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The hierarchical formation of a stellar cluster

Ian A. Bonnell,[1★] Matthew R. Bate[2] and Stephen G. Vine[1]

[1]*School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS*
[2]*School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL*

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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: 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 time-scales 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 mass of the star and the density of 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, owing 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, because it requires the existence of self-gravitating clumps that have gas densities that are 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 & 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

★E-mail: iab1@st-and.ac.uk

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 subclusters, 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, and then discuss the resultant mass distribution in Section 4. 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 1000 $M_\odot$ 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 5×10^5 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 matches the observed variation with size of the velocity dispersion found in molecular clouds (Larson 1981). The velocities are normalized to make the kinetic energy equal to the absolute magnitude 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), given by

$$M_J = \left(\frac{5R_g T}{2G\mu}\right)^{3/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}, \tag{1}$$

where T is the gas temperature, R_g is the gas constant, G is the gravitational constant, μ is the mean molecular weight and ρ 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 of the order of 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 produced a protostar, we replace the constituent SPH particles with a single sink-particle (Bate, Bonnell & Price 1995). These sink-particles, used in the simulation 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 ≈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 $\gtrsim 1.5 \times 10^{-15}$ 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 on to the stars then increases their masses and removes SPH particles from the simulation. In order to minimize 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 to 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 et al. 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. Fig. 1 plots the column density through the molecular cloud at four different times over the 4.5×10^5 yr (2.6 free-fall times, t_{ff}) for which we follow the evolution. The stars that form first are in the highest-density gas, where the dynamical time-scale 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 towards 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 into the existing potential wells. This process repeats itself until several hundred stars are formed and are 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 Fig. 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 ten nearest neighbours of the star. 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

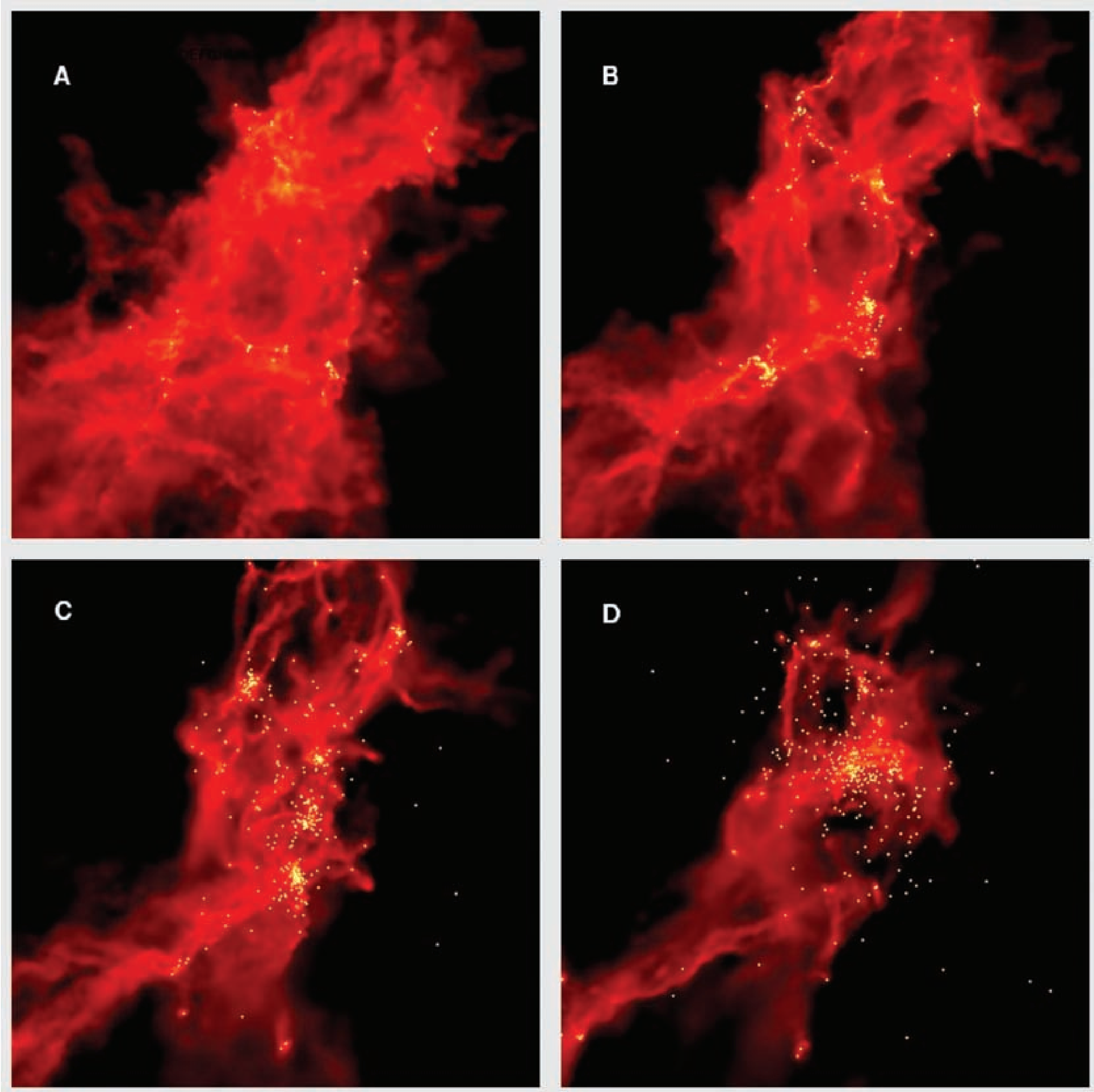

Figure 1. The stellar cluster forms through the hierarchical fragmentation of a turbulent molecular cloud. Each panel shows a region of 1 pc per side. The logarithm of the column density is plotted from a minimum of 0.025 (black) to a maximum of 250 (white) g cm^{-3}. The stars are indicated by the white 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 $t_{\mathrm{ff}} = 1.9 \times 10^5$ yr. The turbulence causes shocks to form in the molecular cloud, dissipating kinetic energy and producing filamentary structures, 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.

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 the number-density for a monolithic collapse. The difference between the two values indicates that the stars occupy only a small fraction of the total volume of the star-forming region. This has significant implications for the probability of interactions occurring (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

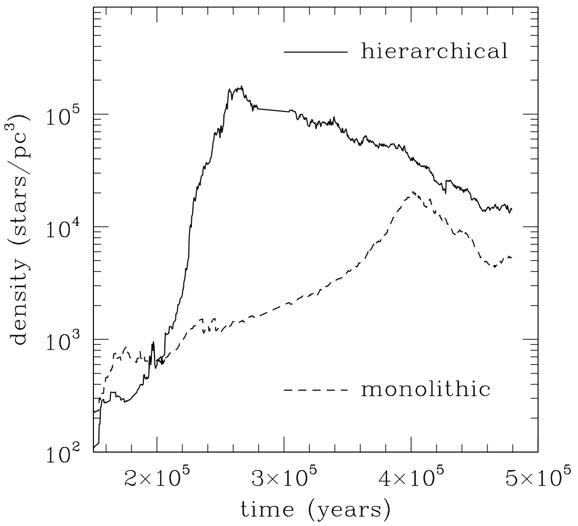

Figure 2. The evolution of the local and global stellar number-densities are plotted as a function of time in yr (the initial free-fall time is $t_{\rm ff} = 1.9 \times 10^5$ yr). The local stellar number-density (solid line) is calculated from the volume required to hold the 10 nearest neighbours of the stars; the star having the median density is shown. The global stellar number-density (dashed line) is calculated from the volume required to fully contain half of the total number of stars. This is equivalent to the local density for a monolithic formation process (see text). The rapid rise of the local (hierarchical) stellar density compared to the global (monolithic) stellar density is due to the formation of subclusters. The discrepancy between the two values decreases with time as the substructure is erased to produce a single cluster.

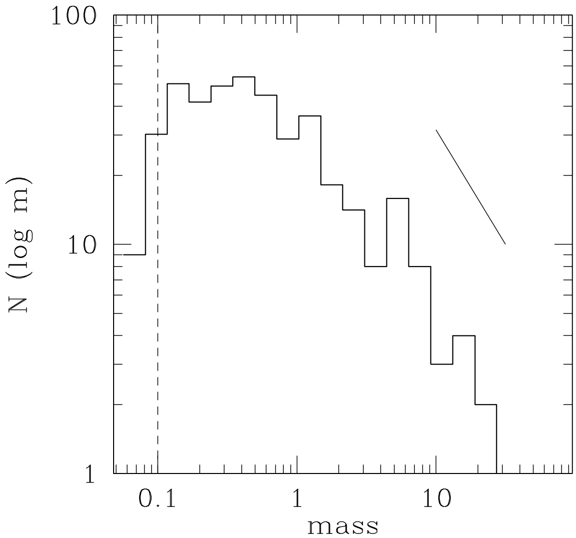

Figure 3. The final mass distribution of stars is plotted as a function of the logarithm of the mass. The distribution uses bins in the logarithm of the mass such that a Salpeter IMF has a slope of $\Gamma = -1.35$. The minimum mass for the simulation is plotted as the dashed line, whereas the diagonal line notes a $\Gamma = -1$ slope. The higher-mass stars appear to have a steeper distribution, whereas intermediate-mass stars have a shallower one. Stars below $\approx$1 M$_\odot$ have an approximately flat distribution.

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 on to 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, 2001b). Thus the first stars to form are frequently the most massive, as a result of 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. 2001c; 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 Fig. 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, which turns into an increasingly steeper slope for more massive stars (see also Bonnell et al. 2001c; Bate et al. 2003). The higher-mass distribution is broadly consistent with a $\Gamma \approx -1$ slope [$dN(\log m) = m^\Gamma \, d\, m$, where the Salpeter slope has $\Gamma = -1.35$], although it 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, in which 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, owing 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, because the fraction of mass in stars is a function which continuously increases with 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 Orion nebula cluster (ONC) (Kroupa, Aarseth & Hurley 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. 2001c).

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); can truncate circumstellar discs (Hall, Clarke & Pringle 1996; Bate et al. 2003),

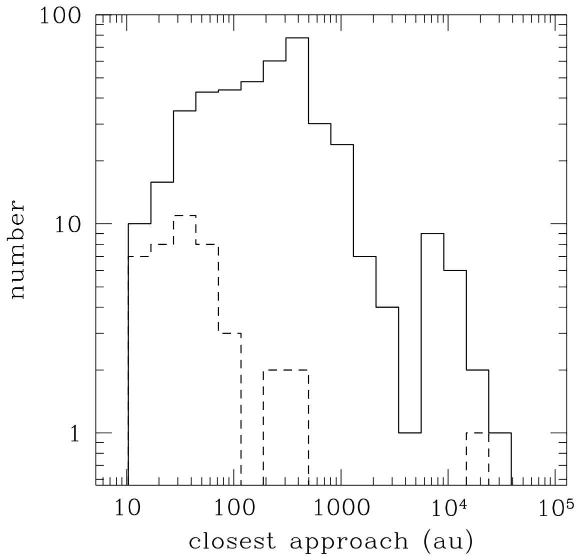

Figure 4. The distribution of minimum closest approaches for all stars (solid line) and stars more than three $M_\odot$ (dashed line) is plotted as a function of the logarithm of the minimum separation. Gravitational softening occurs for approaches within 160 au. Thus the measured values for the closest approaches are upper limits in these cases.

decreasing their masses and thus their lifetimes; can trigger fragmentation in the disc (Boffin et al. 1998; Watkins et al. 1998); and can possibly even liberate a population of planets from their parent stars, if planets form quickly (Bonnell et al. 2001a; Hurley & Shara 2002). The maximum number-density of stars is sufficiently high (10^7 to 10^8 stars pc^{-3}) that stellar mergers may play a role in forming the most massive stars (Bonnell, Bate & Zinnecker 1998; Bonnell & Bate 2002).

Fig. 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 at any time during the evolution. The distribution extends from 10 to $>10^4$ 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 Fig. 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 truncate 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). Fig. 4 also plots the corresponding distribution of closest approaches for more massive stars, with $\geqslant 3\ M_\odot$. 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 found in young stellar clusters – and virtually all the massive stars – 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 as a result of 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 are much more important than they 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), which shows the hierarchical organization of the submillimetre cores in the Serpens molecular cloud. Detection of the subclustered phase at optical and near-infrared wavelengths is problematic, as a result of 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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