Heating the Local Interstellar Cloud

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Abstract. The Local Interstellar Cloud (LIC) is the region of the interstellar medium (ISM) that surrounds and helps to shape the heliosphere. The LIC is part of a collection of nearby low density warm clouds known as the Complex of Local Interstellar Clouds (CLIC), all of which exist inside the hot Local Bubble. Observations of interstellar neutral He atoms flowing into the heliosphere by the IBEX mission and Voyager have constrained the temperature of the LIC to be roughly 7500 K. This temperature is consistent with that derived from absorption line measurements toward nearby stars. Such observations also indicate that the LIC is partially ionized with elemental abundances consistent with a moderate level of depletion onto dust grains as might occur for low density ISM that has been subject to a shock that partially destroyed the dust. The temperature of the cloud is not unusual for the warm ionized medium in the ISM, but it is less ionized than typical. We discuss the various processes that may be important for heating the LIC. We show that the only viable heat source for the ongoing heating of the CLIC is photoionization. Equilibrium models of the ionization and heating of the LIC allow for solutions that match the observations, but the likely origins of the local interstellar medium suggest that the situation is more complex. We propose an evolution scenario in which the clouds were formerly cold and were heated by shocks to reach their current warm state. We present new magneto-hydrodynamical calculations of the evolution of the local ISM. Multiple supernova models can match the parameters of the Local Bubble and heat the cold clouds as desired, though the many constraints on the clouds and bubble have yet to be fully satisfied by the models.

1. Introduction
The Local Interstellar Medium (LISM) is dominated by the large low density bubble or cavity that surrounds the solar location known as the Local Bubble (LB). The dimensions of the bubble have been mapped out both by absorption lines, e.g. using the lack of Na I absorption toward nearby stars [1], and by the lack of dust extinction [2]. The existence of the Local Bubble has also been inferred by observations of soft X-ray (∼ 0.25 keV) emission [e.g. 3, 4] which has been observed in every direction over the sky and from which it is inferred that the low density cavity is filled with hot, $T \approx 10^6$ K gas. From the intensity of the emission and its inferred temperature as well as the dimensions of the cavity and models for the emissivity of the plasma, the pressure and density of the hot gas has been determined. The relatively high value of $P/k_B \approx 1.5 \times 10^4$ cm$^{-3}$ K has been found, though details about possible contributions from distant backgrounds and foregrounds (discussed below) create uncertainties in this value. Such a pressure value leads to an estimated density of $\sim 0.005$ cm$^{-3}$.

Despite the very low average density of the LB, there are some denser, cooler regions detected in the bubble. In particular the Complex of Local Interstellar Clouds (CLIC) is a collection of
15 identified clouds that are within 15 pc of the Sun [5]. The cloud properties do vary from cloud to cloud, but all are warm, \( T \sim 4000 - 9000 \) K and partially ionized, \( X(\text{H}^+) \sim 0.25 \). The clouds have been detected using primarily UV absorption lines toward nearby stars and most lines of sight show multiple absorption components (i.e. velocities). Combinations of line column densities and models for the ionization levels of different elements yield estimates of the gas phase elemental abundances. The results indicate significant depletion onto dust for silicate dust elements including Fe, Si and Mg but less depletion than is typical for so-called diffuse H\(_i\) clouds. Another relevant property of the CLIC clouds is that they apparently have a low level of turbulence. We discuss this further below.

The closest cloud in the CLIC, the Local Interstellar Cloud (LIC), is believed to surround the Solar System and, with the solar wind, creates the heliosphere. In fact we might want to define the LIC as that region immediately outside the heliosphere, though the name LIC has been associated with a particular velocity component of gas seen in absorption toward nearby stars. The fact that the velocity, density, temperature and ionization of the LIC and the ISM inflowing into the heliosphere appear to be consistent makes us confident that the gas seen in absorption and that detected \textit{in situ} are coming from the same “cloud”. As we discuss below, there are good reasons to believe that small scale variations are common in the CLIC and that regions that appear as a single velocity vector may be complex in their spatial morphology [see also 6]. Nevertheless we will assume from here on that the LIC is the source of the inflowing ISM. The combination of \textit{in situ} measurements and line-of-sight observations in many directions makes the LIC the most tightly constrained cloud there is and gives us the ability to probe the physical processes at work in such low density ISM with a level of completeness that is not available anywhere else.

2. Heating Mechanism for Diffuse Warm Gas

The local ISM is like the ISM as a whole in that it exists at a wide range of temperatures and densities. In the ISM it is seen that certain temperatures, densities and ionization states seem to be more common and these have come to be referred to as “phases” [7]. One of the primary phases of the ISM is known as the warm ionized medium (WIM) and was first found to be widespread by its faint diffuse H\(\alpha\) emission [8, 9]. This emission is observed over the entire sky implying that the WIM is present throughout the ISM as a low density intercloud medium rather than being confined to the environs of hot stars in H\(_{\text{II}}\) regions. The characteristics of the WIM have been determined by those H\(\alpha\) observations as well as associated optical [N\(_{\text{II}}\)] and [S\(_{\text{II}}\)] emission [see 10, for a review]. The source of the ionization and heating of the WIM is not certain though there have been several proposals put forward. The power needed to balance the cooling associated with the H\(\alpha\) emission and to provide its ionization is substantial, roughly equivalent to the power associated with supernova explosions in the Galaxy.

The WIM, however, differs significantly from the warm partially ionized medium of the CLIC. First, because of the weakness of [O\(_{\text{I}}\)] \(\lambda\)6300Å emission relative H\(\alpha\) associated with the WIM, it is clear that in the WIM H is highly ionized, \( X(\text{H}^+) > 67\% \) [11]. The weakness of He\(_{\text{I}}\) \(\lambda\)5876Å line shows that the He ionization fraction is small, \( X(\text{He}^+) < 0.27X(\text{H}^+) \) [12]. This contrasts to the conditions in the LISM wherein observations of H\(_{\text{I}}\) and He\(_{\text{I}}\) continuum absorption toward nearby stars observed by \textit{EUVE} indicate that He is more ionized than H [13]. Since the ionization of the WIM differs from that in the CLIC, it is likely that its heating differs as well. Nevertheless the temperatures and density of the WIM and the CLIC are similar and thus it is worth considering the heating mechanisms put forward for heating the WIM as possible heat sources for the CLIC.
3. Heating Sources Proposed for the Diffuse ISM

Most of the heating sources we discuss here are expected to mostly heat the warm ionized ISM, though some could also be sources for diffuse neutral gas in the ISM, the so-called warm neutral medium (WNM) and cold neutral medium (CNM). The mechanisms that have been gotten the most attention are the following:

- photoionization heating from the FUV/EUV/Soft X-ray radiation field
- photoelectric emission from dust grains
- dissipation of MHD turbulence
- low energy cosmic rays
- shocks (mostly from SNRs, though stellar winds and outflows could also contribute).

The most obvious source of heating for the WIM is photoionization heating since the photoionization that produces the ionization of the WIM will necessarily be accompanied by heating. This heating comes from the excess energy of the electrons that have been freed from H atoms (primarily) which are then thermalized. O and B stars generate plenty of photons and energy to account for the ionization and heating of the WIM. However such early type stars are comparatively rare and it is unclear if the photons can escape the H\textsuperscript{ii} regions surrounding the stars in adequate numbers to account for the relatively smooth distribution of WIM seen via H\textalpha emission. For the CLIC, the problem is that there is a dearth of early type stars that are near enough to provide the ionization, only two B stars known to be inside the Local Bubble. Hot white dwarfs also contribute to the ionizing radiation field, though they have much lower flux per star.

Photoelectric emission from grains can be effective as a heat source for the gas if the dust abundance is large enough [14]. It is in fact believed to be the primary source of heat for the WNM [15]. Radiative transfer is a less important effect in this case because the radiation field that is effective is that longward of the Lyman limit, i.e. the far UV, which is only effectively absorbed by dust and thus has a long mean free path even in the Galactic plane. Grain heating becomes less effective, however, as the temperature rises above $\sim 6000$ K since cooling of the gas via collisions with the grains becomes important. In the case of the CLIC, this is compounded by the fact that there is evidence for significant grain destruction with a gas-to-dust mass ratio is higher than the typical value of 100 by 50–100%. PAHs are believed to be important sources of heat in some regions but can be destroyed in warm ionized regions [16]. Detailed photoionization models (discussed below) find that dust heating is not significant for the LIC.

Dissipation of turbulence was proposed as a heating source for the WIM by [17] and [18]. This is a means of transferring the energy in the magnetic field and the kinetic energy in non-thermal motions to the thermal energy of the gas. [18] found that only certain types of dissipation lead to a heating rate that would balance the radiative cooling rate in the WIM and that Landau damping would create too much heating. Details of that model were later disputed by [19] who claimed that the heating and cooling rates could be reconciled with the correct cut-offs in wavenumber space. This debate has continued, but for our purposes of looking at the heating of the CLIC, it appears that it is not relevant and that turbulent heating cannot be a significant contributor to the heating. The reason is that the absorption line observations have shown that there is very little energy in turbulence in the CLIC. By using lines from elements with a large difference in atomic mass, e.g. D and Fe, the non-thermal (presumably turbulent) width and the thermal width of the lines can be determined. Using this method it has been found [5] that the turbulent widths in the CLIC are $\sim 1 – 3$ km s$^{-1}$ implying a low turbulent dissipation rate.

The amount of heating that might be available from low energy ($\sim 1$ MeV) cosmic rays has been very uncertain due to modulation of those cosmic rays by the heliospheric magnetic field. Recently [20] proposed that low energy cosmic rays could be an important source for heating the WIM based on new values for the inferred rate of ionization in diffuse molecular gas in the
solar neighborhood. The mechanisms for this heating are collisional ionization of neutral gas and direct heating of electrons via Coulomb collisions. Recent observations by Voyager I in the outer heliosheath have finally constrained the lower end of the cosmic ray energy spectrum, however, and calculations by [21] indicate that the cosmic ray ionization rate is a factor of $\sim 10$ below the “local” rate cited by [20]. Since [20] was already taking the high end of estimates for the cosmic ray ionization rate, it would appear that cosmic rays are not a significant contributor to ionization or heating of the CLIC.

The final suggested heating source above was shocks. For the CLIC, it is likely that in the past the clouds were shocked by the same shock that heated the surrounding gas to its current high temperature ($T \sim 10^6 \text{ K}$). However, there is no clear signature for a strong shock passing through the CLIC at present, though weaker shocks may be present [6]. Since the post-shock cooling time for such shocks is short, they do not present a viable mechanism for maintaining the clouds at their current temperature, though their ionization could be significantly affected by past and current (weak) shocks.

4. The Interstellar Radiation Field
Given the discussion above, it seems clear that the most viable source of heating for the CLIC is photoionization by the interstellar radiation field. However, to determine if that works in detail requires a closer look at the radiation field. In [22] we presented photoionization models of the LIC. The radiation field that was constructed included radiation from known nearby hot stars observed by EUVE and the FUV background that is due to many A and B stars within a few kpc of the Solar System. In addition we included modeled soft X-ray background emission from the hot gas in the Local Bubble and from the edge of the cloud that was assumed to be evaporating via thermal conduction. In Figure 1 we show an example radiation field. Using radiation fields like the one in the figure we calculated the ionization created assuming thermal and ionization equilibrium, making use of the code Cloudy. As detailed in [22] we found satisfactory fits to the data on the ionization and temperature of the LIC. Since the publication of [22] there were questions raised about the soft X-ray background and the nature of the Local Bubble [see e.g. 23]. Understanding the origins of the Local Bubble and the CLIC may be essential to understanding the current observed state of the bubble and clouds.

Figure 1. The components of the model interstellar radiation field used for calculating the ionization in the LIC. The stellar parts are based on observations, though some modeling is needed as well. The soft X-ray background part, though modeled, is constrained by the broad band observations. There is no direct evidence for the cloud interface component, though, if present it contributes to the lowest energy bands of the soft X-ray background that have been observed.
4.1. Properties of the Local Bubble

The model of low density hot gas within the local cavity as the source of the observed soft-X-ray diffuse background, i.e. the Local Bubble model, was first put forward in 1983 [3], though it has been refined over the years [e.g. 4]. The model assumes that hot gas of uniform temperature and density fills the neutral gas cavity and thus the emission brightness gives the path length in any given direction. The size of the cavity thus derived matches fairly well with that derived from absorption line measurements, though the required thermal pressure, $P/k_B \sim 1.5 \times 10^4$ cm$^{-3}$ K, is substantially higher than that derived for the warm clouds of the CLIC [24]. More recently though the model has faced other, potentially more serious, challenges.

It was recognized soon after the discovery of X-rays from a Comet Hyakutake [25] that charge exchange of highly ionized solar wind ions with the neutrals flowing out from the comet is the best explanation for the emission. In this process the highly ionized atom, e.g. O$^+7$, gains an electron in an excited state and the cascade that follows results in emission of soft X-ray photons. Cox [26] first recognized that interstellar neutrals flowing into the heliosphere, specifically neutral H and He, should also undergo similar solar wind charge exchange (SWCX) reactions and emit soft X-rays, possibly contributing significantly to the observed soft X-ray background and thus altering our view of the nature of the Local Bubble. Lallement [27] showed that indeed the amount of soft X-ray emission attributable to hot gas could be significantly reduced if one took into account SWCX emission. More modeling of the emission followed that work [e.g. 28], though substantial uncertainties remained because of uncertainties in the atomic data regarding the charge exchange process and the solar wind parameters.

Recently the Diffuse X-rays in the Local Galaxy (DXL) mission carried out new observations with the observing geometry designed with the specific goal of separating the SWCX emission from the hot gas emission [29]. Results from DXL were that in the Galactic plane, roughly 60% of the emission comes from the hot gas. At high Galactic latitudes, where the emission is brightest, that fraction is higher. Based on the DXL results, [30] used SWCX models along with the data from ROSAT to create “cleaned” all-sky maps with only emission from the hot gas included. They found a fairly uniform temperature distribution with $T = (1.12 \pm 0.17) \times 10^6$ K (where the statistical and systematic errors have been combined). Assuming a uniform electron density of $4.68 \times 10^{-3}$ cm$^{-3}$ leads to a cavity size and shape that is a fairly good match to that derived by extinction measurements with typical radius in the Galactic Plane of $\sim 100$ pc and more like 200 pc out of the plane. This combination of temperature and electron density implies a thermal pressure in the bubble of $P/k_B \sim 10^4$ cm$^{-3}$ K. Note that the thermal pressure in the LIC is estimated to be closer to 3000 cm$^{-3}$ K. It has been suggested that the magnetic pressure in the cloud can balance the excess pressure in the hot gas [31, 32].

5. Simulating the LISM

The picture of the CLIC located within the old, hot Local Bubble appears to be consistent with the data, generally speaking, but we may still ask if it is physically realistic. The most curious aspect of this scenario is the existence of these low density clouds within the bubble. If we presume that the bubble was created by fast shocks that heated the gas to temperatures above $10^6$ K, then the question presents itself, why weren’t the clouds swept up or heated as was the rest of the medium? Warm gas with a density of $\sim 0.3$ cm$^{-3}$, such as is inferred for the clouds in the CLIC, is typical of the lowest density ISM in the Galactic plane other than hot gas. Therefore we conclude that the gas that currently makes up the CLIC was substantially denser at the time the shock (or shocks) that created the Local Bubble swept past. In particular the gas needed to be denser than its surroundings then, as it is now. Thus we posit that the CLIC originated as a cloud or clouds of relatively high density gas, probably CNM type gas, embedded in a lower density medium. With this as an initial state, it is to be expected that the clouds would be left behind as fast shocks swept past, creating the hot gas that is seen now
via its soft X-ray emission. Such an origin for the CLIC could have significant impacts on its current thermal and dynamical state.

While this scenario appears to be plausible, it is unclear whether it can work in detail and if it does, what constraints it imposes on the nature and history of the LISM. We report here on our current progress in simulating the LISM using numerical magnetohydrodynamical calculations. Among our goals in this work are to match:

- temperatures in the clouds—which requires conversion of initially cold gas into warm gas,
- densities of the warm cloud gas, \( n \sim 0.1 - 0.3 \, \text{cm}^{-3} \),
- velocity field of the clouds that allows them to be seen as separate velocity components as in the work Redfield & Linsky,
- not so much small scale turbulence as to violate observed constraints of \( v_{\text{turb}} \sim 1 - 3 \, \text{km} / \text{s}^{-1} \).

For the Local Bubble the observational constraints are:

- a fairly uniform apparent distribution in temperature with \( T \sim 10^6 \, \text{K} \),
- the absolute level on average of soft X-ray intensity, while allowing for variability,
- the size of cavity with radius of \( \sim 100 \, \text{pc} \).

The combination of all of these constraints on the bubble and clouds is difficult to match and no model put forward to date has attempted to match them all. Smith & Cox [33] created 1D numerical hydrodynamical models (though with an approximate magnetic pressure term) with multiple SNRs with the primary goals being replicating the magnitude, spectrum (as seen with broad band proportional counters) and variation of the soft X-ray background. Schulreich et al. [34] used fully 3D simulations employing a hydrodynamical code with adaptive mesh refinement to simulate the bubble including examining how the observed \(^{60}\text{Fe} \) enhancements found on Earth could be attributed to the same supernovae that created the Local Bubble. Breitschwerdt & de Avillez [35] used a similar code in a large scale simulation that included the gravitational field and ongoing supernova activity to establish a global dynamical equilibrium. Their focus was to match both the Local Bubble attributes and those of the nearby Loop I bubble. Our simulations are the first to attempt to match both the Local Bubble and CLIC characteristics at the same time.

5.1. Methods

While a full description of our results and methods is beyond the scope of this paper, we give here a basic overview. We have used the multidimensional numerical magnetohydrodynamical (MHD) code FLASH [36] with adaptive mesh refinement. We have enhanced the code by including optically thin radiative cooling and heating due to photoionization, both via lookup tables that contain the cooling and heating coefficients vs. temperature. Cooling in the diffuse ISM is due primarily to the collisional excitation of lines, radiative recombination and bremsstrahlung and is thus proportional to \( n_e n_{\text{H}} \), where \( n_e \) is the electron density and \( n_{\text{H}} \) is the H density. Heating by photoionization, on the other hand, is proportional to the photon flux (assumed uniform) and the \( n_{\text{H}} \). This leads to the well-known result that, for a range of thermal pressures, there are two stable thermal phases (see equilibrium curve in Figure 4). In our calculations the initial setup has clouds in the stable cold phase with \( T = 100 \, \text{K} \) and \( n = 25 \, \text{cm}^{-3} \) and the surrounding medium is in the warm stable phase, \( T = 7500 \, \text{K}, \, n = 0.358 \, \text{cm}^{-3} \). The magnetic field is assumed to be uniform with value \( B_z = 5 \, \mu \text{G} \). We use adaptive mesh refinement with 4 levels of refinement and the unsplit staggered mesh method for the MHD. Our calculations have been done in 2D with cylindrical symmetry \((r - z)\) because of the need for high spatial resolution. A collection of clouds was placed near the origin \((10 - 20 \, \text{pc})\) and supernova explosion(s) were
Figure 2. Density, temperature and magnetic field for run with two explosions, $1.1 \times 10^6$ yr after the second explosion. It can be seen that the initially compact cloud complex has split into two groups and that most of the cloud material is relatively warm. The temperature appears relatively uniform, consistent with the observations of the soft X-ray diffuse background. The magnetic field appears to be, on average, stronger in the clouds though it is also strong in certain regions of the hot gas. The multiple shocks including reverse shocks and reflections have created a complex magnetic field morphology.

set off with an explosion energy of $10^{51}$ erg at the origin. We have included thermal conduction with saturation but have not included its anisotropy due to the magnetic field – though we have tested uniform reduction of the conductivity.

5.2. Results

It seems clear from our calculations that reaching a state similar to that of the hot gas in the Local Bubble is attainable, though we have found that allowing for thermal conduction is necessary. We find that reducing the conductivity relative to the Spitzer value is helpful in achieving the desired size of the bubble and the thermal pressure, temperature and rough uniformity of temperature in the bubble. We are able to achieve the correct size and temperature of the bubble with just two explosions and have not tested the effects of more. It appears that the temperature and size of the bubble depends on a combination of the number of explosions, the conductivity, and the radiative cooling rate (set by a combination of the cooling curve and pressure in the ambient medium). In Figure 2 we show the density, temperature and pressure at a time of $1.1 \times 10^6$ yr after the most recent explosion for a run with two explosions, the second one occurring $5 \times 10^5$ yr after the first one.

A general result for the clouds is that they are heated by the shocks and contain mostly warm gas at late times, i.e. several $10^5$ yr to more than $10^6$ yr after the most recent SN explosion. The velocity field seen in the clouds is somewhat complex, though motion of complexes of clouds that remain at late times are not highly turbulent. We are still evaluating to what extent the velocity fields in the clouds in the simulations are consistent with observations of the CLIC, though it is clear that, despite substantial motions of the clouds relative to the grid, their relative motions
Figure 3. Velocity field for a cloud complex for the same run and time as in Figure 2. Velocities relative to the ambient medium (left) show that the cloud group has a substantial velocity, though when the mean velocity is subtracted (right) it is clear that the relative velocities of different parts of the clouds and the different clouds is fairly small.

Figure 4. Phase diagram for the same run and at the same time as Figure 2. This is a 2D histogram (volume weighted) of density and pressure of only the gas inside the cavity. The red curve is the locus of points at which there exists an equilibrium between heating and cooling. The dashed magenta line shows the ambient thermal pressure before the SN explosions occur. The hot gas has the desired temperature and pressure, but the the cloud gas ($T \sim 10^4$ K) is denser than typical for the CLIC.

are relatively slow. This can be seen in Figure 3 where the absolute motion and relative cloud motions are shown. It can be seen that there is at least one high density knot in the cloud at right while most of the cloud is at a relatively low density. While the figure with the mean motion removed shows that there are gradients within clouds and velocity differences between clouds, the velocity field appears to be coherent on scales of $\sim 0.5$ pc.

In Figure 4 we show a 2D histogram of the density and thermal pressure for the same time and run as in Figure 2. Here we have only included points inside the hot bubble. Also plotted is the equilibrium curve on which heating and cooling balance. The blue and orange points indicate the two phases, cloud and intercloud respectively, in the initial ambient medium. The dashed magenta line is the thermal pressure in the ambient medium. It can be seen that the hot gas does concentrate around $10^6$ K and a pressure of $\sim 10^4$ cm$^{-3}$ K, as inferred for the Local Bubble. The cloud gas, which concentrates near $10^4$ K has roughly the temperature of the CLIC,
though its thermal pressure is apparently too high. It remains to be seen if other parameter choices will lead to a better match with the thermal pressure for the clouds. Nevertheless, it is clear that the shock heating has lead to the creation of warm clouds that persist inside the hot bubble.

6. Summary
Having reviewed the possibilities it seems clear that the only heat source capable of maintaining the nearby clouds of the CLIC at their warm temperatures is photoionization by the interstellar radiation field. However, shocks must have played a role in the past in heating the clouds up to their current temperature. We have shown via our numerical simulations that the shocks that created the hot gas of the Local Bubble are capable of heating the initially cold gas clouds up to the warm temperatures they have now. The ongoing heating via the interstellar radiation field helps to maintain the clouds at a warm temperature.

The low current level of turbulence in the CLIC, which is substantially subsonic, does not contain enough energy to allow for turbulent dissipation to be a significant source of heating at this time. At the same time, we see substantial flows within clouds, which are filamentary, and suggests that the distinct velocity components of the CLIC may not correspond to physically distinct clouds.

The long thermal equilibration time of the cloud gas, illustrated by the large spread in density and temperature in the phase diagram (Figure 4), and the ongoing motions in the hot gas make it clear that non-equilibrium effects are important. Therefore understanding the history of the LISM is necessary for assessing the roles of the various physical processes at work, such as radiative cooling, photoionization heating and thermal conduction.

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