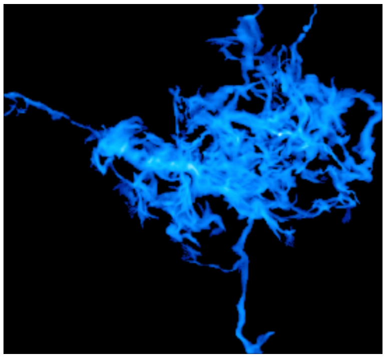

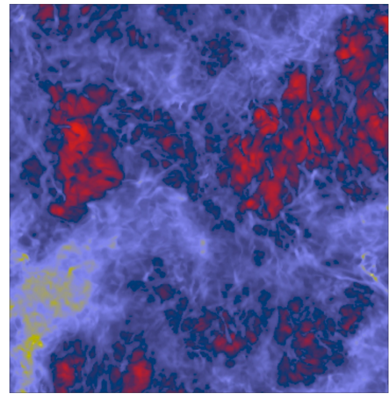

Lifetime of Interstellar Clouds

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April - July 2011.

M2 internship

This internship has been done in the Radioastronomy Laboratory (LRA) of the Ecole Normale Supérieure (ENS) , under the supervision of François Levrier [1] (Maître de Conférence de l'ENS Paris) and Patrick Hennebelle [2](astronome-adjoint de l'ENS Paris).

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Abstract

The established paradigm to describe the interstellar medium is that of multiphasic MDH turbulence. We aim to characterise the properties if these flows, searching in particular for differences with monophasic systems (isothermal), or without magnetic field. What are for example the observational diagnostics whose results would differ, and which could therefore be used to constraint those models?

In this internship, we will focus on lifetime of the dense structures of the atomic interstellar medium, as it constrains stellar formation theories (see [13], [12]).

Previous studies of the structure of the turbulent interstellar medium (see [1] for example) have shown that isothermal flows behave differently than 2-phase flows. Indeed, in the latter, a large fraction of the gas is maintained in a thermally unstable domain, forming cold structures isolated from the rest by stiff thermal fronts. These high density cold structures are thus expected to have a larger lifetime than clouds issued from isothermal simulations.

The goal of this work is thus to compare the lifetime of interstellar clouds according to two large-scale 3-dimensional hydrodynamical simulations of 2-phase and isothermal flows performed by Patrick Hennebelle. I achieve this by processing data issued from those simulations, identifying high density structures and estimating their lifetime.

Résumé

Le paradigme quasi-établi pour décrire le milieu interstellaire est celui de la turbulence MHD multi-phasique. On cherche à caractériser les propriétés de ces écoulements, en cherchant notamment les différences avec des systèmes monophasiques (isothermes) ou sans champ magnétique. Quels sont par exemple les diagnostics observationnels qui donneraient des résultats différents, et qu'on pourrait donc utiliser pour contraindre les modèles?

Pour le sujet de ce stage, on s'intéresse au temps de vie des structures denses du milieu interstellaire atomique car celui-ci contraint en partie les théories de la formation stellaire (voir [13], [12]).

Des études de la structure du milieu interstellaire turbulent (voir [1] par exemple) ont montré que les écoulements isothermes se comportaient différemment que les écoulements bi-phase. En effet, dans ce dernier cas, une fraction importante du gaz est maintenue dans des régions thermiquement instables, formant ainsi des structures froides isolées du reste du fluide par de raides fronts thermiques. On s'attend dès lors à ce que ces structures froides de haute densité aient un plus grand temps de vie que les nuages issus de simulations isothermes.

L'objectif de ce travail est de comparer les temps de vie de nuages interstellaires issus de deux simulations hydrodynamiques à grande échelle isothermes et bi-phases réalisées par Patrick Hennebelle. Ceci est réalisé en analysant les données issues de ces simulations, identifiant les régions de haute densité, et estimant leur temps de vie.

Contents

1 Introduction

Understanding the interstellar medium is of great importance in the context of molecular clouds and star formation. Many theoretical works and numerous numerical simulations have kept been performed over the last decades (see for example [2], [1] and [3]) to constantly improve our understanding of the interstellar medium. Although considering isothermal flows constitutes a reasonable assumption for the densest parts of the molecular clouds, it is not an appropriate assumption for the description of the interstellar atomic hydrogen, which is 2-phase in nature, and therefore for the formation of molecular clouds (see [6] but also theoretical studies on the dynamics of fronts [5], [9] for a more recent work, and multiphases simulations [1], [8], [10], [7]).

Recent simulations by Edouard Audit and Patrick Hennebelle (see [1]) have shown that in 2-phase flows (providing there is enough turbulence), a large fraction of the gas is maintained dynamically in cold dense structures, isolated from the rest by stiff thermal fronts. These structures are expected to have a larger lifetime that the average lifetime of clouds in the isothermal case.

We can mention in passing competitive theories for the lifetime of molecular clouds(for example [11] for collisional accretion, predicting lifetimes of the order of 10^8 years or [4] for giant molecular clouds formation in large-scale density waves, predicting lifetimes of the order of 10^7 years), though these scenarios are more relevant for the formation of structures at larger scales (i.e. Galactics) than for the domains of interest here (a few 100 pc).

1.1 About the simulation

I will work on *large scale* high resolution 3-dimensional hydrodynamical simulations of 2-phase and isothermal flows, performed by Patrick Hennebelle.

These simulations consider the MHD equations for an optically thin gas. The gas is able to cool radiatively and is heated by an external radiation field. The equations governing the evolution of the fluid are the classical equations of magnetohydrodynamics, where a cooling function is added in the energy conservation equation:

$$\partial_t \rho + \bigtriangledown.[\rho u] = 0 \tag{1}$$

$$\partial_t \rho u + \bigtriangledown.[\rho u \otimes u + P] - \frac{1}{\mu_o}(\bigtriangledown \otimes B) \otimes B = 0 \tag{2}$$

$$\partial_t E + \bigtriangledown.[u(E + P)] = -\mathcal{L}(\rho, T) \tag{3}$$

$$\partial_t B - \bigtriangledown \otimes [u \otimes B] = 0 \tag{4}$$

where ρ is the mass density, u the velocity, P the pressure, E the total energy, B the magnetic field, and L the cooling function (see [1] for details). The gas is assumed to be a perfect gas with $\gamma = \frac{5}{3}$ and with a mean molecular weight $\mu = 1.4 m_H$, where m_H is the mass of the proton.

We start from uniform density (5 particles per centimeter cube), temperature (2000 K for the 2-phase simulation, 500 K in the isothermal case), and magnetic field (2 muG) . The velocity field is almost "turbulent", having a $k^{-\frac{5}{3}}$ power spectrum but random phases. The total RMS velocity equals 20 km/s.

These simulations have been performed on IDRISS clusters using the adaptive mesh refinement code *RAMSES*.

The size of the computational domain is 500pc on 512^3 cells, leading to a spatial resolution of about 1 pc.

Information on the state of the fluid are extracted about every 10 kyrs, spanning approximately a one-million year time. The typical column densities reproduce those observed ($\sim 10^{23} cm^{-2}$).

$2^{21} = 2097152$ neutral (masse-less) tracer particles are added to the flows. They are passive scalars advected with the flow of gas.

We wait until the simulation reaches an equilibrium state to perform the subsequent analysis.

1.2 Outline of this work

I will use the data issued from Patrick Hennebelle's simulation, providing all the thermodynamical properties of the flow for a succession a time-steps. Prior to lifetime analysis, clouds need to be identified. These sur-dense regions are extracted using a simple friends-of-friends algorithm on the density field of the gas. In order to follow the evolution of clumps, neutral particles are added into the fluid as part of the simulation and are driven with it, enabling us to follow them, and thus trace the evolution of fluid elements. That drives the need of first checking the Lagrangian nature of their distribution as a proof of reliability for the particles to trace the flows. Figure 1 illustrates the evolution of such a cloud over the 20 time-steps supplied by the isothermal simulation.

In this work, I aim to find an estimation of the lifetime of high density structures, and compare for the isothermal and 2-phase simulations. As a mesure of the *lifetime* of a cloud, I will compute its *coherence* time, i.e. the time during which particles stay together in the same dense structure. It will be estimated two ways: tracing the percentage of particles initially constituting a cloud which remain in the cloud, and looking at their spacial spreading with time.

After checking the Lagrangian behaviour of the particles distribution in section 2, the next section presents the two ways of estimating the lifetime of structures. The results are presented in the fourth section. The fifth and last section summarizes the results and concludes my work.

Note that I will subsequently use indifferently the words *clouds* and *clumps*.

Both *IDL* and *Python* [3] will be used for data analyzing.

All the clumps extraction will be performed with a lower threshold of 100 particles per centimeter cube, unless specified otherwise.

[3] http://www.python.org

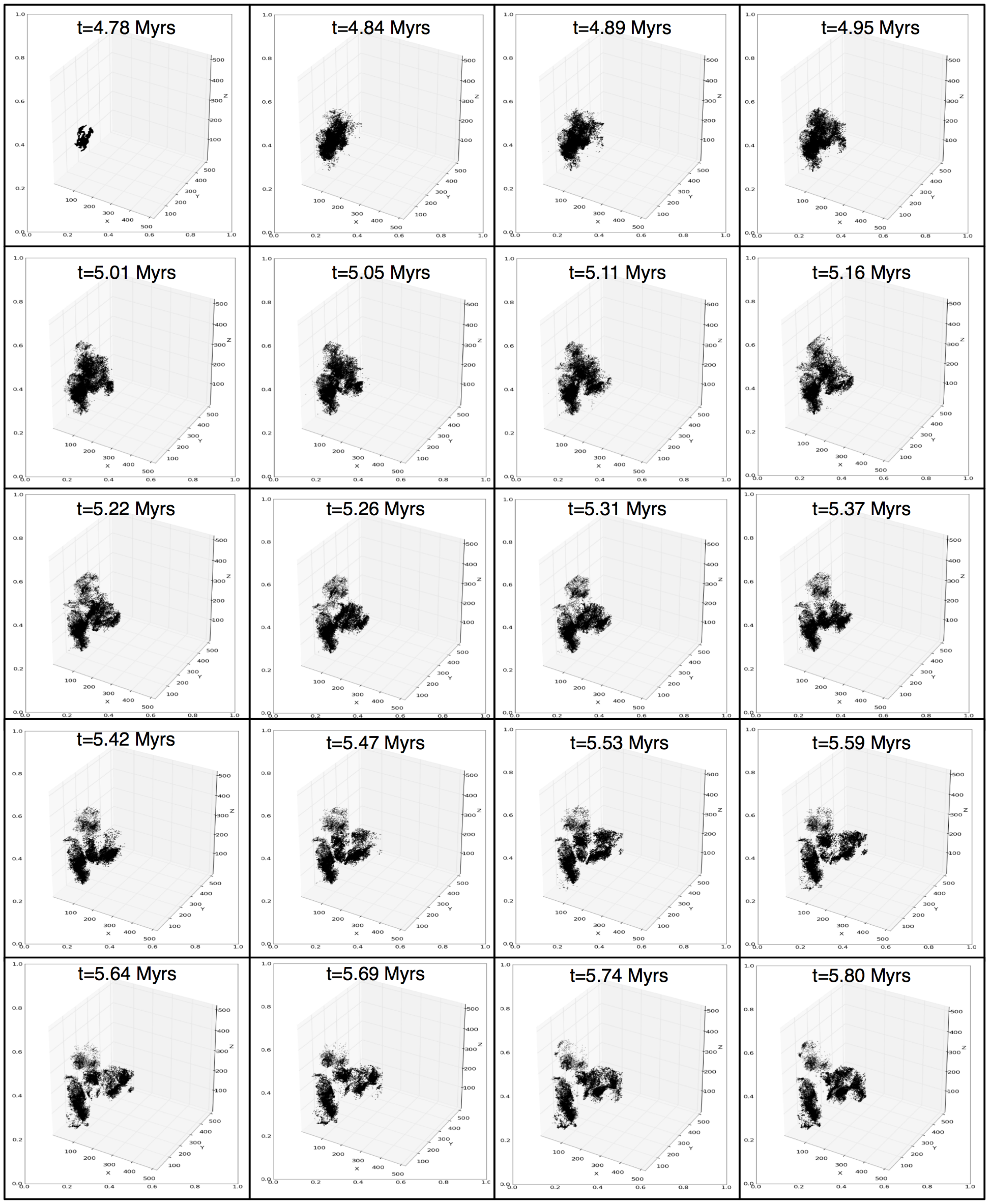

Figure 1: Evolution of a massive cloud shown on 20 time-steps ($M = 4.5.10^5 M_{\odot}$, isothermal simulation).

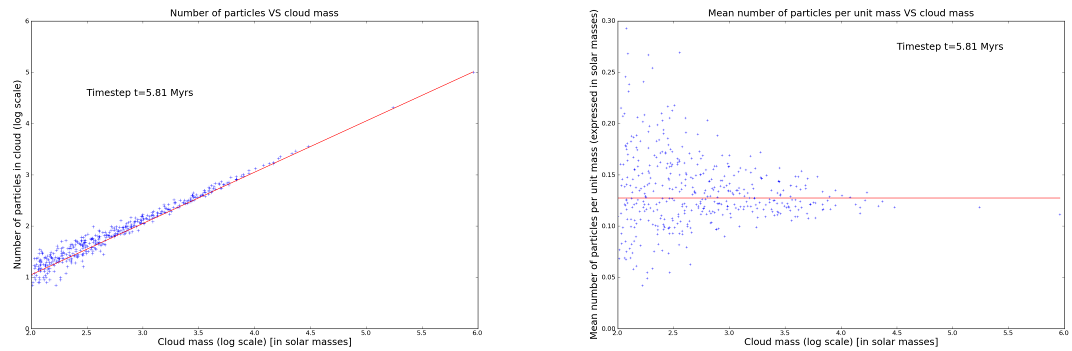

Figure 2: Left: Number of particles in clouds versus clouds mass for the 764 clouds at time-step $t = 5.81 Myrs$ for the isothermal simulation. As expected, the number of particles they contain is proportional to clumps mass as shown by linear regression (in red, line of slope 1, beware that this is a log-log scale graph). Right: Mean number of particles per unit mass in clouds versus cloud mass fitted by a constant (red line).

2 Lagrangian nature of the flow

So to check if the particles flow is Lagrangian (i.e. the particles are passive scalars, which we need to rely on them to trace clumps evolution), we visualize the number of particles contained in clumps as a function of their mass (for every clump at a given time-step). This is illustrated on figure 2. If the flow is Lagrangian, the number of particles per clouds must be proportional to their mass, i.e. the number of particles per unit mass of the fluid should be a constant. Fig. 2 seems to favor such a linear relation.

The linear regression coefficient $\alpha = 0.111$ (ordinate at origin on this log-log scale graph) remains the same with a 10^{-3} accuracy for all 22 time-steps for both simulations .

2.1 Noise

This verification can be rendered more precise by studying the noise in the mean number of particles per unit mass. Indeed, as it represents the mean over a large number a particles (for big enough clouds at least), the central limit theorem predicts that the noise decreases as the number of particles increases as its inverse square root. Figure 3 presents concluding results.

We will focus on most massive clouds, say $M > 10^{2.5} M_{\odot}$, as we want to ensure to accurately describe the structures (i.e. making sure that their properties are not resolution-dependant). For those clouds, the noise on the mean number of particles per unit mass is smaller (less than 20%), thus improving the accuracy of the subsequent results.

This “Lagrangian verification” gives similarly good results for the 2-phase simulation.

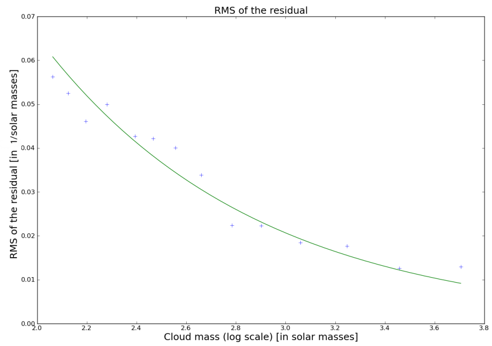

Figure 3: Root Mean Square calculated on 22 bins containing each 30 points of the residual error of the mean number of particles per unit mass versus cloud mass fitted by a constant (time-step $t = 5.81 Myrs$, isothermal simulation). The green line is a fit by an inverse square root law.

3 Estimating lifetime of clouds

3.1 Cloud depletion

As stated in the introduction, as the lifetime of a cloud, I will compute its *coherence* time, i.e. the time during which particles stay together in the same dense structure. A first way to do this is to compute the percentage of particles initially constituting a cloud which remain in the cloud as they evolve.

To do this we need to define a lineage between the clouds at successive time-steps. The process is sketched on fig. 4: the son cloud is simply defined as the one containing the greatest number of particles issued from the father cloud.

The computation of the "coherence time" is then relatively easy. Once we have found the particles ID in a given clump at a given time-step, we compute the number of those particles remaining in the clump at each following time-steps. A typical result is shown in figure 5, where we plot the percentage of particles initially constituting a cloud which remain in the cloud versus time.

A look at the figure suggests that it might be fitted be an exponential profile (first order differential equation type model), which takes the form:

$$f(t) = e^{-ln(2)\frac{t}{\tau}} \tag{5}$$

where τ is the only free parameter and represents the time at which half of the particles have left the cloud. It will be used as the parameter to quantify the lifetime of the clump and will often be called abusively *lifetime* of the cloud.

Fits are made using a simple least-square minimisation with downhill simplex algorithm.

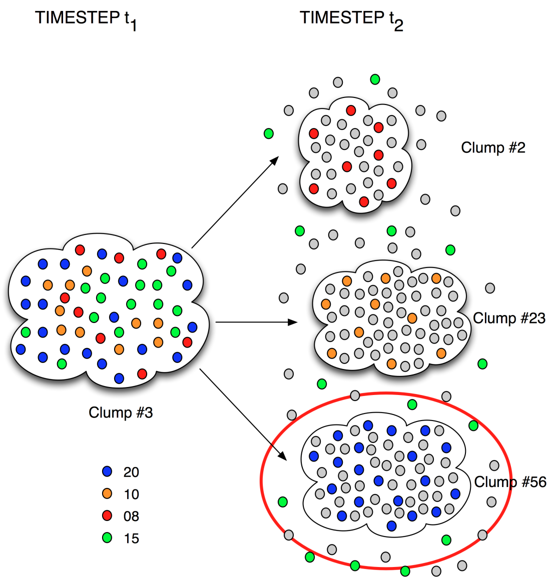

Figure 4: Establishing a lineage between the clouds at successive time-steps. The son cloud is simply defined as the one containing the greatest number of particles issued from the father cloud.

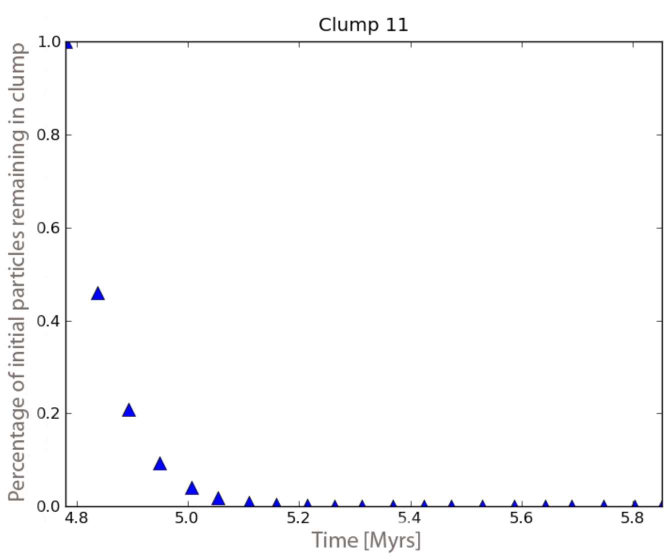

Figure 5: Time evolution of the percentage of particles initially constituting a massive cloud of $6.2.10^5 M_\odot$ (bi-phase simulation) which remain in the cloud.

3.2 Cloud spreading

A second way of computing a coherence time of a cloud is to follow the evolution of the particles it contains, and see "how much time they stay together", i.e. looking at their spreading with time. There again, the computation seems relatively easy: following a given cloud as it evolves with time, we estimate its size by calculating the mean-distance between the particles it contains. But two problems arise:

- First, for computational reasons, the simulations are done with periodic boundary conditions and some clumps are therefore "cut" by the edges. If that happens, we need to "re-assemble" and reconstitute the real shape of the cloud.
- Secondly, the size of the cloud can be big (more than 10^5 particles) and calculating the mean distance between the particles has a n^2 complexity. We cannot compute its exact value in a reasonable time for the biggest clouds.

To overcome the first problem, we need to come back to the clumps themselves, which are continuous (contrariwise, the particles distribution is not). Starting from any point inside a clump, for can therefore fill the clump from this point with a "friends-of-friends-like" algorithm. When reaching an edge of the box, we know than the position of all the particles encountered thereafter must be corrected. A sketch illustrating the method is shown on figure 6 and an application of this algorithm is illustrated on figure 7.
This works well for the particles that are contained in a clump, but as they evolve, a large majority of them will quit their initial clump and won't necessary belong to an another clump at latter time-steps. Thus we apply our algorithm to the first time-step only, while for further time-steps the particles positions are corrected relatively to their previous position, assuming that the crossed distance is small compared to the size of the box, i.e. they don't go too far away from their previous position (see fig. 8).

To reduce the computational time, we will resort to Monte-Carlo simulations, i.e. we will estimate the mean distance between the particles in the cloud from a set of particles chosen randomly amongst the cloud. For each picked particle, we calculate its mean distance to all of the others, improving therefore the estimation at each step. As the number of picked particles grows up, the estimated value of the cloud size converges towards it's real value; we stop picking up particles when the convergence is estimated to be good enough. For this we need a convergence criterion, below which we will assume that the convergence is reached. I defined this criterion as the post-fit RMS of the last hundred estimated values by a constant function. Particles stopped being picked as soon as this criterion goes below the threshold. The threshold is determined in an empiric way, and is taken to be one percent of the mean value of the one hundred last estimations. This is illustrated in figure 9.

Comparing the results with an exact calculation performed upon one time-step only, the difference from the exact values follows a gaussian distribution, with an error of $\pm 3.7\%$.

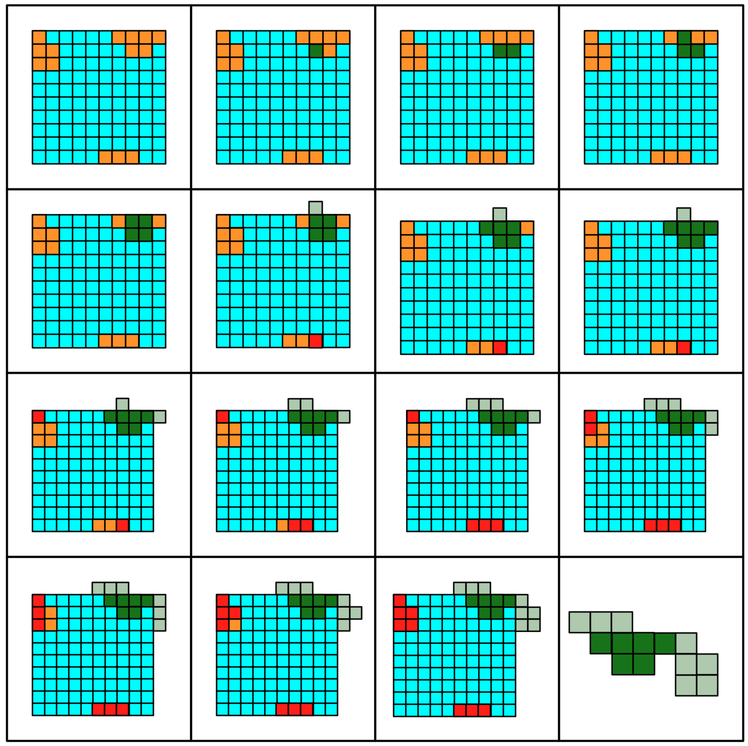

Figure 6: Illustration in 2 dimensions of the method of real shape recovery of clouds. The "cut clump" is shown in orange, and at each step one additional box is selected (green colored boxes). After crossing an edge, all positions of selected boxes must be corrected (red boxes become light green boxes).

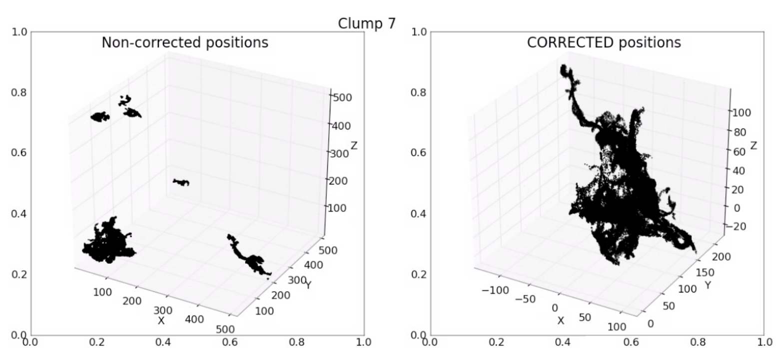

Figure 7: Reconstitution of the real shape of a cloud using the algorithm presented above (isothermal simulation).

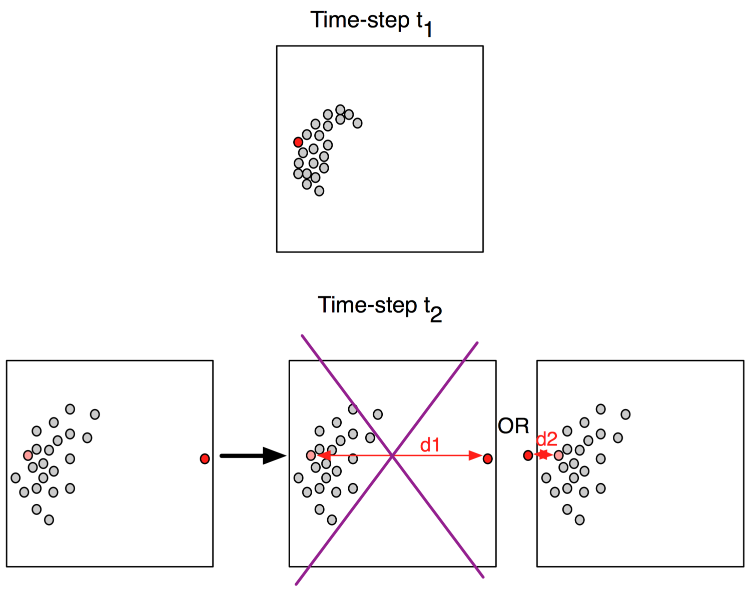

Figure 8: For all time-steps but the first, particles positions are corrected relative to their previous position, assuming that the crossed distance is the smallest between all the possibilities enabled by periodic boundary conditions.

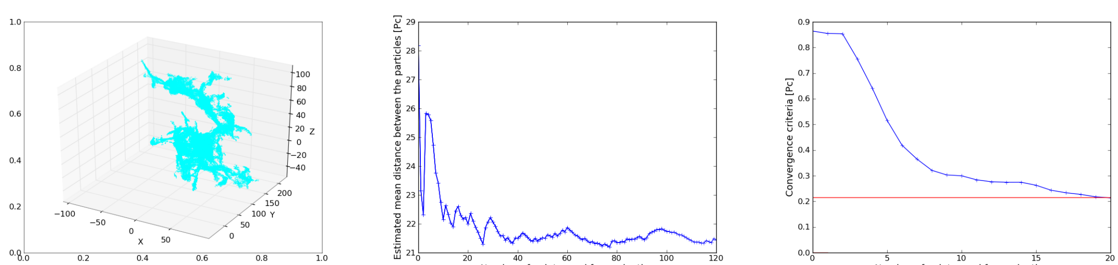

Figure 9: Monte-Carlo estimation of clump size. Left: Clump extracted from the bi-phase simulation at time-step $t = 4.78 Myrs$ containing 73 555 particles. Middle: Evolution of the estimated size of the cloud as the number of picked particles (in abscissa) grows up. Right: Evolution of the convergence criterion and the chosen threshold (red line) .

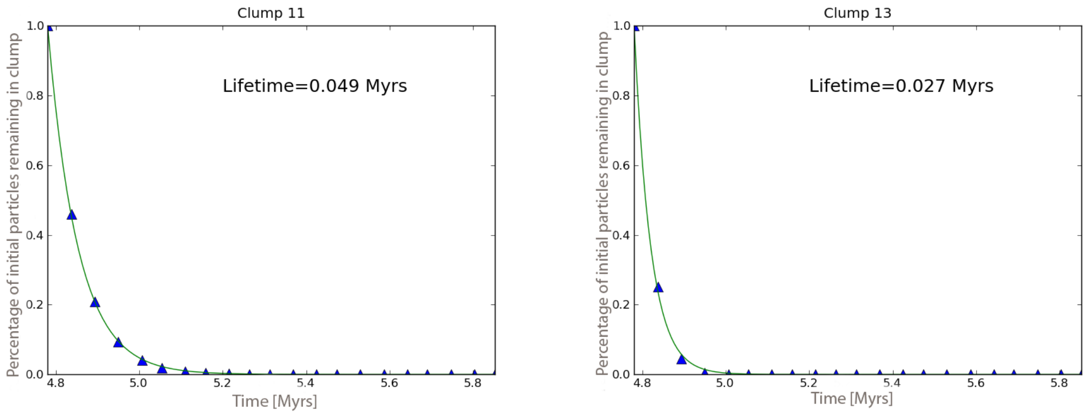

Figure 10: Time evolution of the percentage of particles initially constituting clouds which remain in the cloud, and fits by exponential functions for two clouds (of mass $6.2.10^5 M_\odot$ (left plot) and $1.9.10^5 M_\odot$ (right plot)) from the isothermal simulation.

4 Results

4.1 Cloud depletion

We present two plots with fits and associated lifetime calculated from clumps depletion on figure 10. We see that the lifetime of these clouds is of the order of a few tens of thousands years.

Fig. 11 summarizes the obtained results, presenting a scatter plot of estimated lifetimes of the most massive clumps ($M > 10^{2.5} M_\odot$) for both simulations (iso-thermal and 2-phase) .

4.2 Cloud spreading

We present two plots with fits and associated lifetime calculated from clumps spreading on figure 12. A look at the figures and the idea of Brownian movement suggest a fit by a square root law. Similarly to the previous section, lifetime of the clouds are taken to be the time for the size of the cloud to double relative to its initial value. These estimated lifetime of the clouds are of the same order of a few tens of thousand years.

Fig. 13 summarizes the results, presenting a scatter plot of estimated lifetimes of the most massive clumps ($M > 10^{2.5} M_\odot$) for both simulations (iso-thermal and 2-phase) .

4.3 Exploring different threshold densities for clumps extraction

The chosen threshold of 100 particles per centimeter cube corresponds to typical densities of the Cold Neutral Gas (CNM) (see figure 14 for a large overview of typical densities encountered within the interstellar medium). I have analyzed the data issued of both simulations over a wider range of threshold values (from 50-100 to 400 particles per centimeter cube) for clumps extraction, each time computing the mean lifetime of the

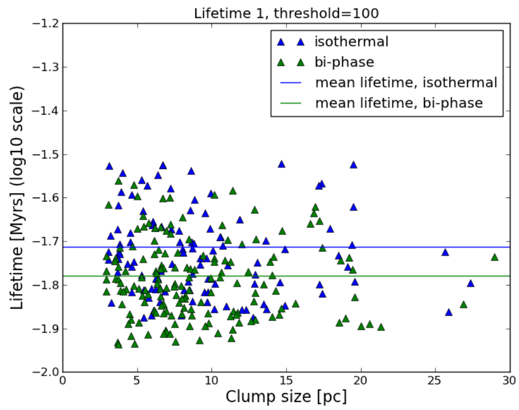

Figure 11: Lifetimes of the most massive clumps ($M > 10^{2.5} M_{\odot}$) estimated from clouds depletion for isothermal and 2-phase simulations. Blue and green lines represent the mean estimated lifetimes for both simulations.

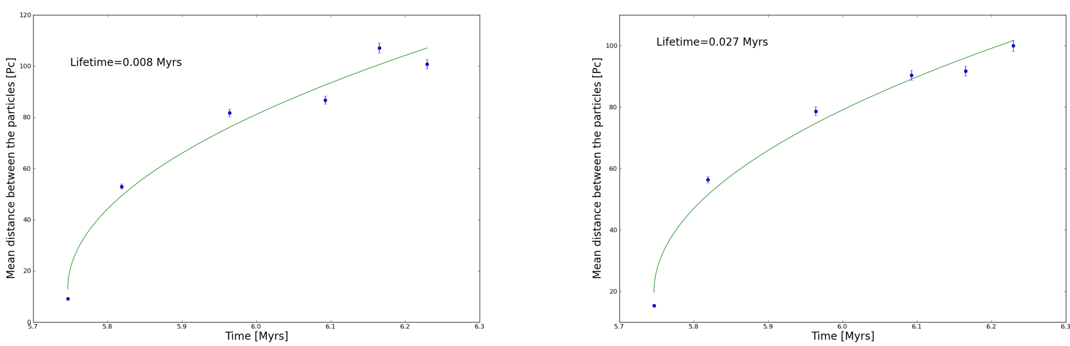

Figure 12: Time evolution of the size of two clouds (of mass $4.5.10^5 M_{\odot}$ (left plot) and $2.7.10^5 M_{\odot}$ (right plot)) issued from the isothermal simulation, and fit by a square root law.

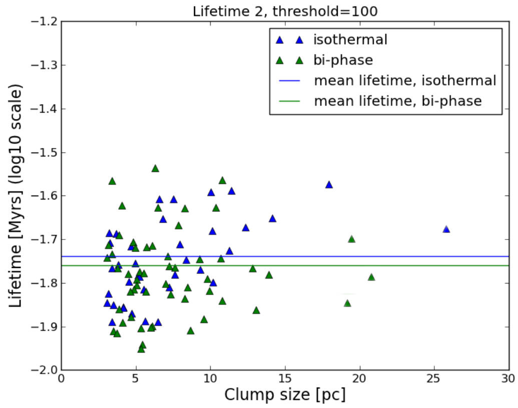

Figure 13: Lifetimes of the most massive clumps ($M > 10^{2.5}M_{\odot}$) estimated from clouds spreading for isothermal and 2-phase simulations. Blue and green lines represent the mean estimated lifetimes for both simulations.

cloud using the "clump depletion" method. Prior to lifetime analysis, it seems relevant to see the variation of clumps mass and size with the chosen threshold. These results are presented on figures 15 and 16.

As we expect the lifetime of the clouds to increase with their size (see fig. 17), it seems irrelevant to compare the average clumps lifetime over a wide range of clumps sizes, but we shall rather compare it for fixed size clumps. Figure 18 presents the variation of clumps mean lifetime with chosen density threshold for both simulations for two size binings ($0pc < L < 5pc$ and $5pc < L < 10pc$, L being the characteristic size of the clump defined as the mean distance between the particles it contains).

4.4 Discussion

We conclude that both methods ("clouds depletion" and "clouds spreading") give coherent results , as they give an estimate of clumps lifetime within the same range of values (a few 10^4 years). This is surprisingly low comparing to models prediction (10^7-10^8 years, see [11] and [4]). We shall question the relevance of our methods of lifetime determination, wondering if the particles left the clouds, staying nonetheless in a dense structure. But the agreement between the two methods used here seems to confirm the accuracy of the estimated values.

It is interesting to compare with typical time-scales for molecular clouds, i.e. the free-fall time $t_{ff} \sim \frac{1}{\sqrt{G\rho}}$ and the crossing time of the cloud $t_c \sim \frac{L}{V_{RMS}}$ where L is the size of the cloud and V_{RMS} the speed dispersion. Calculating those from the clumps data, it is found that clouds lifetime are of the same order than the crossing time ($\sim 10^4$ years), while two orders of magnitude below the free-fall time ($\sim 10^6$ years).

Also, unlike we expected, clumps mean lifetime is not found to be bigger for clumps issued from the 2-phase simulation, than for clumps issued from the isothermal simulation. This could be explained by the difference of temperature between the two simulations, leading to density contrasts, and a density lower for the isothermal simulation, clouds thus being larger in the latter for a fixed mass.

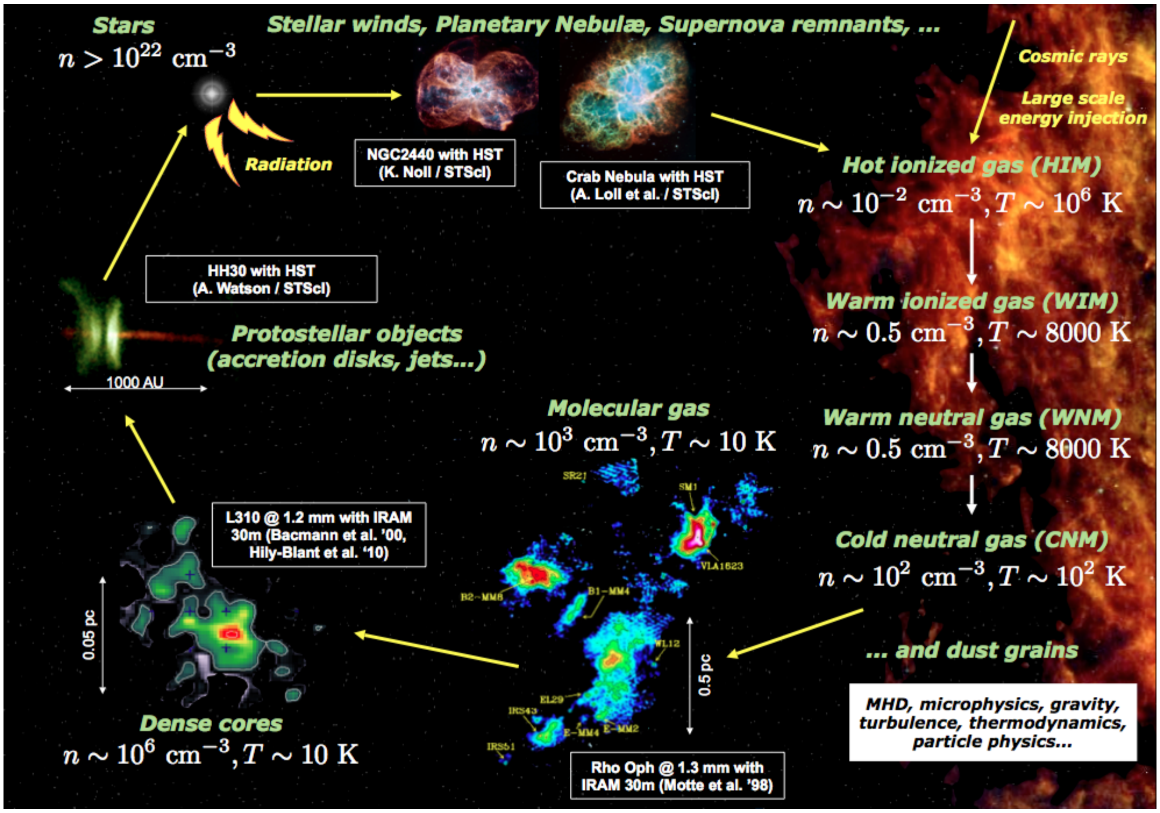

Figure 14: The cycle of matter in the interstellar medium. Credits to François Levrier for this figure.

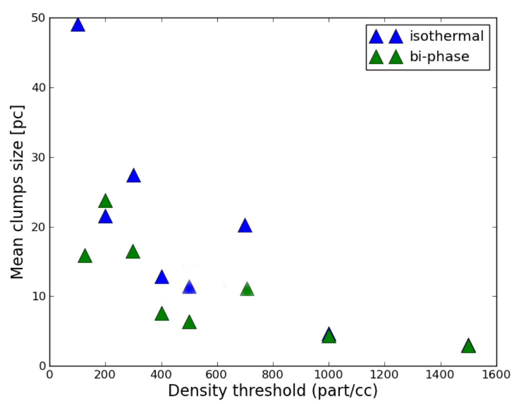

Figure 15: Evolution of clumps mean size as a function of the chosen density threshold for clump extraction.

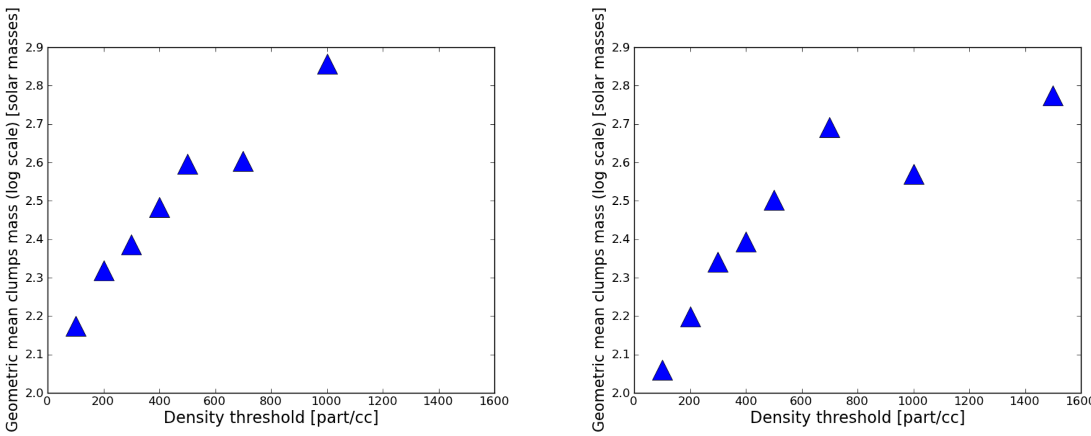

Figure 16: Evolution of clumps geometric mean mass as a function of the chosen density threshold for clump extraction (Left: isotherm simulation, Right: bi-phase simulation).

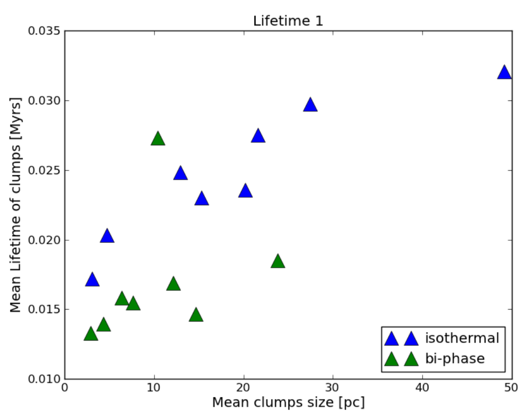

Figure 17: Mean clumps lifetime increases with clumps size (plot for a density threshold of 100 particles/cc).

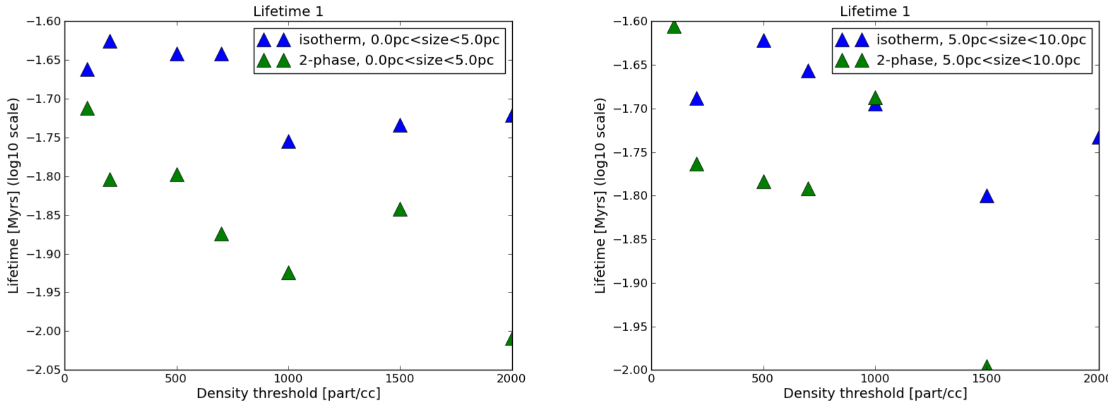

Figure 18: Variation of clumps mean lifetime with chosen density threshold for both simulations for two size binings (Left: $0pc < L < 5pc$, Right: $5pc < L < 10pc$)

It would be interesting to compare those results with those of 100K simulations.

5 Conclusion

Studies of 2-phase flows had shown a property of some interstellar clouds to be confined in a thermally unstable domain, i.e. cold structures isolated from the rest of the flow by stiff thermal fronts. This had lead us to assume that these clouds must have a greater lifetime than clouds issued from isothermal simulations. Though this study of lifetime of interstellar clouds has not enabled to support our initial assumption, further analysis would have to be done (e.g. comparing 100K simulations) to explain this result.

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