Mon. Not. R. Astron. Soc. **420,** 1457–1461 (2012) doi:10.1111/j.1365-2966.2011.20131.x

Rapid star formation and global gravitational collapse

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Accepted 2011 November 3. Received 2011 November 2; in original form 2011 August 28

ABSTRACT

Most young stars in nearby molecular clouds have estimated ages of 1–2 Myr, suggesting that star formation is rapid. However, small numbers of stars in these regions with inferred ages of $\gtrsim$5–10 Myr have been cited to argue that star formation is instead a slow, quasi-static process. When considering these alternative pictures it is important to recognize that the age spread in a given star-forming cloud is necessarily an upper limit to the time-scales of local collapse, as not all spatially distinct regions will start contracting at precisely the same instant. Moreover, star-forming clouds may dynamically evolve on time-scales of a few Myr; in particular, global gravitational contraction will tend to yield increasing star formation rates with time due to generally increasing local gas densities. We show that two different numerical simulations of dynamic, flow-driven molecular cloud formation and evolution (1) predict age spreads for the main stellar population roughly consistent with observations and (2) raise the possibility of forming small numbers of stars early in cloud evolution, before global contraction concentrates the gas and the bulk of the stellar population is produced. In general, the existence of a small number of older stars among a generally much younger population is consistent with the picture of dynamic star formation and may even provide clues to the time evolution of star-forming clouds.

Key words: stars: formation – stars: pre-main-sequence.

1 INTRODUCTION

Roughly a decade ago, Ballesteros-Paredes, Hartmann & Vázquez-Semadeni (1999) and Hartmann, Ballesteros-Paredes & Bergin (2001) argued that star-forming molecular clouds in the solar neighbourhood evolve rapidly and produce stars on short – dynamical – time-scales (see also Elmegreen 2000). The starting point for this picture was the observation that most nearby molecular clouds of significant mass are forming stars with typical ages of $\sim$1–2 Myr; only a small fraction of the stellar population exhibits ages $\gtrsim$5–10 Myr. A straightforward interpretation of the observations is that local star formation ensues quite quickly after molecular cloud formation, and that lifetimes of these nearby star-forming clouds are typically only a few Myr. Furthermore, in some cases the spread in ages of the bulk of the stellar population was considerably less than a *lateral* crossing time. To explain these observations, we proposed that molecular clouds in the solar neighbourhood tend to be formed by 'large-scale flows', accumulating material in a direction roughly perpendicular to the lateral extension of the cloud (Ballesteros-Paredes et al. 1999; Hartmann et al. 2001; Heitsch et al. 2008). Building clouds in this manner thus eliminates the need for communicating the 'information' needed to trigger star formation roughly simultaneously along the length of the cloud. The swept-up material is initially atomic; only after substantial column densities develop, as a result of both accumulation of gas and lateral gravitational contraction, does the cloud become molecular (Bergin et al. 2004). This evolution, driven largely by gravity at late stages, helps explain why star formation is initiated shortly after 'molecular cloud formation'.[1]

Since then there has been substantial discussion of apparent age spreads in star-forming regions (see Jeffries 2011; Jeffries et al. 2011). One of the common findings is that, even though the bulk of the stellar population is young, there exist a small number of stars with apparent ages $\sim$5–10 Myr or more which seem to be members of the region (see e.g. Palla et al. 2005, 2007). The question then arises: does the presence of a few older members in star-forming clouds contradict the idea of dynamic cloud evolution and star formation? Do these apparently older stars instead indicate a long phase of quasi-static cloud evolution, possibly supported by turbulence and/or magnetic fields?

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[1] Hartmann et al. (2001) specifically limited their discussion to the solar neighbourhood, where most of the gas is atomic and therefore molecular clouds must be made from atomic gas. In other regions, where most of the gas is molecular, there should be more non-star-forming molecular clouds.

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In this paper, we use numerical simulations to show that dynamic models of cloud formation can account for age spreads comparable to those observed, without introducing turbulent or magnetic field support, simply because fluctuations in initial conditions as a function of position result in some regions collapsing faster than others. Moreover, the dynamic models exhibit global gravitational collapse, which produces an increasing rate of protostellar core and star formation over time, in a manner qualitatively similar to the accelerating star formation rates inferred from observations by Palla & Stahler (1999, 2000)). A similar argument has been made independently by Abelardo Zamora-Aviles & Vazquez-Semadeni (2011), on a semi-analytical basis.

2 A CASE STUDY: THE ORION NEBULA CLUSTER

To illustrate the issues typically presented by observations of young stellar populations, we use results from recent observational analyses of the Orion nebula cluster (ONC). We focus on the ONC because it has been so well studied and because its density allows one to limit consideration to a restricted area of the sky, thus minimizing the problems of possible contamination (see Section 4).

Fig. 1 shows the age distribution determined by Da Rio et al. (2010) using two differing sets of evolutionary tracks and binning linearly in age as in Palla & Stahler (2000). (We use only the observed members of Da Rio et al. (2010) without correction for completeness, but the difference is negligible for our argument.) Based on their analysis, the majority of the stars have ages $\lesssim$4 Myr using the Siess, Dufour & Forestini (2000) evolutionary tracks, or $\lesssim$2 Myr using the Palla & Stahler (1999) tracks (Fig. 1). In a later study of the data, Reggiani et al. (2011) infer that the ONC stars are not coeval, with star formation activity between $\sim$1.5 and 3.5 Myr. Similar results were found by Jeffries et al. (2011), who estimated that the apparent mean age of the ONC is about 2.5 Myr, with 95 per cent of the low-mass stars formed between 1.3 and 4.8 Myr.

It is important to consider these estimates in the context of the crossing time of the region. The Da Rio et al. (2010) observations span a region of about 30 arcmin north–south, or about 3.6 pc at the adopted distance of 414 pc. The (one-dimensional) velocity dispersion of stars in the region is about 2.5–3 km s^{-1} (Jones & Walker 1988; Fűrész et al. 2008), implying a full crossing time of $\sim$1.2–1.4 Myr. The age spreads of the main peaks in the stellar distribution [$\sim$4 Myr using the Siess et al. (2000) tracks and $\sim$2 Myr using the Palla & Stahler (1999) tracks] are thus $\sim$2–3 crossing times. These values do not create a major difficulty for the picture of rapid star formation, as the onset of gravitational collapse of individual objects need not be coordinated better than a small number of dynamical time-scales (see e.g. Elmegreen 2000). Moreover, it should be emphasized that these dynamical time-scales refer to the *current* state of the region. If, as we suggest in Section 4, the ONC region has *contracted* significantly over the last few Myr, the relevant dynamical time-scale is longer than the crossing times estimated above.

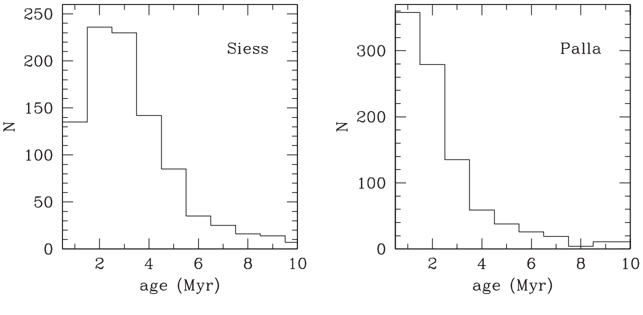

Figure 1. Histograms of the estimated ages of stars in the ONC, from Da Rio et al. (2010), using isochrones from Siess et al. (2000, left) and Palla & Stahler (1999, right). The observations, binned in linear rather than the typical log age, show a strong skewed behaviour with time (see text).

Finally, it is worth noting that observational uncertainties and problems with theoretical isochrones can produce spurious age spreads of similar order to those discussed above (Hartmann 2001, 2003). Indeed, Jeffries et al. (2011) suggest that this apparent age spread is dominated by a combination of observational uncertainties and differences in the formation processes of individual stars.

The biggest challenge to dynamic models of star and cloud formation is the 'tail' of older stars with apparent ages between $\sim$5 and 10 Myr. Palla & Stahler (2000) showed that skewed apparent age distributions such as in Fig. 1 were typical of nearby star-forming regions and argued that this was evidence for accelerating star formation over periods of $\sim$10 Myr in molecular clouds. There are observational problems which can lead to spurious large age spreads (Section 4), but these may not account for all of the apparently older stars, especially objects with infrared excesses implying the presence of circumstellar discs, or signatures of accretion (Palla et al. 2007; Jeffries et al. 2011). Can the dynamic picture of star formation be reconciled with the presence of such older stars?

3 STAR FORMATION WITH GLOBAL GRAVITATIONAL COLLAPSE

In the dynamic picture, star-forming clouds are not in a quasi-steady state, but instead are continually evolving. Initially, the cloud forms by sweeping up mass via large-scale flows driven by stellar energy input or perhaps spiral density waves; eventually, gravitational collapse leads to runaway contraction in local regions (Heitsch et al. 2006, 2008a; Vázquez-Semadeni et al. 2007; Heitsch & Hartmann 2008; Hennebelle et al. 2008; Heitsch, Ballesteros-Paredes & Hartmann 2009). Turbulence leads to density fluctuations which are the seeds of subsequent gravitational collapse, modified by global contraction which increases densities everywhere prior to disruption by outflows, stellar winds, supernovae, etc. Because some initial fluctuations will create denser structures than others, some regions will collapse before others, even without special turbulent or magnetic support; and because cloud densities increase with time, initially due to accumulation of material in the post-shock regions, and later due to gravitational collapse, one would expect the star formation rate to increase with time.

To illustrate this sequence, we examine the results of two numerical simulations of cloud formation from colliding large-scale atomic flows. (The mechanism is more general than the specific setup designed for computational convenience, as any swept-up flow can be turned into a colliding flow in a frame of reference moving with the swept-up gas.) It should be emphasized that these simulations *minimize* differences in the onset of collapse along the cloud because the flows collide all along the interface exactly at the same time. Moreover, no injected turbulent support or magnetic fields are included. Even in these idealized cases, star formation occurs over a finite time.

The first simulations we consider are those of Heitsch et al. (2008). At a resolution of $\sim$0.08 pc, these calculations cannot follow fragmentation down to (low-mass) protostars; instead, as a proxy for star formation, we use the criterion of the formation of gravitationally bound, dense cores. We identify cores initially via

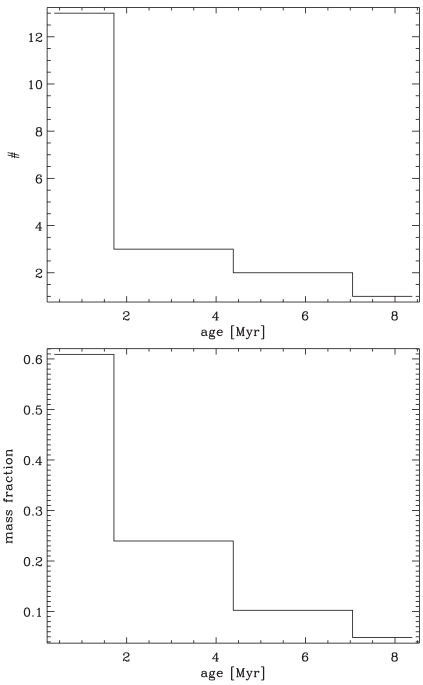

Figure 2. History of massive core formation in the simulation Gs of Heitsch et al. (2008), plotted as a function of time prior to the end of the simulation (see text).

`clumpfind` (Williams, de Geus & Blitz 1994). We consider only gas with $T < 100$ K to avoid having to analyse all the volume of the simulation, and demand that the local free-fall time in the clump is at least a factor of 10 smaller than the global free-fall time of the cloud. The bulk of the core masses have temperatures near 20 K.

Fig. 2 shows the time sequence of massive core formation in simulation Gs of Heitsch et al. (2008). As these cores are quite massive, we alternatively plot both the number of cores and the mass in cores as a function of 'look-back time' from the end of the simulation. Although the resolution is limited and the time steps are crudely binned for reasons of statistics, it is clear that this model produces an accelerating rate of core formation (as well as mass growth).

Fig. 3 shows what is happening globally. After a sufficient amount of mass is accumulated in the post-shock region by the colliding flows, gravity begins to take over, resulting in a more rapid increase in densities. The structures are more local than in smaller cloud simulations Gf1 and Gf2 of Heitsch et al. (2008), where the densest regions are the result of collapse into a filament. The latter simulations, though harder to use for tracking core formation because less mass was involved and therefore fewer cores were made, illustrate the type of evolution we envisage for the ONC, where gravitational contraction over a few Myr has led to the dense gas residing in the narrow 'integral-shaped filament' (Section 4).

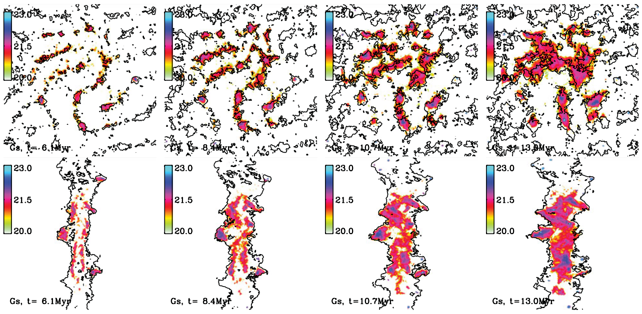

Figure 3. Surface density plots for model Gs (see Fig. 2) as a function of time, seen face-on (upper set of panels) and edge-on (lower set). The colours correspond to the column density in log cm^2 as given in the colour bars.

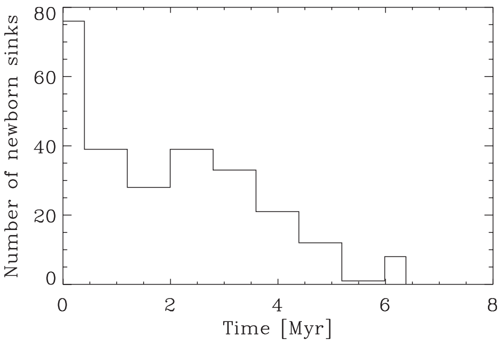

Figure 4. Histograms of the newborn sink particles as a function of time for run 20 in Vázquez-Semadeni et al. (2007). The number of newborn sink particles increases rapidly with time during the first 4–6 Myr. After this time, the mass involved in sink particles is such that, assuming a typical IMF, there would be enough massive stars to disrupt the cloud (see Vázquez-Semadeni et al. 2007 for details).

The cores in this simulation are quite massive, ranging from about 150 to 800 M$_\odot$. To relate this to star formation requires an assumption that these cores do not remain inert, but instead continue to collapse beyond what we can determine given our resolution, fragmenting into more typical protostellar cores of a few solar masses (e.g. André et al. 2010) and then into stars. If the efficiency of star formation is directly related to the amount of dense core mass, as seems reasonable (see e.g. Alves, Lombardi & Lada 2007, and references therein), then the core mass and number evolution of model Gs can serve as a proxy for star formation.

The other simulations we consider are those by Vázquez-Semadeni et al. (2007), which are comparable to the previous ones, in that two warm, thermally bistable streams collide to form a dense, collapsing, cold cloud. These simulations used GADGET, the smooth particle hydrodynamics (SPH) code developed by Springel, Yoshida & White (2001), which includes the possibility of sink particle formation.

In Fig. 4 we show the back-in-time histogram of the newborn sink particles for the fiducial run 20 (Vázquez-Semadeni et al. 2007). In this figure, $t = 0$ Myr corresponds to $t \sim 23$ Myr since the beginning of the collision and thus $t = 6$ Myr corresponds to the time in which the first sink particles are formed, i.e. to ~18 Myr from the start of the simulation.[2] From Fig. 4 it is clear that, as in the case of the dense cores in the previous figure, the sink particles are being formed at an accelerated rate. We must note that at the final epoch plotted, the mass involved in sink particles is such that there would be enough OB stars to disrupt the cloud (see Vázquez-Semadeni et al. 2007), assuming a typical initial mass function (IMF) (e.g. Kroupa 2001). Thus we omit the subsequent evolution of the simulations as likely being unrealistic.

In both cases, the formation of dense structures (cores and sinks) occurs at an accelerated rate due to gravitational collapse, becoming denser and thus evolving locally faster, especially in filaments

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[2] It is worth emphasizing that during the initial evolutionary stages the flow-formed cloud is atomic, and will only become a molecular (CO) cloud when column densities become sufficiently large to shield the molecules from the dissociating interstellar radiation field (see Heitsch & Hartmann 2008).

(see e.g. Pon, Johnstone & Heitsch 2011). While there are limitations to these simulations – for example, there probably would be continuing fragmentation beyond the resolution limits, and the initial conditions are idealized – the qualitative resemblance of the simulations to the observational results is suggestive.

4 DISCUSSION

Given the current state of observational constraints, possible errors and uncertain physics of star formation, one must exercise caution in interpreting the age distributions of star-forming regions (Hartmann 2001, 2003; Jeffries 2011; Jeffries et al. 2011). We agree with Jeffries et al. (2011) that it is especially difficult to be certain of age spreads in the range of ∼1–3 Myr, particularly as differing initial conditions for protostellar formation may result in significant initial dispersions in luminosity (Baraffe, Chabrier & Gallardo 2009; Hartmann, Zhu & Calvet 2011; Hosokawa, Offner & Krumholz 2011). There may even be difficulties in assigning the ages of ∼10 Myr old stars; contamination by foreground stars is an issue, especially for stars without discs or accretion, as star-forming regions are spatially correlated. Even stars with discs can appear anomalously faint for their colours if observed edge-on, and thus mostly detected in scattered light.

Nevertheless, our simulations show that the presence of small numbers of older stellar members in molecular clouds does not pose a particular problem for the idea of rapid or dynamic star formation. All such models begin with turbulent fluctuations, and it is plausible that a few especially dense perturbations collapse first (Heitsch et al. 2008). The effects of global gravity then generally result in ever-increasing densities, with runaway contraction in subregions, as argued by Burkert & Hartmann (2004), and by Hartmann & Burkert (2007) specifically for the Orion A complex. In this scenario, a small number of stars are formed by a few especially dense initial turbulent fluctuations before the overall collapse leads to the main phase of star formation. The two simulations presented here suggest that time-spans of 5 to 10 Myr can be accommodated by purely dynamic models, as long as the initial star formation rate is quite low (e.g. compare Figs 2 and 4 with Fig. 1).

Absent observational problems, it is difficult to understand the age distribution shown in Fig. 1 without invoking substantial evolution of the ONC region over the last several Myr. For instance, if the suggestion of Krumholz & McKee (2005) that the star formation rate per free-fall time is roughly a constant is correct, the age distributions in Fig. 1 imply that the free-fall time has varied by an order of magnitude, and thus the average density by two orders of magnitude, over the last 10 Myr. Indeed, the recent simulations by Krumholz, Klein & McKee (2011) of an 'ONC-like cluster' show strong evolution over $<10^5$ yr, while a somewhat longer contraction time-scale is exhibited by the cluster simulations of Bate, Bonnell & Bromm (2003) and Bonnell et al. (2011).

The suggestion of significant cloud evolution is also consistent with kinematic studies of the ONC stars (Proszkow et al. 2009; Tobin et al. 2009), which suggest that both the gas and stars in the ONC are collapsing towards the central regions. Moreover, the spatial distribution of the stars (see e.g. Da Rio et al. 2009, 2010) is wider in right ascension than the narrow dense 'integral-shaped filament' of molecular gas and dust (Bally et al. 1987). This difference is qualitatively consistent with global gravitational collapse; many stars could have been formed from the gas in the region in a more distended state, which has now collapsed to form a filament, as in the simple model of Hartmann & Burkert (2007) for Orion A.

The idea of large-scale gravitational collapse is also consistent both with observed column density probability density functions (Ballesteros-Paredes et al. 2011b) and with recent discussions showing that the 'Larson laws' relating velocity dispersions ('turbulence') with size scales are not independent of surface density (Heyer et al. 2009). These results can be interpreted as the natural outcome of star-forming molecular clouds being in a state of hierarchical and chaotic gravitational collapse (Ballesteros-Paredes et al. 2011a).

On the other hand, the concept of global collapse has been challenged by Dobbs et al. (2011), who argue on the basis of galactic-scale simulations that cloud–cloud collisions and stellar feedback prevent global gravitational forces from becoming dominant. In a narrow sense, this is not a problem for our picture, as we are focused on the dense star-forming regions of clouds, which Dobbs et al. (2011) agree do become bound (and form stars). Future observations of stellar proper motions from the *Gaia* spacecraft might be able to test whether or not star forming regions are globally collapsing.

5 CONCLUSIONS

We have shown that models of flow-driven, dynamic dense cloud formation and evolution predict that star formation occurs over a finite interval of time necessarily greater than the time-scales of local collapse for individual stars. Moreover, there is generally a strong increase in the dense core/star formation rate over time due to the increase in overall density and filament formation during global gravitational collapse. The small number of stars apparently older than a few Myr found in or projected upon star-forming regions may be a signature of this cloud evolution, though care must be taken to avoid observational problems. It may eventually be possible to use carefully vetted age distributions of pre-main-sequence stars to infer the global evolution of the clouds from which they formed.

ACKNOWLEDGMENTS

We acknowledge a useful report from the referee. This work was supported in part by US National Science Foundation grant AST-0807305, NASA grant NNX08A139G, the University of Michigan and UNAM/DGAPA grant IN110409.

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