Part II

UV and Soft X-ray Observations of the LISM

Despite the fire incident: entertaining talks ...

... critical remarks and controversial discussions.

https://doi.org/10.1017/S0252921100070652 Published online by Cambridge University Press

Observations of the Local Interstellar Cloud

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Abstract. Constraints on the ambient (circumsolar) interstellar medium can be derived from observations of interstellar neutrals or their derivatives in the heliosphere. New results have been recently obtained which, when combined with optical and UV observations of the nearby stars (HST-GHRS, EUVE), remove long-standing contradictions and allow us to infer for our local cloud, pressure, ionization and limits on the magnetic field. The electron density in the circumsolar gas is found to be between 0.04 and 0.15 cm^{-3}. Its total thermal pressure is within the interval $1700 - 2600\,\mathrm{cm}^{-3}\,\mathrm{K}$. If the local magnetic field is nearly perpendicular to the interstellar wind flow, which is likely, then its intensity is smaller than 3.6 μG. Our Sun is located very close to the edge of the local cloud (the volume of gas which has the same physical properties as the circumsolar gas), while there are at least 5 other cloudlets within 10 pc. Abundances vary from cloudlet to cloudlet. How they are located and whether they are separated by tenuous gas or shock discontinuities is not clear yet. Semi-hot (10^5 K) gas has been detected in absorption towards nearby stars (Wood et al, 1996), which probably originates in the "H walls" surrounding our heliosphere and other asterospheres. This shows that semi-hot gas is not necessarily linked with cloud interfaces with the hot gas of the Local Bubble.

1 Our Heliosphere: the "Solar Wind Bubble"

Our Sun is travelling through an interstellar diffuse cloud (herafter Local Interstellar Cloud, or LIC), one of the moderately warm ($T = 5,000 - 10,000\,\mathrm{K}$) cloudlets which have been detected in the solar vicinity (Fig.1 (top) and Fig.3). By definition, here the LIC is the very small mass of gas moving at the same velocity as the interstellar helium flow in the heliosphere, at variance with the larger volume of gas within 30 pc whose mean motion has been detected by Génova et al (1990), which includes the LIC.

The Solar Wind is blowing a cavity in the LIC, whose size and shape are determined by pressure balance between the radially expanding solar plasma and the surrounding ISM. This cavity, the heliosphere, is certainly asymmetric, because in the direction ot the relative motion of the Sun with respect to the ambient medium, the dynamic pressure associated with this motion (at $\simeq$ 20 km/s) adds up to the other interstellar pressure forces such as the thermal pressure, the magnetic tension, and the low energy cosmic ray pressure (those which do not penetrate the heliosphere) (Fig.1 (middle)). Interstellar charged particles are diverted around the heliopause, the contact-discontinuity surface which, in principle, separates the solar wind and the ISM. The solar wind is probably stopped in its radial expansion and also diverted along the inner

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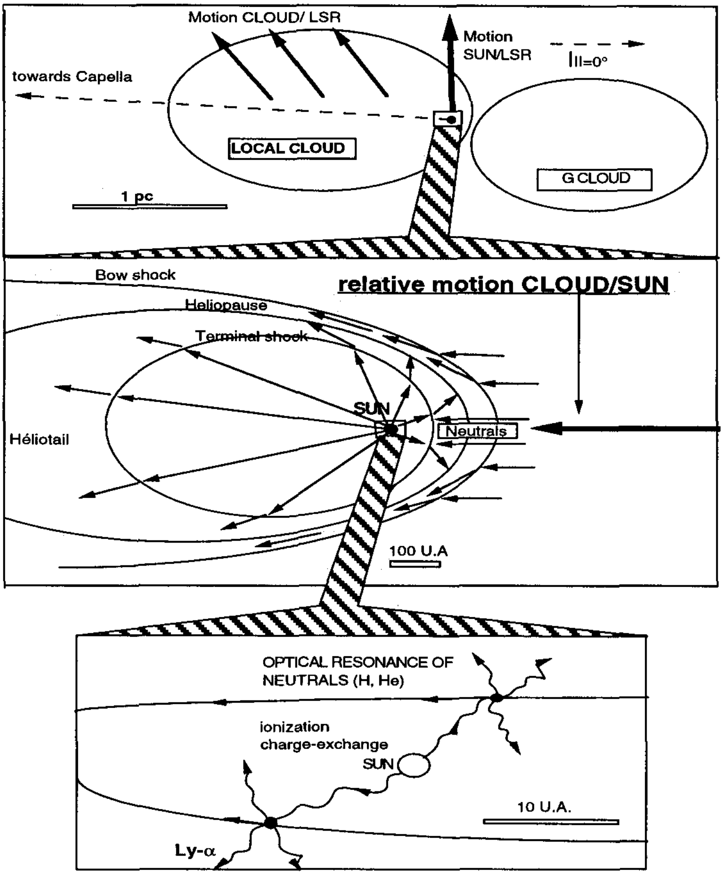

Fig. 1. The heliosphere in the Local Interstellar Cloud, at three different scales

part of the heliopause to finally merge with the ISM flow. The supersonic-subsonic transition of the solar wind is supposed to occur at the so-called "termination shock", the first discontinuity the outer probes as the Voyager and Pioneer 11 should encounter. Interstellar neutrals are the only "thermal" species to enter the heliosphere, where they can be observed through resonance scattering of solar light (Fig.1 (bottom)), but there are filtration processes at the interface due to coupling with the plasma through charge-exchange collisions. As a result, an additional and non-negligible pressure is associated to those neutrals which interact with the plasma, in particular the neutral hydrogen.

By nature, those parameters which have the strongest influence on the heliospheric size, i.e. the plasma density and the magnetic field intensity and orientation are not directly measurable in the heliosphere, and one has to rely on indirect determinations, or on interstellar measurements.

2 Constraints on the Ambient Gas from Heliospheric Observations

2.1 From Helium and Hydrogen

There has been a long-standing debate about neutral He and neutral H properties. The models predict deceleration, heating, and filtration of H at the entrance in the heliosphere while He, being not coupled to the plasma, enters the heliosphere without any perturbation. One then expects the helium flow properties to be the same in the local cloud and inside the heliosphere (before the direct interaction with the Sun). However, resonance scattering of the solar H and He Ly-alpha radiation by the inflowing H and He gives $T_{\rm H}^{\rm perp} = 8000\,{\rm K}$ (perpendicularly to the flow) and $T_{\rm He} = 15000 - 17000\,{\rm K}$. This contradiction has disappeared now, since the Ulysses in-situ detection of the neutral He (Witte et al, 1993, 1996) shows that $T_{\rm He} = 6700\,{\rm K}$, and $V_{\rm He} = 25.5\,{\rm km/s}$ from $\lambda = 254°$ and $\beta = 5°$, in perfect agreement with the properties of the LIC (see section 3). When compared with this "zero perturbation" state, H appears to be decelerated by a few km/s when entering the heliosphere (Lallement et al, 1993), providing evidence for a non-negligible plasma density outside the heliosphere, namely $n_{\rm e} = 0.05 - 0.1\,{\rm cm}^{-3}$ when using the Baranov and Malama (1993) filtration model.

Until very recently it was also generally admitted that helium is predominantly neutral in the local clouds if T≤10,000K. As a result, any significant ionization of the ISM implies that the neutral H density inside the heliosphere is significantly smaller than 10% of the neutral He density (for a cosmological ratio H/He= 10), due to both the ionization of the LIC itself and filtration processes. Recently, the H density in the inner heliosphere has been revised upward (e.g. Quémerais et al, 1995). The preferred values for $n_{\rm H}$ range from 0.10 (compiled UV glow data, see Quémerais et al, 1994) or 0.11 (H^+ pick-up ions measurements by Ulysses, Gloeckler et al, 1996) to $0.16\,{\rm cm}^{-3}$ from radiative transfer models. Due to the existence of the H wall (see section 4) the density found at large distance is somewhat larger than the density at 20 AU before close interaction with the sun and for this reason we will retain $0.15\,{\rm cm}^{-3}$ as the upper limit for the inner heliosphere density. For helium, three independent experiments have provided determinations of the neutral helium density which agree well at $n_{\rm He} = 0.015 - 0.017\,{\rm cm}^{-3}$ (Witte et al, 1996, Gloeckler, 1996, Möbius, 1996).

These ranges for $n_{\rm H}$ and $n_{\rm He}$ include H/He = 10 and do not require a filtration of H. However, according to the EUVE results this conclusion is now modified. As a matter of fact, helium is shown to be more ionized than hydrogen (Dupuis et al, 1995), i.e. $n_{\rm H} > 10 n_{\rm He}$ in the ISM. This leaves room for the exclusion from the heliosphere of a fraction of the neutral H, in agreement with the deceleration.

The combination of the H and He heliospheric data, the EUVE results, and the H filtration as a function of the electron density taken from a model,

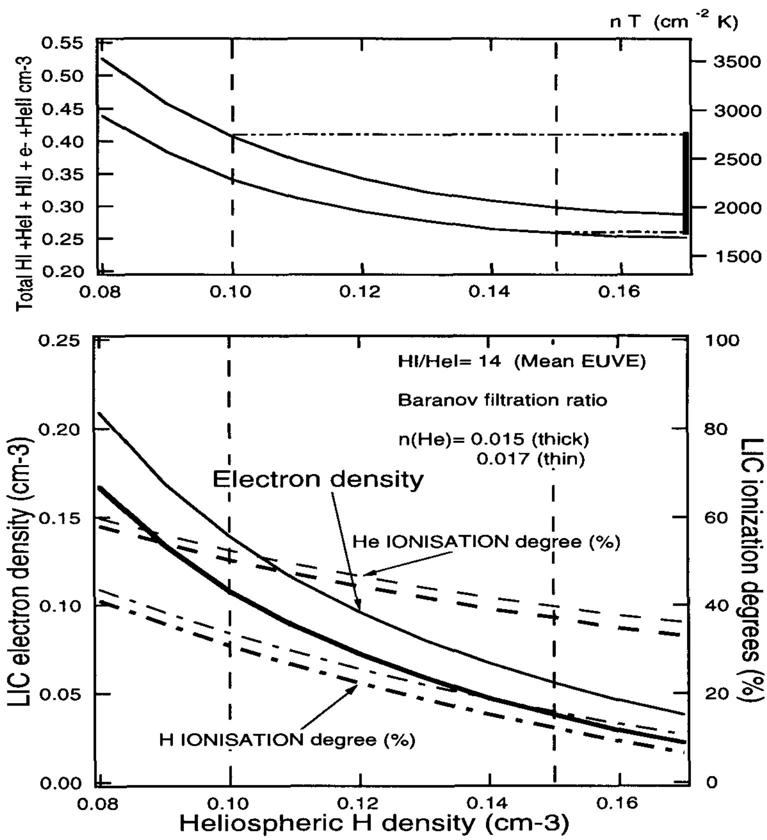

Fig. 2. Circumsolar pressure

allows us to constrain N_e. To do so, Lallement (1996) has used the Baranov and Malama (1993) model (a plasma/neutrals self-consistent model). The most appropriate value for the LIC HI/HeI ratio is 14, as measured towards G191B2B by Dupuis et al (1995). As a matter of fact, most of the neutral gas towards this star belongs to the LIC (Lallement et al, 1995, Lemoine et al, 1996), and corresponds to what is also detected towards the angularly close Capella (12.5 pc) (Linsky et al, 1995).

According to the total range for $n_{\rm H}$, one infers for the ambient ISM N_e= $0.04 - 0.15\,{\rm cm}^{-3}$ (Fig.2). This range is compatible with the deceleration of H. The corresponding neutral H density before the filtration and the total gas pressure in the LIC are shown on the top graph in Fig 2. It can be seen that the total thermal pressure is found to be $1700 - 2600\,{\rm cm}^{-3}\,{\rm K}$. This interval is much smaller than what would have been quoted three years ago.

https://doi.org/10.1017/S0252921100070652 Published online by Cambridge University Press

2.2 From Oxygen Filtration

Oxygen atoms suffer significant filtration processes on entering the heliosphere, just as does neutral hydrogen, through charge-exchange with the protons. It had been concluded from studies neglecting the inverse reaction $O^+ + H \rightarrow O + H^+$ that oxygen is almost totally excluded from the heliosphere for ISM plasma densities as small as $0.01\,\mathrm{cm}^{-3}$ (Fahr, 1991), leading to the belief that the ambient medium has to be neutral, because neutral oxygen is not underabundant in the heliosphere (e.g. Gloeckler, 1996). Recently, Izmodenov et al (1997) have used Ulysses measurements of O^+ pick-up ions (interstellar ionized oxygen), the recent precise determination of the neutral oxygen abundance in the local cloud from Capella GHRS data (Linsky et al, 1995) and a refined model of the O and O^+ flows, and shown that there is no contradiction between the presence of oxygen in the heliosphere and a moderate ionization of the ambient ISM. On the contrary, the data allow a filtration by a factor of two of this species, i.e. an ambient plasma density of up to $0.1 - 0.2\,\mathrm{e}^-\,\mathrm{cm}^{-3}$. Another approach has been used by Frisch (1995), using Anomalous Cosmic Rays (ACR) Voyager data. ACR are those pick-up ions which have been accelerated to high energies at the interplanetary shocks and at the heliospheric shock. This study also allows for large electron densities ($0.2\ \mathrm{cm}^{-3}$)

2.3 From Voyager Distance and Radio Observations

If R_s is the distance to the heliospheric shock, the solar wind pressure at the heliopause is: $N_\mathrm{sw}\, m\, V_\mathrm{sw}^2 \,/\, K\, R_\mathrm{s}^2$, where N_sw, V_sw are the solar wind density and velocity at 1 AU, m is the proton mass, and K is a corrective factor which takes into account the pressure increase between the solar wind shock and the heliopause (K is close to 1.1). This "inner" pressure is balanced by the "outer" pressure terms:

- the thermal and dynamic pressure of the ISM plasma: $(N_\mathrm{i} + N_\mathrm{e})\, kT + 2N_\mathrm{i}\, mV^2$, where N_i, N_e are the ion and electron densities
- the pressure of the fraction of the neutrals coupled to the plasma by charge-exchange: $\epsilon\, N(\mathrm{HI})\, m\, V^2$, where ϵ is a function of $N(\mathrm{H})$, $N(\mathrm{HII})$
- the pressure of the low-energy cosmic rays reflected by the heliosphere
- the ISM magnetic pressure: $\alpha B^2 \,/\, 8\pi$

where α depends on the field orientation and is maximum when the magnetic field is perpendicular to the relative flow. In this case the magnetic field lines are draped around the heliopause and compressed close to the stagnation line, and the magnetic tension adds to the plasma pressure. In the very improbable case of a magnetic field being by chance parallel to the flow, the situation is totally different and there is no additional pressure. In intermediate cases, one expects a partial draping and a non-zero pressure. There is evidence that the local magnetic field B is almost perpendicular to the relative flow (see Frisch, 1995) and in this case α should be close to 2 (2.2 if one uses Parker's calculations for a solar wind expanding in a pure magnetic field). The fraction of the energetic particles which are entering the heliosphere, and the neutrals which are not interacting with the plasma are not contributing to the confinement of the heliosphere.

Limits from Voyager's Present Location A straightforward way to get an upper limit on the pressure acting on the heliosphere, is by simply considering that the distance to the solar wind shock is larger than the distance already reached by the outer probes. As a matter of fact, plasma instruments on board the Voyager 1 indicate that the spacecraft are still cruising in the supersonic solar wind.

The total interstellar pressure required to confine the solar wind shock within 70 AU (Voyager 1's distance will be 69 AU at the end of 1997), is then $\Pi_\mathrm{i} < 3.0\,10^{-12}$ dynes cm^{-2}. In case of a confinement by the plasma alone the maximum density compatible with this pressure is $N_\mathrm{e} = 0.17\,\mathrm{cm}^{-3}$ (for $N(\mathrm{H}) = 0.2\,\mathrm{cm}^{-3}$). In case of pure magnetic confinement, then $\mathrm{B}_\mathrm{perp} <$ 6μG. The maximum plasma density is compatible with the range of densities derived above (but not with the 0.25 cm^{-3} derived from ACR data). As we will see, it is also compatible with some of the diagnostics derived from stellar spectroscopy, but not all of them.

Limits from the Interpretation of Voyager Radio Emission A very exciting new measurement from the voyagers is the time delay between strong solar wind events and the reception by the spacecraft of the 2 – 3 kHz radio emissions believed to be generated at the heliopause by shocks and discontinuities associated to these events (Gurnett and Kurth, 1996). According to the delay of about 400 days, the distance to the heliopause should be 110-160 AU, which roughly corresponds to R_s between 75 and 95 AU. For the most probable value in this interval Π_i is about $2.6\,10^{-12}$ dynes cm^{-2}, i.e. a lower limit than what has been inferred above. This corresponds to $N_\mathrm{e} < 0.15\,\mathrm{cm}^{-3}$ in case of a pure plasma confinement. Now, what can be said about the relative contributions to confinement of the plasma and the magnetic field? Here we will distinguish between two cases which are based on different diagnostics:

i) The Voyager plasma experiment has detected a 2 kHz emission which, contrary to the 3 kHz radiation, is not stronger along the wind axis. This emission has a very precise low cutoff at 1.8 kHz. There are no satisfying explanations for this emission yet, but the presence of such a marked cutoff, which corresponds to the plasma frequency of a medium with $N_\mathrm{e} = 0.04\,\mathrm{cm}^{-3}$, suggests a phenomenon linked with the ambient ISM. If this is true, then we have an extremely precise determination of the circumsolar electron density. In this case, one can infer the plasma pressure $\Pi_i = 0.5\ 10^{-12}$ dynes cm^{-2}, and estimate the additional pressure connected with the neutrals

https://doi.org/10.1017/S0252921100070652 Published online by Cambridge University Press

linked to the coupling with the plasma. A rough estimate from comparison with the Baranov and Malama models with and without neutrals gives $\Pi_{\text{neutrals}} = 0.4\,10^{-12}$ dynes cm^{-2}. Subtracting those terms from the total pressure results in a pressure associated with the magnetic field and the cosmic rays $\Pi_{\text{magnetic+CR}} < 1.7\,10^{-12}$ dynes cm^{-2}, and $\Pi_{\text{magnetic}} < 1.2\,10^{-12}$ dynes cm^{-2} if $\Pi_{\text{CR}} = 0.5\,10^{-12}$ dynes cm^{-2} (Ip and Axford, 1986). This corresponds to $B_{\text{perp}} < 4.4\mu$G if $\Pi_{\text{CR}} = 0$ and $B_{\text{perp}} < 3.7\mu$G if $\Pi_{\text{CR}} = 0.5\,10^{-12}$ dynes cm^{-2}.
ii) If the 1.8kHz cutoff is not the ISM plasma frequency, then the most likely value for N_e is of the order of $0.1\,\text{cm}^{-3}$ according to the deceleration of H (section 2.1), the filtration of H (idem), the CII/CII* ratio (see section 5). Replacing 0.04 by 0.1 in the above estimates results in $B_{\text{perp}} < 2.4\mu$G if $\Pi_{\text{CR}} = 0$ and $B_{\text{perp}} < 0$ (!!) μG if $\Pi_{\text{CR}} = 0.5\,10^{-12}$ dynes cm^{-2}.
These rough estimates should be refined in the future: (i) thanks to a better understanding of the radio emissions (ii) from better constraints on the filtration and the shape of the heliosphere (iii) by simply waiting: the progression of the spacecraft continuously changes the upper limit on the pressure, and there is hope that the heliospheric shock will be reached some time between 2010 and 2015, assuming that the solar wind is not decelerated to the point where no shock, as such, is in fact formed.

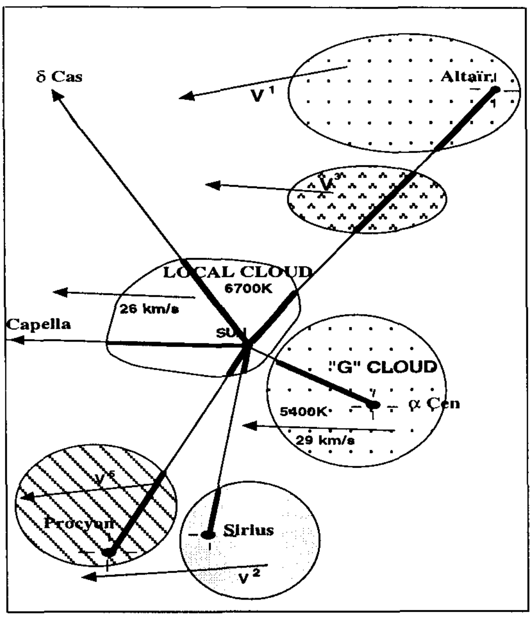

Fig. 3. Schematic view of the local cloudlets

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3 LIC Characteristics from Stellar Spectroscopy

The identification of the local masses of gas relies upon the study of the Doppler shifts and the depths of the absorption lines detected in the spectra of the nearby stars. If the LIC is moving like a solid body, then for each target star the Doppler shift of the absorption line which is actually associated to this cloud is simply the projection of its velocity vector onto the line-of-sight. In other words, if one can find a set of coherent Doppler shifts in a large enough number of directions covering the sky, for a single velocity vector, then this motion is probably that of the mass of gas in which the Sun is embedded,as seen via the Doppler triangulation method.Towards α Aql, for example, three different motions are detected. One has a Doppler component compatible with the Local cloud vector (Fig 3). In fact, two masses of gas were detected in this way, in two opposite regions of the sky (see Lallement et al, 1995). The GAS instrument on board Ulysses measured 26 km/s from $\lambda = 254°$ and $\beta = 7°$ (Witte et al, 1993, 1996) in agreement with the cloud which was seen towards the largest fraction of the sky. Later the temperature measured by Ulysses (6500 K) was found to be comparable to the temperature of this cloud (6700 K) measured from D and H lines by the GHRS towards Capella (Linsky et al, 1995). The temperature of the second cloud, called the G cloud, has been determined by Linsky and Wood (1996), from α Cen spectra, and found to be 5400 K.

Once the LIC is identified, one can use all the absorption lines at the LIC Doppler shift and combine them to infer some of its physical properties. Up to now, attempts have been made with the help of the Mg^+/Mg^o , Na^+/Na^o and C^+/C^{+*} ratios (C^{+*} is the excited state). In the first two cases, N_e is deduced from the assumed equilibrium between photoionization and recombination. Those estimates are then dependent on the radiation field. The C^+/C^{+*} method has the great advantage of being independent of the field because this ratio depends only on the temperature (otherwise measured from the line widths of different species), and the electron density. As a result, this is very likely the most reliable determination. The resulting ranges for the electron density from the different methods are:

a) MgII/ MgI equilibrium with the HST-GHRS: towards Sirius (2.7 pc) (Lallement et al, 1994) $N_e = 0.3\,\mathrm{cm}^{-3}$, towards ϵ CMa (200 pc) (Gry et al, 1995) $N_e = 0.2\,\mathrm{cm}^{-3}$, towards δ Cas (22 pc) (Lallement and Ferlet, 1997) $N_e = 0.25\,\mathrm{cm}^{-3}$ assuming $T = 7000\,\mathrm{K}$.

b) Na ionization (ground): towards δ Cas (Lallement and Ferlet, 1997) $N_e = 0.05\mathrm{cm}^{-3}$

c) CII/CII* equilibrium (HST-GHRS): towards Capella (12.5 pc) (Wood and Linsky, 1997) $N_e = 0.11\mathrm{cm}^{-3}$

The results show rather strong discrepancies between the quantities derived from magnesium and those from carbon or sodium. It may be a sign of an absence of ionization equilibrium. This certainly deserves further studies because such a lack of equilibrium points in favor of a recent ionizing event in the Local Bubble. It may also simply reflect ionization gradients in the clouds (e.g. Vallerga, 1996).

4 Boundaries Between Cloudlets and Semi-hot Gas?

4.1 Existence of Shocks

Any collision between two masses of ionized gas, or partially ionized gas should produce propagating shocks in the colliding clouds. The similarity between the velocities and temperatures of the two local masses of gas (the LIC and the G cloud) may be due to the existence of a traveling weak shock dividing a single cloud into two media with slightly different properties. In other words, there would be a unique cloud and a shock front separating it into the LIC (the post-shock warmer gas) and the G (the pre-shock gas). Grzedzielski and Lallement (1996) have calculated the magnetic field intensity compatible with this scenario, assuming the shock is a perpendicular shock (those shocks are found to have the longest lifetime). The resulting values of the order of 1.5-2 μG were encouraging. However, it was recently demonstrated by Linsky and Wood (1996), that the abundances of FeII and MgII in the G cloud with respect to deuterium are a factor of 4 larger than in the LIC. There is no explanation for such a difference in terms of propagating shocks, and the existence of two very different histories for the two masses of gas is now much more likely. If these two clouds are independent, then one can argue that the faster one, the G cloud at 29 km/s, has probably not yet caught the LIC. As a matter of fact, if it had caught the LIC, two reverse shocks would have been produced, and there would be a contact discontinuity with no velocity jump at the location of the encounter. The LIC-G transition is not such a discontinuity, (the velocities are different), and unless by chance the collision has occured extremely recently, and the three surfaces (the two shocks and the contact discontinuity) are very near from each other, it is probable that the two masses of gas are not in contact. This has some importance with respect to the Local Bubble pressure, since in this case, if the clouds are embedded in hot gas, there should be hot gas between the two clouds and two hot-warm conductive interfaces close to the Sun.

4.2 Semi-hot Gas from H Walls

Semi-hot gas has been recently detected by the GHRS in the local ISM from its Ly-α absorption lines (Bertin et al, 1995, Gry et al, 1995). The existence of gas at temperatures of order of 10^5 K is of crucial importance since this gas is supposed to separate the warm clouds from the ambient hot gas of the LB. However it is clear now that there are other sources of semi-hot gas. Linsky and Wood (1996) detected an extra absorption by neutral H at 20,000 K towards α Cen and argued convincingly that this column of gas corresponds to the "H wall", a region of decelerated and compressed interstellar gas in front of the heliosphere. Spectra of the stars λ And and ϵ Ind also showed the existence of semi-hot gas, which Wood et al (1996) attributed to H walls around those stars. Moreover, Williams et al (1996) have suggested the existence of semi-hot gas in the tail of the heliosphere, due to the mixing of the main flow and neutral H resulting from charge-exchange with the fast solar wind protons. This shows that one should be careful in interpreting the amount of semi-hot gas in terms of interfaces with the ambient hot gas only.

Acknowledgements. If this paper is readable, it is due to the careful work of the native english referee from the La Palma group who corrected all errors. Many thanks to him.

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