Simulating the Local Interstellar Medium

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Abstract. The Local Interstellar Medium (LISM) in many ways exemplifies the diffuse ISM of the Galaxy and star forming galaxies in general. Though devoid of molecular gas, it includes warm gas, hot, supernova-heated gas and even cold neutral gas clouds. The complex of local interstellar clouds (CLIC), which includes the cloud that directly surrounds the heliosphere, is made up of warm, low density, partially ionized gas. These clouds have somehow come to be embedded within the hot Local Bubble, apparently having survived the passage of the shock that heated the gas. We describe our attempts to understand this surprising situation and to explain the thermal and ionization state of the CLIC as well as the state of the Local Bubble via hydrodynamical and photoionization modeling. We also discuss the broader implications of our results for the interaction of the different temperature-density phases in the diffuse ISM of galaxies.

1. Introduction
The Local Interstellar Medium (LISM) has been defined by convention as that region within roughly 50 - 100 pc of the Sun that comprises the so-called Local Bubble (a.k.a. the Local Cavity) and all that is contained within it. This bubble has been detected in a number of ways including Na i and Ca ii absorption lines and dust extinction mapping. Shown in Figure 1 is a projection onto the Galactic plane of the 3D map of the bubble made by [1] using Na i absorption lines. The irregularly shaped bubble is essentially empty of neutral Na out to 50 - 150 pc in the plane. At high Galactic latitudes where the sampling is sparser, the size of the bubble is less well defined but clearly extends farther than in the plane, to distances well beyond 100 pc.

Important progress was made in understanding the LISM when it was realized that the diffuse soft x-ray background, first observed by sounding rockets [2], is coming from hot gas mainly contained within the Local Bubble. In Figure 2 we show the ROSAT All Sky Survey map of the emission in 1/4 keV band. While there has been some controversy regarding the nature of the emission [see 3, 4, 5], it now seems clear that most of the 1/4 keV emission does originate from hot, $T \sim 10^6$ K, low density, $n \sim 0.005$ cm$^{-3}$ gas within the neutral gas cavity that surrounds us.

Though the Local Bubble is nearly devoid of the cold neutral gas that contains neutral Na, it is known that there is warm and partially ionized gas close to the Sun. The Complex of Local Interstellar Clouds (CLIC) is a collection of about 15 of low density, $n \sim 0.3$ cm$^{-3}$, warm, $T \approx 7000$ K clouds located within 15 pc of the Sun. These clouds have been identified by absorption lines with distinct velocity components along several lines of sight, each of which is consistent with a single velocity vector [6, 7]. The ratios of several ion column densities, e.g. Mg i/Mg ii and C ii*/C ii provide evidence of their partial ionization and warm temperatures. In
Figure 1. The Local Bubble as inferred from Na I absorption line measurements projected onto the Galactic plane [1, used by permission].

Figure 2. ROSAT 1/4 keV map of the diffuse soft x-ray background. The emission, especially at low Galactic latitude, is believed to come primarily from hot gas contained within the Local Bubble. The units of the map are $10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$.

Figure 3 we show a schematic view of the clouds as reconstructed from the data and projected onto the Galactic plane [from 4]. In Figure 4 we show some recent absorption line data from HST observations toward Sirius B, only 2.64 pc away. As can be seen there are two velocity components in this direction, one of which corresponds with the cloud that surrounds the heliosphere, known as the Local Interstellar Cloud (LIC). A recently proposed alternative possibility to the multiple cloud picture is that all of the CLIC cloud material is part of a single
monolithic cloud that has a variety of flows within it [8]. There is, in addition, a cold \((T \approx 20\) K) and dense cloud known as the Local Leo Cold Cloud located roughly 20 pc from the Sun, which has a variety of interesting properties [9, 10, 11], though space does not permit discussion of that cloud here.

![Figure 3. Schematic view of the CLIC, projected onto the Galactic plane, based on absorption line data toward nearby stars [from 4]. The location of Sirius \((d = 2.64\) pc, \(\ell = 227.2, b = -8.9\)) on the plot is \((x, y) = (-1.77, -1.91)\), inside the Blue Cloud.](image)

The various clouds of the CLIC (or velocity components of the LIC) share a similar overall velocity that is away from the Galactic center and the Scorpius-Centaurus OB association. Within the complex there is significant dispersion in velocity around the mean velocity, but for the single cloud that surrounds the heliosphere, the velocities for the more than 80 lines of sight are remarkably consistent with a single velocity vector which is in turn consistent with the velocity of neutral interstellar helium that has been detected flowing through the heliosphere [12]. In addition, determinations of the turbulent broadening of absorption lines, based on the assumption that line widths are determined by the combination of a constant turbulent broadening and a thermal broadening (which of course depends on the mass of the ion), find typical values of only \(\sim 1 - 3\) km s\(^{-1}\). These facts argue that at least a portion of the LIC is quite quiescent at present.

2. Mysteries of LISM
As detailed above, we now have a fairly clear picture of the nature of the LISM from observations. What is much less clear is how the LISM came to be in its current configuration. Among the open questions on the LISM are:

- How did the CLIC come to be inside the Local Bubble?
- How was the Local Bubble created? A supernova? Multiple supernovae?
- What is the ionization source for the CLIC? What is heating the clouds?
Figure 4. Absorption lines observed in the HST spectrum of Sirius B. The profiles are fitted here with a smooth continuum (blue) and two velocity components (green) corresponding to the LIC velocity and the so-called Blue Cloud velocity.

- What can the LISM tell us about the energetics and dynamics of the diffuse ISM in the Galaxy and galaxies more generally?

The first question is important because the low density of the nearby clouds is closer to that associated with the intercloud medium. If, as we suspect, the Local Bubble was created by one or more supernovae, we would have expected any low density material to be swept by the shock into the expanding shell.

As mentioned above, the nearby clouds are partially ionized. Photoionization by the radiation field from nearby hot stars has been investigated [13] and found to be insufficient for either the ionization (particularly for He) or the heating of the gas. It was suggested [14] that the ionization could be due to non-equilibrium recombination caused, for example, by the passage of a shock. The problem with this idea is that overionized gas tends to cool too quickly. That is, if you ionize the gas via a shock that is slow enough that cooling sets in behind it, then the gas cools much more quickly than it recombines dropping in temperature well below 7000 K while it is still highly ionized, $X(H^+) > 0.5$. As an example, the gas behind a 100 km s$^{-1}$ shock into a density of $0.25$ cm$^{-3}$ will cool in only $\sim 200$ yr, while it will take close to $8 \times 10^4$ yr for it to recombine. To get something like the currently derived conditions for the LIC, $X(H^+) \sim 0.25$ and $T \sim 7000$ K would require a substantial heating source. If that source is the radiation field, then there is ionization associated with the heating and we still need to identify that additional source of ionizing photons. The only other identified source of ionization is turbulent heating, but the low level turbulence in the CLIC makes it questionable if such a source is viable.
In our modeling of the ionization of the LIC [15] we included radiation from the boundary of the cloud under the assumption that it was evaporating via thermal conduction. With this source in addition to the radiation field from nearby hot stars and diffuse emission from the hot gas in the Local Bubble, we were able to match the observed ionization level. However, it is not certain that the cloud is evaporating since the expected column densities of highly ionized species in the evaporative boundaries, e.g. C iv and O vi have not been observed. The possibly more complex dynamics and energetics that is hinted at by the spread in velocities of the CLIC may be playing a role. The situation as it stands clearly demands more sophisticated modeling.

![Figure 5. Heating and cooling rates vs. temperature for conditions similar to those in the LISM. Note the three intersections, which allow for thermal equilibrium. Only the low temperature and high temperature equilibria are stable.](image)

3. Physical Processes in the ISM
To increase our understanding of the ISM in general and the LISM in particular requires inclusion of all the most important physical processes. Among those that are central to the energetics of the diffuse ISM are radiative cooling and heating via photoionization. In the diffuse ISM, particularly in the warm medium, cooling results mainly from collisional excitation of forbidden lines, though radiative recombination and free-free emission also contribute. Those processes are all two-body mechanisms and thus the cooling rate goes as density squared. Heating, in contrast, is mostly caused by photoionization of H and He, though in some circumstances photoelectric ejection from dust grains is also important. In Figure 5 we show the heating and cooling curves for LISM conditions. Note that the curves intersect in three places leading to three possible thermal equilibrium solutions. The middle intersection, however, results in an unstable equilibrium in which any displacement leads to movement away from the equilibrium temperature and toward either the warm equilibrium near 7000 K or the cold one near 70 K. The thermal pressure assumed in making this plot sets the overall scaling of the two curves. A high pressure will raise the cooling curve relative to the heating curve and result in only the single equilibrium at low temperature. A low pressure on the other hand will result in only the warm temperature equilibrium. These ideas are illustrated in Figure 6 in which we show the thermal equilibrium curve, which is the locus of points for which heating equals cooling given a range
of pressure values. For combinations of pressure and density above the curve cooling exceeds heating and the gas will move down towards the curve with its path determined by the dynamics, i.e. whether the cooling is so fast as to be isochoric (constant density), isobaric, adiabatic or some combination. Similarly gas with pressure and density putting it below the curve will have a heating rate that exceeds the cooling and will heat up, moving upward toward the equilibrium curve. The speed with which the equilibrium curve is approached can vary by large factors however, with dense gas that’s far from equilibrium having much shorter equilibration times than lower density gas that is relatively close to equilibrium.

We have proposed that the CLIC was at one time colder and denser that it is currently so that it could be left behind when the shock that heated lower density gas to X-ray emitting temperatures passed by. In this picture then the clouds are shocked and overpressured and subsequently expand. If the expansion overshoots, the clouds will then fall below the equilibrium curve and could then get heated to the warm temperatures we see in the CLIC currently.

**Figure 6.** Phase diagram for interstellar gas in the local ISM. The blue curve is the locus of points for which heating and cooling balance. As indicated, for the region below the curve heating exceeds cooling, while above the curve cooling exceeds heating. The orange circles correspond to equilibrium points at the labeled “LIC Pressure” (here approximated as 3000 cm$^{-3}$ K) for a cold, dense phase and for a warm, low density phase. Example paths that could be followed for gas that is cooling adiabatically, shocked by a slow shock or evaporated via thermal conduction are shown.

Thermal conduction can also be very important in multi-phase environments in the ISM, especially those that include hot gas in which the conductivity is expected to be very high. There are ongoing questions about the efficacy of thermal conduction in diffuse plasmas, but we do not have space to discuss those here. At this point we are exploring the consequences of thermal conduction that is only limited by so-called saturation of the heat flux. Under such conditions a cold or warm cloud, $T < 10^4$ K, that is embedded in a hot medium, $T > 10^5$ K, is expected to evaporate as the heat flux into the cloud drives a mass outflow. Solutions have been found to the cloud evaporation problem under various conditions [e.g. 16, 17, 18, 19] though
these are typically quite idealized. In particular the cloud is generally assumed to be spherical or planar and at rest in the surrounding medium. Nevertheless they do illustrate that thermal conduction can lead to the destruction of clouds and play an important role in the evolution of the ISM.

![Figure 7. Temperature profile for numerical calculation of an evaporating cloud. The results of the calculation (green) are overplotted with a Dalton & Balbus [19] type analytical profile (red dashed curve). A “classical” Cowie & McKee profile which has the same asymptotic temperature is also plotted (blue dot-dashed line) for comparison.

Figure 8. Mass loss rate for numerical calculation of cloud evaporation. The rate is calculated from that predicted for the temperature profile given the Dalton & Balbus [19] solution (blue line) and compared with the rate found from the decrease of cloud mass over time (green line). After an initial adjustment period, the rates match very closely.

As we discuss below, we have undertaken a series of investigations of the LISM employing the FLASH code. As part of these we have made use of the built-in capacity to include electron thermal conduction with saturation of heat flux in the code. We have tested FLASH’s thermal conduction unit by doing cloud evaporation calculations. For these we put a warm spherical cloud in a hot surrounding medium in 2D cylindrical symmetry. In Figure 7 we show the temperature profile for the evaporating cloud along with a fit to the profile using the analytical solution from Dalton & Balbus [19]. They found an analytical solution for the temperature profile under the assumption that radiative cooling is not important but including the effects of heat flux saturation. As can be seen from the figure the match is extremely good. For comparison we also show the profile one would derive under the assumption of no heat flux saturation as in the “classical” solution of Cowie & McKee [16]. In Figure 8 we compare the cloud mass loss rates derived from fitting the temperature profiles with Dalton & Balbus type curves and the rate from calculating the change in cloud mass. Again, the match, after an initial non-steady evaporation period, is excellent. These results give us confidence that the implementation of thermal conduction with heat flux saturation in FLASH is accurate.

4. Numerical modeling of the LISM
We are currently involved in taking the next steps to modeling the LISM employing the magnetohydrodynamical code FLASH (version 4.3). Our simulations to date start with a single or multiple cold ($T = 100$ K), dense ($n = 25$ cm$^{-3}$) clouds embedded in a warm ($T = 10^4$ K), lower density (0.25 cm$^{-3}$) intercloud medium. We set off a supernova explosion close, 10 to 20 pc away from, the cloud(s). The physical processes included are thermal conduction including...
heat flux saturation, and cooling and heating using look-up tables for the coefficients. We have not included the magnetic field as yet, but that is the next step planned. We have used AMR with a resolution at highest refinement of 0.02 pc and done the calculations in 2D assuming cylindrical symmetry.

Figure 9. Comparison of runs with a single cloud overrun by a SNR shock. Moving clockwise from upper left the runs include: (upper left) neither cooling nor conduction, (upper right) conduction but no cooling, (lower right) both cooling and conduction and (lower left) cooling but no conduction.

4.1. Single Cloud Runs
In figure 9 we show a comparison of results for a series of single cloud runs designed to test the effects of cooling and thermal conduction. Heating was not included, in these runs. The figure shows the density for the cloud at a time $1.75 \times 10^5$ yr after the SN explosion. The cloud, originally centered at $(r, z) = (10.61, 10.61)$ (so it is 15 pc from the origin), first encounters the shock at $t \approx 6500$ yr after the explosion. The figure clearly shows the effects of cooling and conduction, not only on the cloud, but also on the remnant in which it is embedded. Without cooling or conduction, the cloud is shredded by Kelvin-Helmholtz and Richtmeyer-Meshkov instabilities. The density in the medium surrounding the cloud is very low. When thermal conduction is operating, the instabilities are substantially suppressed, partly because of the evaporative outflow that is generated and partly because the shear layer has been smoothed out. In addition, we see that the density in the surrounding medium is higher because conduction has flattened the temperature gradient in the bulk of the SNR leading to a more uniform density distribution as well [see, e.g. 20]. In the runs that include radiative cooling the cloud is much smaller and denser because the cloud that propagates through the cloud is slow enough to be radiative. The smaller cross section for the cloud then leads to less shredding via hydrodynamical
instabilities. Based on these runs, it appears that cooling is the more important of the physical processes determining the dynamical evolution of the cloud.

Figure 10. Simulation results for multiple cloud run. Clockwise from upper left is density, temperature, pressure and total velocity. Note the filamentary form of the cloud. The velocity field is complex and the temperature, density and pressure vary considerably through the cloud material. The current day CLIC appears more quiescent than this simulated cloud complex.

4.2. Multiple Cloud Runs
To test the effects of multiple clouds we have carried out simulations that start with 15 clouds in close proximity to each other. For this case we have included heating as well as cooling so that we can assess if there is a rebound in the temperature after the shocks pass through the clouds. In Figure 10 we show the results for a run at a time $2 \times 10^5$ yr after the explosion. The cloud complex was located initially around $(r, z) = (15, 15)$ pc so it is clear that it has moved out from the center a small distance. The high degree of variation in temperature, density and pressure as well as the complex and very non-uniform velocity field contrast with the current
day CLIC wherein it appears that there are several different vectors but there is coherence in
the velocity of large patches of the sky. It will be important to examine whether and under
which conditions the cloud complex can dissipate the energy imparted by the shock. We expect
that the magnetic field will play an important role in that evolution.

5. Conclusions
The LISM is a very interesting region of the ISM that provides opportunities that cannot
be found elsewhere for understanding the physical processes that operate in the ISM. Using
numerical simulations that include all the most important physical processes at work, we have
begun to explore plausible scenarios for the origins and evolution of the LISM in general and
the CLIC in particular.

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