MHD Simulations of the Evolution of the Local Interstellar Medium

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Abstract. The Sun is located inside a low density cloud known as the Local Interstellar Cloud (LIC), which is part of a group of nearby clouds known as the Complex of Local Interstellar Clouds (CLIC). All of these clouds are contained within the hot Local Bubble, which contains gas at \( \sim 10^6 \) K and appears to have been created by multiple supernova explosions. We present new results from our ongoing project on simulating the origins and evolution of the Local Interstellar Medium. We aim to model the origins of the CLIC, especially the way that the clouds managed to survive shock passage and reach their current warm (\( T \sim 7000 \) K) and low density (\( n \sim 0.2 \text{ cm}^{-3} \)) state. We find that the magnetic field is important for maintaining the Local Bubble at a high thermal pressure and helps the clouds rebound more effectively after being shocked. Thermal conduction is necessary to make the temperature in the bubble as uniform as observed. We also find that to reach its current state, the Local Bubble requires multiple supernova explosions. The state of the CLIC and the Local Bubble provide important clues as to how supernova feedback operates in the ISM and it interaction with the different phases of the ISM.

1. Introduction
The interstellar medium (ISM) of our Galaxy contains gas at a wide range of temperatures and densities ranging from cold, molecular clouds (\( T \sim 10 \) K) to supernova heated very hot gas (\( T \gtrsim 10^6 \) K). Our local ISM (LISM) is dominated by the hot gas of the Local Bubble, a very low density region that extends 50 to 200 pc in all directions, however it also includes a collection of warm (\( T \sim 7000 \) K), low density clouds, known as the Complex of Local Interstellar Clouds (CLIC) in the region within 15 pc of the Sun. Understanding the nature and evolution of the LISM is important because it is so well observed and exemplifies many important processes that operate in galaxies. We present here an update on our progress in creating numerical hydrodynamical models of the evolution of the LISM [see 1, for our discussion of an earlier stage of this project].

1.1. Orientation to the Local Interstellar Medium
The extent of the Local Bubble has been determined by both absorption lines measurements, most notably of Na\textsc{i} and Ca\textsc{ii}, and dust extinction. Figure 1 from Welsh et al. [2] shows a cut in the plane of the shape of the cavity as derived from the lack of Na\textsc{i} absorption. The bubble is much larger out of the plane as would be expected for a supernova created bubble expanding out of the Galactic disk. Bolstering the view that the Local Bubble is filled with hot gas is the observation of diffuse soft X-ray emission (energies \( \sim 0.25 \) keV and higher) seen in all directions.
of the sky. Since X-rays at these energies are readily absorbed by neutral H, the observation of a substantial flux in the Galactic plane is evidence for their local origin.

![Image of the Local Bubble as inferred from NaI absorption line measurements projected onto the Galactic plane [2, used by permission].](image)

**Figure 1.** The Local Bubble as inferred from NaI absorption line measurements projected onto the Galactic plane [2, used by permission].

The CLIC, like the Local Bubble, was also discovered via absorption line measurements but in this case it was not the lack of absorption as it was for the bubble, but its presence. Using lines of MgII, OI, CII and many other ions that can be detected in low column densities of neutral or partially ionized gas, the clouds have been detected toward stars that are within 15 pc of the Sun. By observing on many lines of sight and by grouping the absorption components according to their consistency with particular space vectors (and other characteristics), Redfield & Linsky [3] were able to identify the 15 separate “clouds” that make up the CLIC, some of which are shown in Figure 2 which is a projection onto the Galactic plane. These clouds have similar, though not identical, qualities such as being warm, low density, partially ionized and having moderate levels of elemental depletions.

1.2. The Properties of the CLIC

The CLIC clouds, in addition to having similar physical characteristics, also have similar space velocities relative to the local standard of rest. Figure 3 shows a projection of the space vectors of the CLIC on the Galactic plane along with a comparison of the radial velocities of absorption components vs. those predicted based on the best-fitting velocity vector for the CLIC as a whole. It’s clear that while the clouds are moving as a group, there is a substantial dispersion in their velocities.

The spatial distribution of the clouds gives us some hints as to possible interactions between them. Figure 4 (left panel) shows the four clouds that are inferred to be closest to the Sun projected onto the sky. While determining their outlines is inexact given the limited number of lines of sight toward nearby stars, their shapes as determined without reference to each other are suggestive of cloud-cloud interactions. Also shown (right panel) are clouds within the CLIC that have relatively large velocities relative to each other. These results suggest possible cloud-cloud interactions within the CLIC. The fact that the group of clouds have these apparent interactions
Figure 2. Schematic of those clouds in the CLIC that are close to the Galactic plane with their projected sizes and inferred shapes [from 4]. The Sun is in the center. Note that the scale is far smaller than in Figure 1. It is not known exactly how close to the edge of the LIC the Sun lies, though it must be fairly close since absorption with the LIC velocity is not seen in some parts of the sky.

Figure 3. (Left) Velocity vectors for each of the clouds of the CLIC projected onto the Galactic plane [from 3]. It can be seen that the clouds are moving in generally the same direction, though with substantially deviations. (Right) Predicted vs. observed radial velocity for individual lines of sight for CLIC clouds. The predicted velocity is based on the best fitting velocity vector for the bulk motion of the CLIC. The points are color coded by the magnitude of their deviation from the bulk motion vector.

and relative velocities and yet each cloud seems to be coherent in velocity within itself presents a challenge for simulating the evolution of the CLIC within the Local Bubble.
1.3. The Local Interstellar Cloud

Included among the CLIC is the cloud that immediately surrounds the Solar System, known as the Local Interstellar Cloud (LIC). The LIC is the best observed interstellar cloud having been identified in absorption lines on over 80 lines of sight toward nearby stars [3, 5]. In Figure 5 we plot the observed radial velocities for lines of sight in which the LIC velocity vector has been identified vs. the angular distance from the downstream direction for the best fit LIC velocity vector. The remarkable level of consistency of the data with the simple solid body motion of the cloud relative to the Solar System indicates that there is little turbulence within the LIC. Turbulence on smaller scales is constrained by the broadening of the absorption lines and can be tested by comparing the widths of high mass ions with low mass ions, e.g. D I vs. Fe II. These determinations generally find turbulent velocities of only 1 − 3 km s$^{-1}$ for clouds in the CLIC.

In addition to absorption lines, neutral atoms from the LIC that flow into the Solar System have been directly detected in situ by spacecraft such as Ulysses [6] and IBEX [7]. The absorption line data and in situ data present a consistent picture of the physical parameters of the LIC.
The physical properties of the clouds are not in dispute.

1.4. The Local Bubble

As discussed above, the Local Bubble is inferred both by the lack of neutral, absorbing gas out to roughly 50 pc or more in all directions and by the detection of soft X-ray emission. Questions have been raised [13], however, about whether that emission is truly generated by hot gas as has been long believed. This uncertainty arises from the fact that soft X-ray emission is also generated within the Solar System through the interaction of the solar wind with neutral H and He flowing in from the ISM. This solar wind charge exchange (SWCX) emission, which results from cascades after charge exchange between the inflowing neutrals and solar wind ions, has been detected and modeled. Recently Galeazzi et al. [14] have carried observations that have shown that at least 60% of the observed soft X-ray diffuse background at energies near 1/4 keV comes from the hot gas of the Local Bubble. Liu et al. [15] have gone farther and produced all-sky maps of the background that have been cleaned of SWCX emission. From these they have derived maps of the temperature and emission measure of the hot gas and have produced estimates of the shape of the Local Bubble in 3D. These latter make very simple assumptions regarding emissivity in the hot gas, namely that it has a uniform temperature and emissivity. Nonetheless they put clear constraints on our models for the evolution of the Local Bubble, in particular that the temperature is \( T \sim 10^6 \) K with only small variations around that value.

1.5. Modeling Goals and Challenges

Given the evidence for the origin of the Local Bubble as resulting from supernovae expanding in the ISM, the existence of the CLIC is surprising. This is because the density inferred for the clouds, \( n \sim 0.1 - 0.3 \) cm\(^{-3}\) is typical of what is called the intercloud medium in the ISM with so-called diffuse clouds having densities more like 10 cm\(^{-3}\) or higher. For a supernova remnant (SNR) expanding into a smooth medium the ambient ISM is either shock heated to high temperatures, \( T \gtrsim 10^{5.5} \), becoming part of the hot, X-ray emitting interior, or if the shock has slowed enough that the remnant is radiative, the swept up gas becomes part of the dense, cold shell. For a cloud to be left behind as the CLIC appears to have been, it must be substantially denser than the surrounding gas. Given that the density of the current clouds is quite low, we therefore have proposed that the CLIC started as colder, denser clouds surrounded by low density intercloud gas and only after having been shocked and existing within the hot remnant for many years did the CLIC reach its current warm, low density state.

We also aim to understand the nature of the Local Bubble with our simulations. To sum up then the challenges for understanding the LISM that we hope to address include:

- How did the CLIC come to be inside the Local Bubble?
- How was the Local Bubble created? One supernova? Multiple SNe?
- How can we explain the low level of turbulence in the CLIC and the multiple cloud structure at the same time?
- What are the dominant physical processes governing the hot gas-cloud interaction? Thermal conduction, turbulent mixing, the magnetic field?
• Is the emissivity of the Local Bubble truly uniform? Is its temperature?

2. Hydro/MHD Modeling of the LISM
We have carried out our modeling of the LISM using the numerical magneto-hydrodynamical adaptive mesh refinement code FLASH [16, http://flash.uchicago.edu/site/flashcode/] (version 4.3). Up to this point the modeling has only been done in 2D assuming cylindrical symmetry (i.e. R − Z). For initial conditions we have a collection of cold (100 K), dense (25 cm$^{-3}$) clouds embedded in a warm (7500 K), lower density (0.358 cm$^{-3}$) intercloud medium. Supernova explosions are set off at the origin and the clouds are located close to the explosions, initially 10 − 20 pc away. The explosions are initiated by injecting an explosions worth of thermal energy, $E_0 = 10^{51}$ ergs, in a spherical region of radius 2.25 pc. We have done runs with only one explosion and runs with two explosions with the second explosion occurring $5 \times 10^5$ yr after the first. We have included the following physical processes in our runs:

• thermal conduction including heat flux saturation using unsplit implicit diffusion,
• radiative cooling and photoionization heating using tables of coefficients,
• the magnetic field using the unsplit staggered mesh scheme which uses the constrained transport method to ensure that $\nabla \cdot B = 0$.

The radiative cooling rate for simulations discussed here was taken from the solar metallicity table of Sutherland & Dopita [17]. The heating rate table was generated from data from Wolfire et al. [18] for solar metallicity and a shielding column of $10^{19}$ cm$^{-2}$. For all runs so far we have assumed a uniform B field with $B_z = 5 \mu$G and $B_r = 0$. As of the presentation at ASTRONUM 2017 we had not yet used MHD and thermal conduction together (though since then we have successfully carried out such runs). For the runs presented here, we used AMR with a base grid of 64x64 and up to five levels of adaptive mesh refinement resulting in a finest resolution of 0.098 pc. This is the highest spatial resolution used in a multi-dimensional simulation of the LISM to date. Previous work on the Local Bubble by de Avillez & Breitschwerdt [19], which was done in 3D, was focused on the hot gas evolution and not on the CLIC and used a resolution that was lower by a factor of 10. The high resolution needed to explore the evolution of the CLIC, along with that of the Local Bubble, makes 3D simulations very demanding. We have some guidance from our recent work on SNR evolution in a cloudy ISM [20]. In that work we carried out simulations in both 2D and 3D including thermal conduction, but not cooling. We found some evidence for an increased evaporation rate in the 3D runs, probably because of the higher surface area to volume ratio of the spherical 3D clouds as compared to the toroids of the 2D simulations, though the effects were not dramatic. We intend to carry out 3D calculations of LISM evolution in the future.

The primary goals of our modeling are, for the CLIC, to match: 1) the present day cloud temperatures, i.e. $T \sim 5000 − 10,000$ K so the initially cold gas is converted to warm gas, 2) the densities of the clouds, $n \sim 0.1 − 0.3$ cm$^{-3}$, 3) dynamics of the clouds, identifiable as coherent velocity structures while having some cloud-cloud differences in velocity, 4) low levels of turbulence as observed. For the Local Bubble we want: 1) temperature in the range of observations, $T \sim 10^6$ K, 2) relatively uniform intensity as observed from inside the bubble, 3) absolute level of soft X-ray intensity close to the observed level, 4) size of the low density cavity of dimensions roughly 40 − 100 pc. This set of goals is quite constraining for both our initial conditions and the physical processes that we include.

2.1. Thermal Evolution of the CLIC
A critical factor in the thermal evolution of the CLIC is the heating and cooling rates assumed in the medium. The cooling is caused by collisional excitation (followed by a radiative cascade) and radiative recombination while heating of the clouds is primarily by photoionization. In
Figure 6 we illustrate the phase curve for the clouds based on our assumed heating and cooling rates. At a low pressure, like that in the ambient medium before being hit by a shock, two different temperature-density phases can coexist as indicated by the points that are intersected by the horizontal line. At high pressures, cooling exceeds heating and gas tends to move down and toward the right toward the equilibrium curve. At low pressure, the heating exceeds cooling and gas moves up and toward the left. Thermal conduction can increase the temperature of the gas at roughly a constant pressure.

![Phase diagram](image)

**Figure 6.** Phase diagram of the ISM gas given our assumed heating and cooling rates. The solid curve is the locus of pressure-density values for which the heating and cooling rates match.

After the blast wave hits the collection of cold clouds, the fast shock in the intercloud medium passes around them while slower shocks propagate through the clouds. The clouds are heated to $\sim 1 - 6 \times 10^5$ K and pressurized. They cool quickly via both radiative cooling and expansion as they rebound. At the same time the pressure in the hot gas surrounding the clouds is decreasing as the bubble expands. The expansion of the clouds to lower densities leads to slower cooling.

The effects of including the magnetic field and those of including thermal conduction are quite different as can be seen from Figure 7. These plots compare the gas inside the shock (and not including the cold shell) for two runs, one with thermal conduction and no magnetic field and the other without thermal conduction but including the magnetic field. For both runs, there were two explosions, with the second one occurring $5 \times 10^5$ yr after the first one. The plots show the state at $t = 9.5 \times 10^6$ yr after the first explosion. With just conduction and no magnetic field, the hot gas tends to have a relatively uniform temperature. The pressure, however can vary substantially, most likely because of the regions around the edges of the clouds where an evaporative outflow is being driven and also substantial cooling is occurring. With no conduction and a magnetic field, the hot gas has a more uniform pressure but varies considerably in temperature. In this case the cloud gas has higher pressure than in the case with thermal conduction. These results are further illustrated in Figure 8 which shows the temperature distribution for the same runs as in Figure 7. For a run with no magnetic field and no thermal conduction, the results are in between those two cases, with the lower thermal pressure as for the HD case and a substantial spread in both temperature, as for the MHD case, and pressure as for the HD case with conduction.
Figure 7. Phase diagrams for runs with thermal conduction, but no magnetic field (Left) and with MHD but no thermal conduction (Right). These are 2D histograms that are volume weighted and include only the region inside of the dense shell. For both runs the time is $9.5 \times 10^5$ yr after the first explosion and a second explosion occurred at $t = 5 \times 10^5$ yr. It’s clear that thermal conduction leads to quite a uniform gas temperature for the hot gas, while the pressure varies considerably. For the MHD run, on the other hand, the pressure is quite uniform while the temperature of the hot gas varies over a large range. The pressure is larger for the case with no conduction because the confining pressure in the surrounding medium, including both thermal and magnetic pressure, is much higher.

Figure 8. Temperature distributions at $t = 9.5 \times 10^5$ yr for run with thermal conduction but no magnetic field (left) and with magnetic field but no thermal conduction (right). Note that the scales are not the same for the two runs. The MHD run has substantially higher temperatures and much more temperature variation.

2.2. Preliminary Comparison With Observations
While we are still exploring parameter space with regards to the initial conditions and investigating the effects of different physical inputs, it is worthwhile to examine where we stand in comparison with the observations. Figure 9 shows a the state of the main cloud in the hydrodynamical run that includes thermal conduction.

As was illustrated in the left plot in Figure 7, the density is mostly moderate $n \sim 0.1 - 3$
Figure 9. Properties of the main cloud complex in a hydrodynamical (i.e. $B = 0$) run that includes thermal conduction at $t = 10^6$ yr. Most of the cloud gas is at moderate density, $n \sim 0.1 - 3$ cm$^{-3}$, and is warm, $T \sim 3 \times 10^3 - 10^4$ K, though cold dense knots remain. The hot gas surrounding the complex shows the presence of intermediate temperature gas created by thermal evaporation. The pressure pane shows that the cloud has not reached dynamical equilibrium yet.

cm$^{-3}$, slightly higher on average than the observed CLIC, while the temperature is mostly warm, $T \sim 3 \times 10^3 - 10^4$ K, similar to the CLIC. The lower right pane shows that the pressure has not equilibrated yet in the region of the cloud complex. This is also illustrated by the complex flow pattern shown in the lower right pane. Most of the cloud complex is moving at low velocity, but it remains to be seen if the velocities of different regions of the cloud could have the sort of velocity coherence observed for different clouds within the CLIC.

In comparing the X-ray emissivity of the simulated bubble with the observed soft X-ray background, it is clear that the MHD run with no thermal conduction is too hot to match the observations. In particular the Wisconsin B band/C band rates constrain the temperature (assuming it is uniform) to be close to $10^6$ K. The run with thermal conduction appears much more promising. In Figure 10 we show the emissivity in the ROSAT R12 band. We see that even in this case where the temperature is fairly uniform, the emissivity varies by orders of magnitude. Of course when integrated across tens of parsecs we expect that such variations will be smoothed out. Nonetheless it is worth noting that the assumption of uniform emissivity that
Figure 10. Emissivity in ROSAT’s R12 band (in counts cm$^{-1}$ s$^{-1}$) for the run with thermal conduction and no magnetic field. It is clear that, despite the fact that the temperature is fairly uniform, the emissivity varies considerably.

is generally applied to interpretations of the soft X-ray data is unlikely to be even approximately true.

3. Summary
We have carried out a series of numerical simulations aimed at improving our understanding of the local ISM. While this is a work in progress we have found some interesting results:

- The cloud complex re-fragments after the second explosion – otherwise it is too concentrated,
- The cold cloud gas is mostly converted to warm gas as desired, but cold knots persist,
- MHD runs without thermal conduction have hot gas with a wide range of temperatures, while hydro runs without a magnetic field have a relatively uniform temperature but tend to cool quickly,
- Even after $10^6$ yr the bubble and clouds are not dynamically equilibrated.

We will be continuing to search for the balance that leads to the right amount of cooling with fairly uniform temperature to match the soft X-ray background results. At the same time we will be looking at how much time is needed after an explosion is needed for the clouds to become as quiescent as they appear to be. As we continue to explore more of parameter space, we intend to subject our results to more thorough testing regarding whether the hot gas distribution is consistent with the soft X-ray background and if the cloud complex has characteristics consistent with observations of the CLIC.

Even without those more stringent tests we can draw certain conclusions from our results: 1) Thermal conduction appears necessary to get the uniformity of temperature implied by the observations of the soft X-ray background, 2) The magnetic field is needed to confine the bubble and maintain the relatively high thermal pressure in the hot gas while allowing a lower thermal pressure in the clouds, 3) The tight cloud grouping combined with relative cloud-cloud motions and low turbulence in the CLIC is not easily achieved. The wealth of observations available
on the CLIC and the Local Bubble provide tight constraints that can serve as a gauge of our understanding of the physics at work and our numerical methods for simulating the LISM.

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