, which supports a mechanism efficient even at these low velocities.

THE LOCAL BUBBLE

In the early 70’s, the brightness distributions of soft X-rays (below 2 keV) were available for most of the sky. Due to photoelectric absorption by neutral hydrogen, their mean free path becomes less than the radius of the Galaxy. Thus, for the ultrasoft component (0.08–0.3 keV) a local galactic origin seemed compelling. Meanwhile, a widespread hot phase of the interstellar medium has been recognized from ubiquitous OVI absorption lines observed with the Copernicus satellite (Jenkins and Meloy 1974). A link between the soft X-ray emission and a supernova origin rapidly became suggestive (McKee and Ostriker 1977). However, a hot medium with the typical temperature of $\sim$5$\times$10$^5$ K of the McKee and Ostriker’s model fails to reproduce the ratios between the C (160–284 eV), B (120–188 eV) and Be (77–111 eV) bands observed with the WISCONSIN rocket survey (see e.g. McCammon and Sanders 1990). This famous model is now thought to be irrelevant to further useful discussion (Cox 1995).

An obvious interpretation of the observed ultrasoft background is the existence of a local cavity, filled with hot plasma and devoid of neutral hydrogen. Assuming that all of this background originates in the cavity, it was thought that the measured X-ray intensity along a given line of sight was directly proportional to its extent. Thus, a Local Hot Bubble was conceived, extending about 200 pc perpendicular to and very much less into the galactic plane, with a complicated 3-dimensional shape (Snowden et al. 1990) and a temperature of 10$^6$ K obtained from a collisional ionization equilibrium model.

In the M–band (0.5–1.0 keV) which samples more distant soft X-ray emission than the B–band, the WISCONSIN survey, later confirmed by the ROSAT All Sky Survey, found the sky brightness away from some identified prominent sources (Loop I, Cygnus superbubble, Eridanus cavity etc.) to be fairly isotropic. This is not easily explained because discrete sources would certainly exhibit intensity variations
with latitude. In fact, this has marked the beginning of a fundamental change in our concept of the Local Bubble thanks to space missions like EUVE, DXS and ROSAT.

One of the first deep pointed ROSAT observations were the so-called shadowing experiments. Snowden et al. (1991) found that the X-ray intensity of a line of sight passing through the Draco nebula is substantially attenuated, i.e. that a minimum of 50% of the C–band emission is from beyond the cloud. With distance limits between 300–1500 pc, at least half the flux was clearly from outside the Local Hot Bubble, in contradiction with the standard assumption that all the soft X-ray background originates in the cavity. For the nearby heavy absorber MBM 12, almost no C–band shadow was observed while less than 30% of the M–bands emission is foreground (Snowden et al. 1993). ROSAT has undoubtedly established the interstellar origin of the soft X-ray background but also the existence of such a diffuse emission from beyond the ”previous” Local Bubble.

The Diffuse X-ray Spectrometer (DXS) experiment was an attached 1993 Shuttle payload consisting of two Bragg crystal spectrometers with ”good” resolution over the range 0.15–0.284 keV (C–band, 8.3–4.4 nm). Emission lines and blends were detected, thus confirming the thermal origin of the low latitude diffuse background: a hot phase of the interstellar medium. However, no collisional ionization equilibrium model (with cosmic abundances or depleted) at any temperature in the $10^5$–$10^7$ K range can adequately reproduce the observed spectra (Sanders et al. 1996). The widths of the OVI absorption lines discovered by Copernicus can only provide an upper limit of the temperature, thus inconclusive for deciding in favor of cooler non-equilibrium models. A hot plasma model can further be dismissed by the observation of two lines of sight crossing the Local Bubble: i) towards β CMa ($\approx$200 pc) which shows an average electron density $n_e > 2 \times 10^{-2}$ cm$^{-3}$ and a very low temperature $\lesssim 5 \times 10^4$ K (Gry et al. 1985), and ii) towards the pulsar P0950+08 ($\approx$130 pc) whose dispersion measure gives $n_e > 2.3 \times 10^{-2}$ cm$^{-3}$ (Reynolds 1990). Nevertheless, i) might not be typical and ii) might be already beyond the Local Bubble.

Due to the short mean free path of EUV photons, shadows are much deeper than for soft X-rays; they are therefore an excellent probe of the very local interstellar medium. Most of the flux from a plasma in collisional ionization equilibrium around $10^6$ K should appear as emission lines in the EUV. The only lines detected in the 16–74 nm range of the EUVE satellite were He I and He II, with intensities consistent with local geocoronal and/or interplanetary scattering of solar radiation (Jelinsky
et al. 1995). These authors derived upper limits for the plasma emission measure that are a factor of 5 to 10 below what is expected in the B– and C–bands from the equilibrium plasma model with solar abundances over the temperature range \(10^{5.7} - 10^{6.4}\) K. Exploring possible scenarios that could reconcile this discrepancy, the authors favored the recent (less than \(10^5 - 10^6\) years ago) heating of the hot gas responsible for the diffuse soft X-ray background by an active blast wave, most likely caused by a supernova. The dominant features at \(T \sim 10^6\) K are high ionization lines of iron and silicon, two refractory elements normally strongly depleted onto dust grains in the cold interstellar medium. Since evaporative mechanisms that return them to the gas phase (e.g. thermal sputtering in shocks) and then raise them to high ionization states require timescales longer than \(10^5\) years (Cox and Reynolds 1987), the diffuse soft X-ray emitting gas may have depleted abundances which would change the spectral distribution and explain the non-detection of Jelinsky et al. (1995). However, such models can only be constrained by real detections of emission lines, not upper limits. The DXS experiment has shown that the data could not be successfully fit with depletion.

SMALL SCALE MORPHOLOGY

As early as 1978, Vidal–Madjar and collaborators suggested for the first time that a small interstellar cloud might be present very close to the solar system. On the basis of the observed gradients in both the hydrogen density and the far UV interstellar flux, and of the possible variations of the local \(\text{Di}/\text{H\textsc{i}}\) ratio, they inferred a distance of few hundredths of a parsec towards the Galactic center. From the polarization of starlight within 35 pc of the Sun, Tinbergen (1982) claimed the existence of a patch of interstellar material corresponding to \(E(B-V) \sim 0.003\) or \(N(\text{H}) \sim 1.5 \times 10^{19} \text{ cm}^{-2}\), also in the general direction of the Galactic center, with the nearest weakly polarized star being at 5 pc. The simple picture which emerged from the Madison Colloquium located the Sun at the inner edge of a cloud – the Local Interstellar Cloud (LIC) – believed to be a single entity immersed within a large, very hot bubble (the Local Bubble).

Absorption spectroscopy is the only method able to probe the nearest interstellar gas outside the solar system, provided the spectral resolution and signal to noise (S/N) ratios are high enough. Separations between adjacent velocity components (clouds or gas moving with the same bulk velocity) in the range 1–2 km.s\(^{-1}\) have
already been identified (Crawford and Dunkin 1995; Welty 1997), requiring thus $R \geq \text{few times } 10^5$. H$\text{I}$ column densities of a few $\times 10^{17}$ cm$^{-2}$ typical for short sight lines translate into equivalent widths in the $10^{-4}$ nm range for common ions in the visible, implying S/N ratios well above 100 to be detected. Many UV lines are much stronger, but the relatively low resolution and S/N of IUE data only allowed to confirm the pervasive presence of low densities towards the North Galactic Pole and anticenter region (see e.g. the survey of Mg$\text{II}$ lines in 51 cool stars within 30 pc by Genova et al. 1990). With the launch of the Hubble Space Telescope, the situation greatly improved. But even with the 3.6 km.s$^{-1}$ resolution of the GHRS, it is estimated that only 10% of the interstellar velocity components are resolved for unsaturated lines (Welty et al. 1996).

The complexity of the local gas has been definitively demonstrated when Ferlet et al. (1986), using the $R=10^5$ Coudé Echelle Spectrometer at ESO–La Silla, detected three velocity components with a total equivalent width of 0.017 nm in the interstellar Ca$\text{II}$ spectrum of $\alpha$ Aql (Altair) at 5 pc from the Sun. Subsequent Ca$\text{II}$ surveys (Lallement et al. 1986; Lallement et al. 1990; Lallement and Bertin 1992) further confirmed this complexity. Most of the stars within 20 pc exhibit two or three absorption components, showing that the solar vicinity comprises different cloudlets. Similarly, Vallerga et al. (1993a) detected several Ca$\text{II}$ components to most of their stars closer than 50 pc except in the third Galactic quadrant. However, Welsh et al. (1990, 1991) failed to detect Na$\text{I}$ in the same sample at less than 42 pc, their S/N ratio corresponding to $N$(H$\text{I})=2.5 \times 10^{18}$ cm$^{-2}$. Studying the spatial correlation of the Ca$\text{II}$ velocities within 50 pc, Vallerga et al. (1993a) also showed that in fact most components do not have a counterpart (at a precision of 2 km.s$^{-1}$) in a nearby sightline. They concluded that most Ca$\text{II}$ clouds subtend angles less than 15°. With an assumed mean distance of 30 pc, this corresponds to a typical upper limit of 7 pc for the size of these clouds.

The three components in $\alpha$ Aql have also been seen in the Mg$\text{II}$ and Fe$\text{II}$ GHRS data (Lallement et al. 1995). Towards the same region, pronounced angular variation in $N$(Ca$\text{II}$) within $\sim 20$ pc are known: log $N$(Ca$\text{II}$)=11.53 cm$^{-2}$ towards $\alpha$ Oph (Crawford and Dunkin 1995) whereas towards $\lambda$ Aql log $N$(Ca$\text{II}$)=9.59 cm$^{-2}$ (Vallerga et al. 1993a). Towards Vega at 7.5 pc, also three components are identified in Fe$\text{II}$ (Lallement et al. 1995). Even towards Sirius ($\alpha$ CMa) at 2.7 pc, two absorption features are detected in Mg$\text{II}$ and Fe$\text{II}$, with log $N$(H$\text{I})=17.23$ cm$^{-2}$ (Lallement
et al. 1994; Bertin et al. 1995). Indeed, the volume of the Local Bubble could
contain about 2000 "standard diffuse clouds" such as those statistically explored
via extinction studies (Spitzer 1985) and assumed to be spherical. An even larger
number could be expected according to the considerably more complete description
provided by optical absorption-line and 21 cm studies.

KINEMATICS

A major issue in the local interstellar medium studies has long been the identifi-
cation of a velocity vector that would show a coherent motion of the local medium.
In that respect, ground-based data are most useful because of their resolution and
their excellent accuracy of absolute wavelength scale. With a simple Doppler trian-
gulation, it is possible to reconstruct a velocity vector from several (at least three)
measured radial velocities, provided the cloud is close enough to the Sun. Following
the first attempt by Crutcher (1982) who used only seven lines of sight shorter than
100 pc, several different vectors were found. Although in disagreement with each
others, all of them indicated nevertheless that material flows more or less from the
higher density regions towards the empty region. Furthermore, they were also in
disagreement with the velocity of the interstellar flow in the inner solar system.

The Sun is moving through the tenuous gas of the LIC, thus creating a flow of
neutral hydrogen and helium atoms from interstellar origin which enter the solar
system (Fig. 1). These atoms are detected through resonance scattering of solar
photons by in-situ experiments. Based on two independent determinations – the
H Lyman α and the He 58.4 nm glows – the direction of the interstellar wind
within the inner interplanetary medium was found to be towards: l=184.3±3.5° and
b=−15.8±3.4° (Bertaux et al. 1985). It is in very good agreement with the direct
detection of the interstellar He I with the Neutral Gas Experiment onboard the
Ulysses spacecraft (Witte et al. 1993). However, the velocity modulus has long
been a matter of discussion. Hydrogen observations give a modulus of 20 km.s⁻¹,
whereas 26 km.s⁻¹ is deduced from helium (Bertaux et al. 1985; Witte et al. 1993).

Using the Doppler triangulation with visible high resolution spectroscopic ob-
servations at high signal to noise ratio of very nearby stars performed at both ESO
and Observatoire de Haute Provence, Bertin et al. (1993a) identified the LIC flow-
ing from l=6° and b=+16°, with an uncertainty of ±3°, and measured a velocity
modulus of 25.7±1 km.s$^{-1}$ with respect to the Sun. These are precisely the characteristics derived through helium backscattered data. They were further strongly confirmed with HST data towards Capella (Linsky et al. 1995) and several other stars (Lallement et al. 1995; Bertin et al. 1995). Together with the Ulysses result, this brings a definitive proof of the LIC identification. An immediate important consequence is the existence of a perturbation, namely a deceleration of $\sim 6$ km.s$^{-1}$, of neutral hydrogen atoms when they travel through the heliospheric interface. While the helium initial velocity of 26 km.s$^{-1}$ is thought to be unaffected because of the weak collisional cross-section of helium with solar protons, hydrogen atoms could on the contrary be primarily coupled to the plasma via charge–exchange reactions and thus expected to be decelerated and heated beyond the heliopause, as predicted by heliospheric models (Baranov et al. 1991; Osterbart and Fahr 1992; Quémerais et al. 1992).

THE LOCAL INTERSTELLAR CLOUD

1 Structure

In order to construct the structure of the cloud surrounding the solar system, one may use the column density of the components detected at the projected LIC velocity towards nearby stars. Whereas the total integrated $N$(H$^\text{i}$) is well determined through the Lyman $\alpha$ line, it is not possible to derive the velocity structure from this line alone because of its heavy saturation even for $N$(H$^\text{i}$)$\sim 10^{17}$ cm$^{-2}$. It is therefore necessary to observe resonance lines from other elements at the highest possible resolution, usually Mg$^{\text{II}}$ and Fe$^{\text{II}}$. Introducing then the detected velocity structure, one may infer $N$(H$^\text{i}$) for individual components. However, although both Mg$^{\text{II}}$ and Fe$^{\text{II}}$ are the dominant ionization stages in H$^\text{i}$ regions, they have the drawback of also sampling some ionized gas as their ionization potentials are slightly larger than for H$^\text{i}$. Furthermore, in the case of late-type stars, the closest ones, interstellar Lyman $\alpha$ is superposed on their chromospheric emission and the modelling of that "continuum" can induce potentially large uncertainties. This type of study has been done with HST for more than a dozen stars closer than 20 pc. The LIC is identified in all of them but $\alpha$ Cen (Lallement et al. 1995; Linsky et al. 1995; Ferlet et al. 1995; Linsky and Wood 1996; Piskunov et al. 1997; Wood and Linsky 1998).
Assuming that the volume density is constant in the LIC, column densities draw its contours. The LIC is flattened in the galactic plane and extends mainly in the first quadrant (towards Altair, Vega). The Sun is located at its very edge towards $\alpha$ Cen (less than about 30000 AU) and at less than 1 pc from its surface in the direction of Canis Majoris (Fig. 2).

It has to be recalled that at 1.3 pc, $\alpha$ Cen is the closest star inspected for absorption lines, whereas the distance to the heliopause (still not precisely known) is only about 0.0005 pc. Therefore, the inferred averaged physical cloud properties might not necessarily correspond exactly to the closest solar system surroundings. For instance, a dense ($\sim 10^5$ cm$^{-3}$), cold ($\sim 50$ K), very thin ($\sim 5$–10 AU) cloud with a typical diffuse interstellar depletion would be barely detectable, especially if blended with adjacent higher column density and/or warmer gas. These kinds of uncertainties might explain why the LIC is not detected towards $\alpha$ Cen (Lallement et al. 1995): it could be hidden by the six times larger absorption due to the main component in that sight-line.

The other nearby cloud seen towards $\alpha$ Cen (often called the G cloud for Galactic center) is of course at less than 1.3 pc from the Sun. This G cloud is also possibly seen towards Altair but for this sight line it is blended with the LIC. Apart from the G cloud and the LIC, six additional components are detected towards Sirius, Procyon, Altair, $\alpha$ PsA and Vega, i.e. at less than 7.5 pc from the Sun (Fig. 2). If one believes that all these components are indeed distinct cloudlets outside the LIC, the highest column density sight lines in the first quadrant imply a density larger than $\sim 0.2$ cm$^{-3}$ for the LIC (see below). Furthermore, the two non-LIC clouds seen towards Sirius (2.7 pc) and Procyon (3.5 pc) 25° apart in the sky are different which implies for these clouds dimensions of about 1 pc or smaller and locations at or just beyond the edge of the LIC.

2 Motion

The excellent agreement between the observed Doppler shifts and those predicted by projecting the LIC/interplanetary wind velocity vector onto target directions covering a very large fraction of the whole celestial sphere (Lallement et al. 1995) secures the LIC motion. Furthermore, the solar apex direction is nearly perpendicular to the LSR upwind direction of the LIC. As a consequence, the Sun has entered the LIC tens of thousands years ago at most; it is leaving it and will
enter the G cloud in less than 70000 years (1.3 pc at 18 km.s$^{-1}$). The G cloud being more rapid than the LIC, both might be already in contact. If not, the solar system would go through the Local Bubble. However, one must keep in mind the possibility to interpret the observed velocity components not as due to physically identified clouds but as the manifestation of large bulk motions like mesoturbulence or as due to interstellar shock waves.

In the LSR velocity frame, the LIC is moving towards us from the direction l$\sim$335$^\circ$, b$\sim$ −2$^\circ$. From a compilation of the velocities of all interstellar components observed for stars within about 100 pc of the Sun, Bertin (1994) has shown an overall motion of the interstellar gas from about the same direction (the Sco–Cen association), again after correcting from the solar proper motion, which is not an effect of the galactic rotation. Moreover, a velocity gradient seems to be associated with this coherent flow: decreasing velocities towards the downwind direction. The dispersion shows, however, that the flow is not uniform. The most plausible explanation of such a situation is an acceleration through a shock front. The energy needed is largely available in a supernova explosion.

For all absorbing gas within 30 pc of the Sun in which N(Na i)/N(Ca ii) has been measured, this ratio is smaller than 0.5 and even smaller than 0.2 for material (including the LIC) within 15 pc (Bertin et al. 1993b). In dense cold clouds, this value is much higher (10 to 100), refractory elements such as calcium being heavily depleted onto dust grains. Since the local clouds are moving at high velocities, in the context of the Routly–Spitzer effect these low ratios are strong evidence of calcium returned to the gas phase through destruction of grains by an interstellar shock. Similar anomalous abundance patterns (lower depletions) are found towards $\alpha$ Oph (Frisch et al. 1987), $\eta$ UMa (Frisch and York 1991), $\alpha$ CMa (Bertin 1994), $\alpha$ Aur and $\alpha$ CMi (Linsky et al. 1995) and $\alpha$ Cen (Linsky and Wood 1996). These last authors have even shown that interstellar metal abundances (measured through magnesium) do vary significantly between the LIC and the G cloud. Piskunov et al. (1997) also found large variations over distances of only a few parsecs within the LISM.

3 Density, pressure and ionization

Thanks mainly to EUVE observations of the continua and photoionization edges of interstellar He I(50.4 nm) and He II (22.8 nm) towards a large set of white dwarfs, values of the H I density in the LISM are constrained to lie between 0.15 and 0.34
cm$^{-3}$ (Vallerga 1996). This is consistent with analyses inside the heliosphere which give 0.165±0.035 cm$^{-3}$ (Quémerais et al. 1994), although some filtration of the H\textsc{i} through the heliosphere interface might be implied. Using this H\textsc{i} density, one deduces a thermal pressure (P/k=nT) $\sim$1200 cm$^{-3}$ K, a factor of about 10 lower than the Local Bubble pressure (P/k$\sim$10000–20000, Bowyer et al. 1995). Already recognized at the time of the Madison meeting, that discrepancy has fuelled a controversy over competing models of the galactic ISM (Cox 1995). This is an unstable situation that requires other pressure sources such as magnetic fields if one wants to maintain a pressure confined local cloud.

Also from EUVE observations, helium is on average 25\% ionized and even seems to be systematically more ionized than hydrogen ($n_{\text{H}\textsc{i}}/n_{\text{He}\textsc{i}} \approx$14, Dupuis et al. 1995; Barstow et al. 1997), which is counterintuitive considering the much larger ionization potential of He\textsc{i} relative to H\textsc{i}. The most likely explanation for Jelinsky et al. (1995) is a recent ($\leq$10$^6$ yrs) ionizing event. However, interstellar parameters derived from EUVE observations depend somewhat on white dwarf model atmospheres. More importantly, the limited spectral resolution of EUVE prevents to resolve individual kinematic components and therefore only total column averages are available, the LIC being hidden in them.

The ionization state of the nearby gas is a long standing problem which had to be re-examined when Vallerga et al. (1993b) discovered with EUVE that the B2 II star $\epsilon$ CMa is 30 times brighter at 60 nm than HZ43, the brightest white dwarf in the sky. One of the more precise methods to derive the electron density $n_e$ is to measure the different ionization states of the same element. Mg\textsc{i} and Mg\textsc{ii} are widely used, but prior to the high resolution of GHRS onboard HST, only average values were obtainable. Although Mg\textsc{i} is very faint in the LIC, it has been unambiguously detected. Provided equilibrium conditions prevail, the measured abundance ratios lead to $n_e=0.09^{+0.23}_{-0.07}$ cm$^{-3}$ towards $\epsilon$ CMa (Gry et al. 1995), $n_e \sim$0.1–0.6 cm$^{-3}$ towards $\delta$ Cas (assuming T=7000 K) and even larger values towards Sirius (Lallement and Ferlet 1997). Indeed, at least the last value is unrealistically large. As a matter of fact, the equilibrium assumption might be somewhat wrong because the hydrogen recombination time in the diffuse interstellar medium can be very long: the distance covered before a recombination can be estimated as 30 pc which is probably not negligible relative to the spatial scale of the EUV flux variations (known to be strongly anisotropic). Furthermore, large errors on $n_e$ are likely to occur in view of the strong
temperature dependence of the MgI ionization rate.

An independent way to evaluate \( n_e \) is to use the measured NaI/CaII ratio. But here again, the equilibrium assumption is needed, as well as an estimation of either the calcium depletion or the neutral hydrogen density. Lallement and Ferlet (1997) derived in that way \( n_e \) of the order of 0.05 cm\(^{-3}\) towards \( \delta \) Cas. Although the error bar overlaps with the range derived from magnesium, both methods are quite discrepant. Another way which has the advantage of being independent of assumptions about the ionization equilibrium is to use the ground state and excited state column densities derived from the interstellar CII absorption features. Towards Capella, this method implies \( n_e \sim 0.11 \text{ cm}^{-3} \) (Wood and Linsky 1997). However, error bars are still large. As already noted, parameters such as column densities are subject to errors in the location of the continuum which the lines are absorbing. In the case of cool stars like Capella, this continuum is in fact the unknown stellar emission line.

For all these methods, the knowledge of the gas temperature is essential. From profile fitting of FeII and MgII lines towards Sirius, Lallement et al. (1994) derived a LIC temperature \( T = 7600 \pm 3000 \text{ K} \). From the interstellar neutral helium within the solar system, Witte et al. (1993) derived \( T = 6700 \pm 1500 \text{ K} \). The Capella and Procyon lines of sight (Linsky et al. 1995) have provided perhaps the most accurate values for the LIC: \( T = 7000 \pm 900 \text{ K} \) together with a most probable speed for the assumed gaussian nonthermal motions (turbulence) of \( 1.6 \pm 0.4 \text{ km.s}^{-1} \). If there is an agreement around 7000 K, error bars are still large enough to prevent a very precise evaluation of the electron density.

A new approach has been developed to provide \( n_e \) in the Local Cloud. On the basis of the invariance principle which relates directly the properties of two media separated by a layer of material – the LIC properties as observed from the Earth orbit and the LIC material outside the heliosphere – Puyoo et al. (1997) derived \( n_e \sim 0.044 \text{ cm}^{-3} \), a value significantly lower than most of the previous ones, except towards a pulsar \( (0.02 \text{ cm}^{-3} , \text{ Reynolds 1990}) \). The same authors also derived \( n_{\text{H}^1} \sim 0.24 \text{ cm}^{-3} \) and \( n_{\text{He}^1} \sim 0.023 \text{ cm}^{-3} \). Towards Capella and Procyon, Linsky et al. (1995) found respectively \( n_{\text{H}^1} \sim 0.04 \text{ cm}^{-3} \) and \( \sim 0.1 \text{ cm}^{-3} \), but both stars lie well outside the LIC. On the contrary, Linsky and Wood (1996) derived \( n_{\text{H}^1} = 0.15 \text{ cm}^{-3} \) with an uncertainty of a factor of two towards \( \alpha \) Cen which lies inside (or almost) the G cloud.

The very low ionization claimed for the LIC by Puyoo et al. (1997) has been
very recently confirmed in the course of detailed analysis of the lines of sight towards Sirius B (Hébrard et al. 1998) and the nearby white dwarf G191–B2B (Vidal–Madjar et al. 1998; see also below). In these sight-lines, no Si III absorption is detected in the LIC (nor in the other component towards Sirius), in contrast with two much longer CMa lines of sight (Gry et al. 1985, 1995). Except if the LIC is extremely inhomogeneous, a very likely explanation is a random superposition in the velocity space of the LIC with the very long ionized CMa tunnel (1 pc relative to 200 pc!).

4 The deuterium abundance

It is widely accepted that deuterium is only produced in significant amounts during primordial nucleosynthesis and thoroughly destroyed in stellar interiors. It is thus a key element in cosmology and for galactic chemical evolution. Amongst the different methods to measure the interstellar abundance of deuterium, the safest one is to observe simultaneously the atomic transitions of D and H of the Lyman series in the far-UV, in absorption against the background continuum of stars (for a review, see e.g. Ferlet and Lemoine 1997). In order to resolve the interstellar velocity structure, we have already noted the need for the highest possible spectral resolution, such as the one offered by HST. Nevertheless, HST can only observe at Lyman α for which D I can only be detected (at −82 km.s⁻¹ from H I) for H I column densities smaller than 10¹⁹ cm⁻², i.e. in the local interstellar medium. Thus, only cool stars and white dwarfs are available. Although the chromospheric emission line of cool stars has to be modeled, the Capella sight-line has provided the most precise measurement of the LIC D/H ratio: 1.60±0.09⁺⁻⁰.⁰⁵⁻⁰.¹⁰×10⁻⁵ (Linsky et al. 1995). However, the trivial velocity distribution of the Capella line of sight (a single cloud) has been derived through Fe II and Mg II lines which may not properly trace the H I gas.

This is why we have chosen hot white dwarfs so as to provide a smooth stellar profile at Lyman α and to also observe N I and O I lines which allow an accurate kinematic sampling of the sight-line. The LIC has been clearly detected at the expected velocity towards G191–B2B, only 8° from Capella on the sky (Lemoine et al. 1995), together with two other components. The sophisticated analysis of Vidal–Madjar et al. (1998) first confirms the Linsky et al. (1995) D/H value for the LIC and second concludes that D/H is of the order of 0.9±0.1×10⁻⁵ on average for the two other components. Therefore, the D/H ratio varies by nearly a factor
of two over a few parsecs, raising thus many striking questions beyond the scope of the present review.

Both the gas temperature and the Doppler parameter (b-value) of the LIC derived by Vidal–Madjar et al. (1998) are compatible with those quoted by Linsky et al. (1995), although the most probable value for T is somewhat smaller. It has to be noted that the commonly used procedure in interstellar absorption studies is to fit Voigt profiles, accounting for radiative damping and Doppler broadening in the microturbulent limit (completely uncorrelated bulk motions). But it has been suggested that a mesoturbulent model in which the influence of a finite correlation length in the stochastic velocity field on the line forming process is accounted for might be more appropriate (e.g. Levshakov et al. 1997). Interpretation of observed profiles may then be substantially changed, with important consequences in particular also with respect to deuterium abundances towards quasars. The excellent agreement between the observed Doppler shifts and those expected from projection of the LIC velocity vector can perhaps be considered as the only proof that the usual microturbulent limit is not wrong.

It is worthwhile to emphasize that in the course of their G191–B2B study, Vidal–Madjar et al. (1998) found for the two other non LIC components very different behaviors, namely very low and high temperatures (∼2000 and ∼11000 K) associated with respectively very high and low b-values (∼3 and ∼0.5 km.s$^{-1}$). This could very well be the signature of an interstellar shock, perhaps related to the other evidence already noted previously.

5 Hot hydrogen... a hydrogen wall?

The physical parameters of the G cloud identified towards α Cen are derived through profile fitting of the FeII, MgII and D1 lines in both components of this visual binary system. However, the single-component fits to the H1 lines yield for H1 i) a large b-value which implies a temperature significantly higher than for the other lines, and ii) a velocity redshift by about 2.2 km.s$^{-1}$ with respect to all the other lines, well above the HST–GHRS accuracy (Linsky and Wood 1996). The most sensible way to resolve this discrepancy was to add a second absorption component to the H1 lines, which has a temperature $T=29000\pm5000$ K, a smaller velocity relative to the LIC inflow and a column density $\log N$(H1)$=14.74\pm0.24$ cm$^{-2}$ much too low to be detected in the other lines. Linsky and Wood (1996) proposed that this gas is
located near the heliopause and is the heated neutral hydrogen from the interstellar medium that is compressed by the solar wind (Fig. 1).

First shown theoretically by Baranov et al. (1991), the pile-up region of compressed H\textsubscript{i} in the upwind direction now called the "hydrogen wall" is predicted by multifluid gasdynamical models of the interstellar gas and solar wind interaction, with physical parameters within the range of the above observed parameters (e.g. Baranov and Malama 1995; Williams et al 1997). One can mention that Quémérasais et al. (1995) found an increase in the diffuse Lyman α emission in the upwind direction in their analysis of low dispersion spectra from the Voyager 1 and 2 spacecrafts, possibly due to the solar hydrogen wall. The Voyagers were then at 54 and 40 AU from the Sun.

Dring et al. (1997) and Wood and Linsky (1998) have tentatively detected a hot hydrogen component with a blueshifted velocity relative to the LIC inflow towards five more nearby late-type stars that they interpret as produced by collisions between the stellar winds (instead of the solar wind) and the LIC flow. Within that framework, Wood and Linsky (1998) provide empirical measurements of wind properties for late-type main sequence stars. One should mention nevertheless that these authors have also found equally good fits of the Lyman α lines without hot hydrogen absorption, but which require then characteristics either stellar (like profiles with a deep self-reversal) or interstellar (like very low D/H ratios) that they judged improbable. However, in the previous section, we have seen that very low D/H values indeed seem to exist. Furthermore, such a hot H\textsubscript{i} absorption has already been found towards Sirius A, with a slightly smaller velocity relative to the LIC inflow, which has been interpreted as due to an evaporation interface around the LIC (Bertin et al. 1995). It has to be noted that Bertin et al. (1995) failed to detect C\textsubscript{IV} as predicted by general conductive boundary models (Slavin 1989). But these models also predict an emission spectrum which can apparently be rejected at the 99.7% confidence level by EUVE observations (Jelinsky et al. 1995). However, the inclusion of an interstellar magnetic field would bring these models into agreement with EUVE data. Although a solar wind compression is attractive, an evaporation interface is not precluded yet.

Revisiting the Capella line of sight and having confirmed the Linsky et al. (1995) results for the LIC, Vidal–Madjar et al. (1998) discovered an additional weak and hot H\textsubscript{i} component which is also entirely compatible with the G191–B2B fits. Again,
it can be related either to a cloud interface or a "hydrogen wall". In this latter case, it would be due to the Capella wind, implying thus a LIC extent all the way to Capella at 12.5 pc. This is not in contradiction with previous sections if other kinematic components seen towards G191–B2B are either cloudlets embedded in the LIC or are interpreted in terms of a passing shock front.

CONCLUSION

The local interstellar medium kinematics indicates outflowing gas from the nearby (∼170 pc) Scorpius–Centaurus Association. Over the past 15 million years, this OB Association has undergone three epochs of star formation. It has been shown that Loop I is well described as a superbubble produced by the collective stellar winds and about 40 consecutive supernova explosions from this association (Egger 1995). Enhanced abundances of refractory elements further indicate that the local gas has been processed through a shock front. Spectral signatures of such a shock have been pointed out towards G191–B2B. Is this shock associated with the above superbubble? If it is clear that the Local Bubble should be no longer regarded as an isolated phenomenon, there is not even a rough agreement on its origin. Loop I and the Local Bubble can be viewed as due to two independent supernova events that are now colliding, or the Local Bubble was sculpted by the Sco–Cen activity which has swept up molecular clouds (see e.g. the discussion and references in Breitschwerdt et al. 1996).

It is interesting to note that using fossil records from antarctic ice cores, Sonett et al. (1987) concluded that the observed $^{10}$Be concentrations, which show two "spikes" at about 35000 and 60000 years ago, gave strong evidence for a recent ($\leq 10^5$ yrs) supernova explosion within a few tens of parsec from the Sun. If this is correct, a supernova is still expanding through the LIC.

The solar wind expands from the Sun at supersonic velocities. Since it depends on the solar latitude, it creates a non spherical cavity, the heliosphere, out to the termination shock. There is a transition region between the termination shock and a forward shock propagating into the interstellar medium which marks the changeover to the LIC region. The external frontier of the heliosphere, the heliopause, is at the pressure equilibrium between the two media. Taking a solar wind velocity of about 400 km.s$^{-1}$ gives a stagnation point with respect to the LIC pressure at about 500 AU. However, the estimated size of the heliosphere (based e.g. on indicators such
as cosmic-ray modulation, anomalous component, upstream plasma waves) is substantially less, only of the order of 100 AU (as indicated in Fig. 1). Amongst several possibilities to resolve that discrepancy, a popular one is pressure confinement through magnetic fields. A field strength of several $\mu$G would be required, whereas the estimated local field is only $\sim1.4\mu$G (Frisch 1995). Conditions for general equilibrium seem not satisfied.

The location of the heliopause as well as the penetration of interstellar matter into the solar system critically depend on the interstellar magnetic field strength and the LIC ionization. Shielding the Earth, the heliospheric frontier is moving according to the local interstellar environment changes. We can hope that the Voyager spacecrafts will encounter this frontier before vanishing around 2020.

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FIGURES CAPTIONS

Figure 1: Schematic illustration of the solar wind–interstellar medium interface. The Sun is moving through the LIC and the supersonic solar wind is blowing a cavity called the heliosphere. The fraction of the interstellar neutral hydrogen which penetrates within the heliosphere is decelerated through charge–exchange collisions, invades the interplanetary medium and backscatters the solar Lyman α radiation.
producing an observed emission glow. The interstellar neutral helium is extremely weakly interacting with the plasma and keeps its initial heliocentric velocity, measured \textit{in situ} by Ulysses and found to be equal to the LIC velocity. The transition from supersonic to subsonic flow is supposed to occur at the so-called termination shock, the first discontinuity the outer probes Voyager and Pioneer 11 should encounter.

**Figure 2:** Schematic morphology of the very Local Interstellar Medium. The Sun is embedded in the LIC (assumed to be a cloudlet with a more or less constant density), very close to its boundary in the direction of \(\alpha\) Cen. This line of sight exhibits a single absorption component at a non-LIC velocity. Cloud multiplicity towards other nearby stars is illustrated. Some kinematical information is also given (in the LSR). It is consistent with an expanding medium from the direction of the Galactic Center, however the 3D velocity vectors are known only for the LIC and the G cloud. The exact location and shape of the different cloudlets are unknown, but filamentary structures are not unusual in interstellar gas. These entities are embedded in the very low density hot Local Bubble, which extends in particular beyond Sirius towards CMa.
