ABSTRACT

Recent surveys of star forming regions have shown that most stars, and probably all massive stars, are born in dense stellar clusters. The mechanism by which a molecular cloud fragments to form several hundred to thousands of individual stars has remained elusive. Here, we use a numerical simulation to follow the fragmentation of a turbulent molecular cloud and the subsequent formation and early evolution of a stellar cluster containing more than 400 stars. We show that the stellar cluster forms through the hierarchical fragmentation of a turbulent molecular cloud. This leads to the formation of many small subclusters which interact and merge to form the final stellar cluster. The hierarchical nature of the cluster formation has serious implications in terms of the properties of the new-born stars. The higher number-density of stars in subclusters, compared to a more uniform distribution arising from a monolithic formation, results in closer and more frequent dynamical interactions. Such close interactions can truncate circumstellar discs, harden existing binaries, and potentially liberate a population of planets. We estimate that at least one-third of all stars, and most massive stars, suffer such disruptive interactions.

Key words: stars: formation – stars: luminosity function, mass function – globular clusters and associations: general.

1 INTRODUCTION

The advent of large, efficient infrared detectors has resulted in a fundamental shift in our understanding of star formation. From the older viewpoint that star formation was something done independently and in isolation (Shu, Adams & Lizano 1987), we now know that star formation is a group activity whereby some tens to thousands of stars form within a fraction of a parsec of each other (Clarke, Bonnell & Hillenbrand 2000). In such environments, the forming stars interact with each other on timescales comparable to their formation, resulting in a highly dynamical picture of star formation (Bate, Bonnell & Bromm 2003; Bonnell et al. 1997; Chapman et al. 1992). Infrared surveys of star forming regions have repeatedly shown that most stars form in clusters (Lada et al. 1991; Lada 1999; Clarke et al. 2000). This is found from both unbiased and pointed observations of molecular clouds and it is estimated that between 50 and 95 per cent of stars form in clusters. Massive stars are even more likely to be found in young stellar clusters (Clarke et al. 2000). Testi et al.(1997) used pointed observations of Herbig AeBe stars and found a clear relation between the star’s mass and a surrounding stellar cluster. This implies a potential causal relationship between the cluster properties and the mass of the most massive star.

The formation of stellar clusters has been an unsolved problem in astronomy due to the intrinsic difficulty of fragmenting a molecular cloud into a large number of stars, coupled with the numerical difficulties in following the subsequent dynamical evolution. The spherical, nearly homogeneous nature of young stellar clusters has generally been thought to imply that the preceding molecular cloud was itself smooth and nearly spherical (Goodwin 1998). Fragmenting such an object is extremely difficult as it requires the existence of self-gravitating clumps that have gas densities significantly higher than the mean gas density of the cloud (Bonnell 1999).

In previous simulations involving smaller, lower-mass clouds, fragmentation into many bodies occurs most readily when the cloud contains filamentary structures which easily satisfy the above condition (Bastien et al. 1991; Inutsuka & Miyama 1997; Klessen, Burkert & Bate 1998; Bonnell 1999; Klessen 2000 & Burkert 2000). Filamentary structures occupy a small fraction of the total volume of the cloud. Thus, the free-fall time of any self-gravitating perturbation in the structure is shorter than the overall dynamical time of the
system. Thus they can collapse to form fragments before colliding together, forming binary and multiple systems (Bonnell et al. 1991). A recent calculation (Bate et al. 2003) modelled the formation of ≈ 50 low-mass stars and brown dwarfs from the fragmentation of a turbulent molecular cloud. In this simulation (see also Klessen et al. 1998; Klessen & Burkert 2000), the turbulence leads to filamentary structures which then fragment as stated above. Cloud-cloud collisions have also been shown to lead to sheet-like and then filamentary structures which subsequently fragment into multiple systems (Chapman et al. 1992).

In this paper, we present the results from the first numerical simulation to follow the formation and evolution of a cluster containing more than 400 stars. The primary new insight from this simulation is that the cluster forms through a hierarchical process of many small sub-clusters which grow and merge through the subsequent dynamics to form the much larger final cluster. In Section 2 we detail the calculation. In Section 3 we describe the evolution of the forming cluster while in section 4 we discuss the resultant mass distribution. Section 5 describes the implications of a hierarchical cluster formation process for stellar properties. Our conclusions are given in section 6.

2 CALCULATIONS

We use a high resolution Smoothed Particle Hydrodynamics (SPH) (Monaghan 1992) simulation to follow the fragmentation of an initially uniform density molecular cloud containing $1000M_\odot$ in a diameter of 1 pc and a gas temperature of 10 K. SPH is a Lagrangian particle-based method that calculates fluid properties by interpolation. Calculations of gravitational forces are facilitated using a tree-structure (Benz et al. 1990). We use $5 \times 10^5$ individual SPH particles to follow the gas dynamics. We model the supersonic turbulent motions that are observed to be present in molecular clouds by including a divergence-free random Gaussian velocity field with a power spectrum $P(k) \propto k^{-4}$ where $k$ is the wavenumber of the velocity perturbations (Ostriker, Stone & Gammie 2001). In three dimensions, this measures the observed variation with size of the velocity dispersion found in molecular clouds (Larson 1981). The velocities are normalised to make the kinetic energy equal to the absolute value of the potential energy so that the cloud is marginally unbound. In contrast, the thermal energy is initially only 1 per cent of the kinetic energy. Thus the cloud contains $1000$ thermal Jeans masses,

$$M_J = \left( \frac{5R_0 T}{2GM_\odot} \right)^{3/2} \left( \frac{4}{3\pi\rho} \right)^{-1/2},$$

where $T$ is the gas temperature, $R_0$ is the gas constant, $G$ is the gravitational constant, $\mu$ is the mean molecular weight and $\rho$ is the density of the gas. Thus, in the absence of the turbulence and hence kinetic support, the cloud could be expected to fragment into order 1000 stars should sufficient structure be present (Bonnell 1999). We force the gas to remain isothermal throughout the simulation, emulating the effect of efficient radiative cooling at the low gas densities present. We do not include any feedback (radiative or kinematic) from the newly formed stars. We expect that feedback, especially from massive stars, will start to become important by the end of the simulation. The simulation was carried out on the United Kingdom’s Astrophysical Fluids Facility (UKAFF), a 128 CPU SGI Origin 3800 supercomputer.

Once fragmentation has produce a protostar, we replace the constituent SPH particles with a single sink-particle (Bate, Bonnell & Price 1995). These sink-particles, used to follow the newly formed stars, interact only through gravitational forces and by accretion of gas particles that fall into their sink-radii. Sink-particle creation occurs when the densest gas particle (at a given time) and its $\approx 50$ neighbours are self-gravitating, subvirial and occupy a region smaller than the sink-radius (200 AU). For the simulation reported here, this requires a gas density of $\gtrsim 1.5 \times 10^{-13}$ g cm$^{-3}$. Gas particles that fall within a sink-radius of 200 AU are accreted if they are bound to the sink-particle whereas all gas particles that fall within 40 AU are accreted, regardless of their properties. A minimum number of SPH particles is required to resolve a fragmentation event (Bate & Burkert 1997) implying that our completeness limit for fragmentation is approximately 0.1$M_\odot$. Thus, we cannot resolve any protostars that would form with (initial) masses below this limit. Therefore, although we do resolve the bulk of the fragmentation, there will be a number of lower-mass stars and brown dwarfs that we do not capture in our simulation. Gas accretion onto the stars then increases their masses and removes SPH particles from the simulation. In order to minimise computational expense, we smooth the gravitational forces between stars at distances of 160 AU. This means that only the widest binaries and multiple systems are resolved and that stellar collisions are not included in the simulation. The use of gravitational softening allows us to evolve the system further than has previously been achieved and thus evaluate the formation process of the stellar cluster.

3 HIERARCHICAL CLUSTER FORMATION

The initial evolution of the molecular cloud is due to the turbulent motions present in the gas. The supersonic turbulence leads to the development of shocks in the gas, producing filamentary structures (Bate, Bonnell & Bromm 2003). The shocks also remove kinetic energy (assumed to be radiated away) and thus remove the turbulent support locally (Ostriker et al. 2001). The chaotic nature of the turbulence leads to higher-density regions in the filamentary structures which, if they become self-gravitating, collapse to form stars.

Star formation occurs simultaneously at several different locations in the cloud. Figure 1 plots the column density through the molecular cloud at four different times over the $4.5 \times 10^5$ years (2.6 free-fall times, $t_f$) that we follow the evolution. The stars that form first are in the highest density gas where the dynamical timescale is the shortest. This generally occurs in the deepest parts of local potential minima. Surrounding clumps with slightly lower gas densities form additional stars. Both the stars and the residual gas are attracted by their mutual gravitational forces and fall toward each other. Gas dynamics dampen the infall velocities allowing the systems to rapidly merge to form a high density subcluster containing from five to several tens of stars. The number of stars in each subcluster increases as further star formation occurs nearby, and these stars fall
Hierarchical cluster formation

Figure 1. The stellar cluster forms through the hierarchical fragmentation of a turbulent molecular cloud. Each panel shows a region 1 parsec on a side. The logarithm of the column density is plotted from a minimum of 0.025 (black) to a maximum of 250 (white) g cm$^{-3}$. The stars are indicated by the white dots. The four panels capture the evolution of the 1000 M$_\odot$ system at times of 1.0, 1.4, 1.8 and 2.4 initial free-fall times, where the free-fall time for the cloud is $t_{ff} = 1.9 \times 10^5$ years. The turbulence causes shocks to form in the molecular cloud, dissipating kinetic energy and producing filamentary structure which fragment to form dense cores and individual stars (panel A). The stars fall towards local potential minima and hence form subclusters (panel B). These subclusters evolve by accreting more stars and gas, ejecting stars, and by mergers with other subclusters (panel C). The final state of the simulation is a single, centrally condensed cluster with little substructure (panel D). The cluster contains more than 400 stars and has a gas fraction of approximately 16 per cent.

into the existing potential wells. This process repeats itself until several hundred stars are formed and mostly contained in five subclusters. The further evolution is marked by a decreasing star formation rate as the subclusters, aided by the dissipative effects of their embedded gas, sink towards each other and finally merge to form one single cluster containing over 400 stars. The final cluster is approximately spherical in shape with a centrally condensed core as is observed in young stellar clusters (Hillenbrand 1997; Lada 1999).

The hierarchical nature of the formation process is illustrated in figure 2 which shows the evolution of the local and global stellar number-densities for the cluster. The local stellar density is calculated for each star from the minimum volume required to contain the star’s ten nearest neighbours. We use the median value of this distribution to quantify a typical local stellar density. In contrast, the global stellar number-density is calculated from the volume required to contain half of the total number of stars. This typifies the
stellar densities expected from a monolithic (homogeneous and structureless) formation scenario. We see that the local number-density increases rapidly once the first stars form and fall towards each other in their local subcluster. The local number density attains a maximum of $10^5$~stars~pc$^{-3}$, up to 100 times that for a monolithic collapse. The difference between the two values indicates that the stars occupy but a small fraction of the total volume of the star forming region. This has significant implications for the probability for interactions (see below).

The local number-density decreases after reaching a maximum during the subclustering phase. This decrease is due to the ejection of stars from the subclusters through dynamical interactions, and due to the kinetic heating during the merging of subclusters. This process erases the substructure fairly quickly, producing a single, centrally condensed cluster.

4 ACCRETION AND THE INITIAL MASS FUNCTION

In addition to acting as a reservoir for star formation and as a damping force of the stellar dynamics, gas is accreted onto individual stars, thereby increasing their masses. The stars compete for the gas, with those in the bottom of their local potential wells accreting the most and becoming the most massive stars (Bonnell et al. 1997, 2001a). Thus, the first stars to form are frequently the most massive due to this accretion process. This process, termed competitive accretion, is a leading candidate to explain the apparently universal initial mass function (IMF) of stars (Bonnell et al. 2001b; Klessen 2001).

Here, gas accretion results in final stellar masses that range from approximately 0.07 to 27~$M_\odot$. The final mass distribution, shown in figure 3, is consistent with observed IMFs (Hillenbrand 1997; Luhman et al. 2000; Meyer et al. 2000). The distribution has a near flat slope for low-mass stars, that turns into an increasingly steeper slope for more massive stars (see also Bonnell et al. 2001b; Bate et al. 2003). The higher-mass distribution is broadly consistent with a $\Gamma \approx -1$ slope ($dN(logm) = m^\Gamma dm$, where the Salpeter slope has $\Gamma = -1.35$) although could also be fit by a shallower slope for intermediate-mass stars and a steeper slope for high-mass stars. This high-mass slope is similar to the recent result where high-mass stars are formed through a combination of gas accretion and stellar mergers (Bonnell & Bate 2002). In this simulation, the gravitational potential was not softened and binary systems, formed through three-body capture, had separations as small as 10 AU.

The median and mean stellar mass are 0.43 and 1.38~$M_\odot$, respectively. At the end of the simulation, 42 per cent of the total mass remains in gas, although much of the gas is no longer bound to the cluster due to the initial turbulence. The cluster contains 494~$M_\odot$ in a 0.25 pc radius, but only 16 per cent is in the form of gas. This star formation efficiency, although comparable to that observed for young
stellar clusters (Lada 1991; Lada & Lada 1995; Clarke et al. 2000), does not include any background molecular cloud not directly involved in the cluster formation process. Furthermore, as the fraction of mass in stars is an ever increasing function of time, its value depends on when we halt the simulation. At some point in the process, feedback from the more massive stars is expected to clear the remaining gas from the system. This gas expulsion will force the cluster to expand as may be occurring in the ONC (Kroupa, Hurley & Aarseth 2001). Feedback from massive stars could also affect the accretion process. As feedback acts relatively quickly and only once the massive stars have formed, its most probable effect will be a freezing of the resultant mass function (Bonnell et al. 2001b).

5 DISCUSSION

The hierarchical nature of the formation process has many interesting implications for star formation. Subclustering means that individual stars are in regions of higher stellar number-density than they would be for a monolithic formation process (Fig. 2 Fall & Rees 1985; Scally & Clarke 2002). The high number-density of stars, coupled with the relatively small number of stars in each subcluster, and thus smaller velocity dispersion, results in closer, and stronger stellar interactions than would otherwise occur (Scally & Clarke 2002). Such stellar interactions can harden binaries to explain the closest systems (Bate, Bonnell & Bromm 2002), truncate circumstellar discs (Hall, Clarke & Pringle 1996; Bate et al. 2003) decreasing their masses and thus lifetimes, trigger fragmentation in the disc (Boffin et al. 1998; Watkins et al. 1998) and possibly even liberate a population of planets from their parent stars if planets form quickly (Bonnell et al. 2001c; Hurley & Shara 2002). The maximum number-density of stars is sufficiently high (10⁷ to 10⁸ stars pc⁻³) that stellar mergers may play a role in forming the most massive stars (Bonnell, Bate & Zinnecker 1998; Bonnell & Bate 2002).

Figure 4 plots the distribution of closest approaches for each of the 418 stars formed in the simulation. This distribution is calculated, for each star, as the minimum distance to any other passing star sometime during the evolution. The distribution extends from 10 AU to >10⁸ AU. The small peak at large separations indicates the few stars that form in relative isolation in the molecular cloud, and never enter into a cluster. Nearly half of the stars in the simulation have interactions within the 160 AU resolution limit where we start to smooth the gravitational forces. These are therefore upper limits for the actual closest approaches.

We see in figure 4 that approximately one third (140/400) of the stars have encountered another star within 100 AU, sufficiently close to perturb the circumstellar disc (McCaughrean & O’Dell 1996) or a binary system (Duquennoy & Mayor 1991). A close passage of a star is likely to disrupt a circumstellar disc down to one third of the minimum separation between stars (Hall et al. 1996), thus limiting their mass reservoirs and lifetimes (although subsequent accretion may replenish the discs [Bate et al. 2003]). Figure 4 also plots the corresponding distribution of closest approaches for more massive stars, with $m \geq 3M_\odot$. The great majority (34/40) of these massive stars have had a close interaction within 100 AU. Interactions within 100 AU result in a disc truncated to 30 AU or less (Hall et al. 1996). This suggests that many of the stars, and virtually all the massive stars, found in young stellar clusters, should have small (less than 30 AU) or non-existent discs. A similar result was found in the smaller cluster simulation of Bate et al. (2003) which resolved discs down to ~10 AU.

6 CONCLUSIONS

The results of the numerical simulation presented here point to a hierarchical formation process for stellar clusters. Star formation occurs along filamentary structures engendered in the molecular cloud due to supersonic turbulent motions. The stars fall together to form many small subclusters. These subclusters grow by accreting other stars and eventually merge to form a large-scale cluster containing over 400 stars. The hierarchical nature of the formation process means that close interactions between forming stars is much more important than would be in a monolithic formation process. Thus, stars are more likely to have suffered close interactions that can truncate their circumstellar discs, harden existing binaries and possibly liberate planets from their parent stars. In particular, the hierarchical process and the corresponding higher stellar number-densities imply that approximately one third of low-mass stars, and most high mass stars, should have had their discs truncated to within 30 AU.

Evidence for a hierarchical formation process exists in the results of Testi et al. (2000) showing the hierarchical organisation of the sub-mm cores in the Serpens molecular cloud. Detection of the subclustered phase at optical and...
near infrared wavelengths is problematic due to the large dust extinction present in the cloud. Fortunately, the upcoming Space Infrared Telescope Facility (SIRTF) will observe star forming regions in the mid-infrared and should be able to determine the level of hierarchical subclustering present in even the youngest stellar clusters.

Finally, this numerical simulation demonstrates that there is a strong link between the large-scale dynamics of star formation and the small-scale stellar and protoplanetary disc properties. This highlights the importance of a global approach to the problem. Future studies will need to include even larger-scale processes such as the formation and evolution of molecular clouds. In this way, we will be able to determine how and when star formation is initiated and thus tie star formation into Galactic evolution.

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