Gravitationally Contracting Clouds and Their Star Formation Rate

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Abstract We present evidence that giant molecular clouds may be in overall contraction, and we show, by both numerical and semi-analytical arguments, that before they collapse significantly as a whole and transform so much of its mass in stars, the feedback from massive stars produced by first local collapses, regulates the fraction of mass that continues forming stars at values consistent with those observed. Moreover, we have found that the gravitational collapse time for non-spherical structures is longer that the standard free-fall time for spherical ones of the same volume density by a factor $\sim\sqrt{A}$, where A is the aspect ratio of the structure. This implies that clumps inside filaments collapse earlier, naturally giving rise to the ubiquitously observed pattern of clumps within accreting filaments, and that the free-fall estimate for the Galactic SFR may have been overestimated, if clouds in general have non-spherical symmetry.

1 Introduction

Recent theoretical and observational evidence has suggested a return to the scenario of Goldreich and Kwan [8] of global gravitational contraction of molecular clouds (MCs; e.g., [2, 3, 7, 9, 10, 19, 22, 24, 25]; see also the discussion by Zamora-Avilés et al. [30]). But in this case, it is necessary to find a solution for the star formation

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rate (SFR) conundrum first noded by Zuckerman and Palmer [31], namely that if all the molecular gas in the Galaxy were in free fall, then the total SFR in the Galaxy would be about two orders of magnitude higher than observed.

In this contribution, we explore the regulation of the SFR and star formation efficiency (SFE) by the feedback from the first stars that form in the clouds, as well as the possibility that the SFR estimated by Zuckerman and Palmer [31] could be an upper limit.

2 Numerical Simulations

In the last decade, a new evolutionary scenario of MC evolution has emerged in which the clouds start as a cold atomic cloud formed by compressive motions in the warm neutral medium (WNM) in environments as the solar neighborhood.

In this scenario, the collision of WNM streams nonlinearly triggers thermal instability, forming a thin cloud of cold atomic gas (e.g., [13, 16, 17, 28]), which becomes turbulent by the combined action of various dynamical instabilities [11, 14, 17, 23, 27]. The cloud soon begins to contract gravitationally as a whole. However, before this global collapse is completed, some local, nonlinear (i.e., large-amplitude) density enhancements produced by the initial turbulence manage to collapse on their own, since their local free-fall time is shorter than the average one for the entire cloud [12,20]. These local collapses thus involve only a fraction of the cloud's total mass. Numerical simulations by Vázquez-Semadeni et al. [26] show that in the absence of stellar feedback this fraction (the SFE) tends to 100 % (see left panels of Fig. 1, which show the SFE evolution for two subregions in a simulation with "large-amplitude" initial velocity fluctuations, simulation labeled as LAF0), whereas when the feedback is included (simulation LAF1), the SFE is reduced by a factor of 10×, reaching values typical of those observed in MCs (see right panels of Fig. 1).

However, these results can not be taken as definitive, because these simulations have a crude modeling of the stellar feedback, since is assumed that massive stars have formed with a single mass, and that these inject an arbitrary amount of thermal energy to reproduce the observed properties of HII regions.

3 A Simple Analytical Model

Zamora-Avilés et al. [30], based on simulations by Vázquez-Semadeni et al. [26], described an idealized, semi-empirical model for the evolution of MCs and their star SFR and SFE. The clouds are assumed to form by the collision of cylindrical WNM streams and to continuously accrete mass from the surrounding diffuse gas, becoming turbulent in the process. The turbulence produces a probability density function (PDF) of the density field, which we assume to have a lognormal form. No

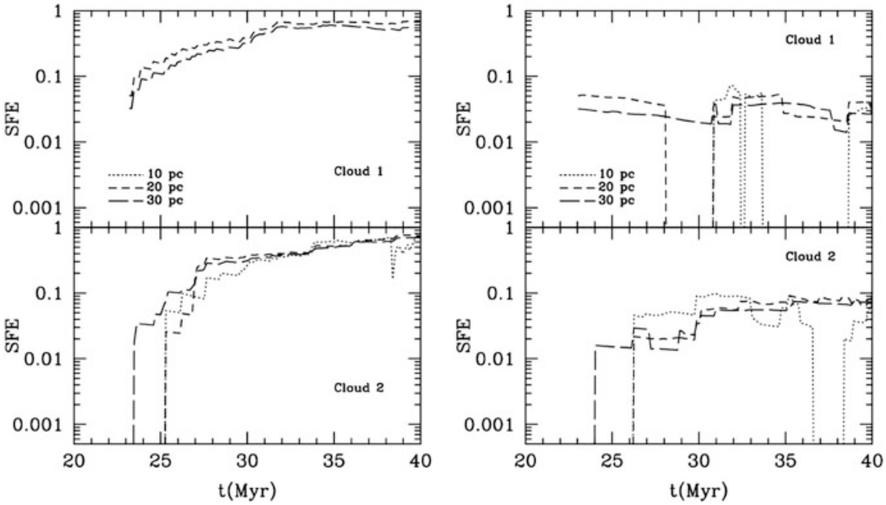

Fig. 1 The *left panels* show the SFE for *Clouds 1* and *2* in the LAF0 simulation (without feedback), for three different cylindrical boxes, of length and diameter indicated in the labels. The *right panels* show the SFE for *Clouds 1* and *2* in the LAF1 simulation (with feedback). In the *left top panel*, no curve for the 10 pc cylinder is shown because there are no stellar particles within that volume in that simulation

turbulent support is assumed, and magnetic fields are neglected, so a model cloud begins to contract gravitationally as soon as it reaches its own Jeans mass. The high-density tail of the PDF, with $n > n_{SF}$, where n_{SF} is a free parameter, is assumed to instantaneously form stars at a rate given by the ratio of the mass at $n > n_{SF}$ to its own free-fall time, while the bulk of the cloud continues to collapse. During the collapse, the mean density of the cloud increases, causing the density PDF to shift towards larger densities over time, and thus the SFR increases in time. From the total instantaneous stellar mass, we compute the instantaneous massive star fraction through an assumed IMF. The massive stars feed back on the cloud through ionizing radiation, eroding the cloud. The evolution is terminated when the entire bulk of the cloud is ionized, or when the mean density exceeds n_{SF}.

We calibrate the parameters of the model by matching its results to those of a numerical simulation. After calibration, only one free parameter remains, the inflow radius R_{inf}, which effectively controls the maximum cloud mass, M_{max}, which we use to compare against clouds of various masses. A GMC model ($R_{inf} = 100$ pc, $M_{max} \approx 10^5\, M_\odot$) adheres very well to the evolutionary scenario recently inferred by Kawamura et al. [15] for GMCs in the Large Magellanic Cloud. Also, a model cloud with $R_{inf} = 10$ pc ($M_{max} \approx 2{,}000\, M_\odot$) evolves in the Kenniccutt-Schmidt diagram, first passing through the locus of typical low- to-intermediate mass star-forming clouds, and then moving towards the locus of high-mass star-forming clumps over the course of $\sim$10 Myr (see the right panel in Fig. 2). Finally, the stellar age histograms for this model a few Myr before the clouds destruction agree

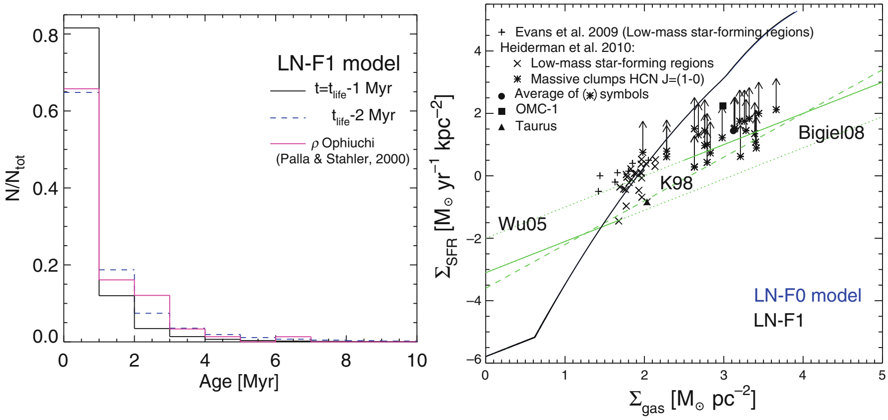

Fig. 2 *Left*: Stellar age distribution for our calibrated model with $R_{\rm inf} = 10\,{\rm pc}$ ($M_{\rm max} \approx 2,000\,{\rm M}_\odot$), calculated at 1 and 2 Myr before the end of the clouds evolution, compared with the corresponding distribution for the ρ-Oph association [18]. *Right*: SFR surface density $\Sigma_{\rm SFR}$ vs. gas surface density $\Sigma_{\rm gas}$. The *dashed line* represents the Kennicutt-Schmidt relation, while the *lower dotted line* represents the observational fit by Bigiel et al. [1] and the *top dotted line* is the fit by Wu et al. [29]. We also plot with different symbols the data for individual star-forming regions. The *solid black line* shows the evolution of our calibrated model with $R_{\rm inf} = 10\,{\rm pc}$

very well with those observed in the ρ-Oph stellar association inferred by Palla and Stahler [18] (see left panel in Fig. 2), whose parent cloud has a similar mass, and imply that the SFR of the clouds increases with time (though strictly speaking it decelerates).

Our model thus agrees well with various observed properties of star-forming MCs when its mass is adjusted to that of the cloud it is to be compared to. This suggests that the scenario of gravitationally collapsing MCs, with their SFR regulated by stellar feedback, is entirely feasible and in agreement with key observed properties of molecular clouds, such as their masses, sizes, lifetimes, and star formation efficiencies and populations.

4 The Free-Fall Time of Sheets and Cylinders

Several studies [2, 4–6, 10, 19, 22, 24, 26] suggest that the cold gas is distributed in sheets and filaments rather than in spherical structures, so it is necessary to calculate the free-fall time for non-spherical structures. These calculations are described in detail in Toalá et al. [21].[1]

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[1] See also Pon et al. [20]

In the cases of sheet-like or filamentary geometries, we find that the free-fall time is increased by a factor of $\sqrt{A}$ (where A is the ratio of the largest dimension to the smallest one) with respect to the case of spherical geometry. This has two important implications for the structure of MCs and their SF. First, it naturally explains the common morphology observed in molecular clouds, where star-forming or pre-stellar clumps are embedded within filaments, because the free-fall time for a filament is longer than for any spheroidal structure within it that contains enough mass to be itself collapsing. Second, the SFR conundrum may not be as marked as originally envisaged, because the relevant free-fall time for the cold gas may be longer than has been considered and hence the free-fall SFR estimate would be an upper limit. In any case, our results suggest that determining the topology of MCs is important for estimating their true expected collapse timescales.

5 Conclusions

Using numerical simulations and a semi-analytical model, we have found that, in a scenario of clouds in overall contraction, the SFE is readily decreased by feedback to levels consistent with observational determinations. Moreover, we have found that the gravitational collapse time for non-spherical structures is longer that the standard free-fall time for spherical ones of the same volume density by a factor $\sim\sqrt{A}$, where A is the aspect ratio of the structure. This implies that clumps inside filaments collapse earlier, naturally giving rise to the ubiquitously observed pattern of clumps within accreting filaments, and that the free-fall estimate for the Galactic SFR may have been overestimated, if clouds in general have non-spherical symmetry.

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