Core dissolution and the dynamics of massive stars in young stellar clusters

S. G. Vine* and I. A. Bonnell
School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS

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ABSTRACT
We investigate the dynamical effects of rapid gas expulsion from the core of a young stellar cluster. The aims of this study are to determine (i) whether a mass-segregated core survives the gas expulsion and (ii) the probable location of any massive stars that have escaped from the core. Feedback from massive stars is expected to remove the gas from the core of the cluster first, as that is where most massive stars are located. We find that gas expulsion has little effect on the core for a core star formation efficiency, $\epsilon$, of greater than 50 per cent. For lower values of $\epsilon$ down to 20 per cent, a reduced core survives containing the majority of the massive stars while some of them are dispersed into the rest of the cluster. In fact, we find that ejected stars migrate from radial to tangential orbits due to stellar encounters once they leave the core. Thus, the location of massive stars outside of the core does not exclude their forming in the dense cluster core. Few massive stars are expected to remain in the core for $\epsilon$ lower than 20 per cent.

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

1 INTRODUCTION
The origin of massive stars is a poorly understood phenomena. One clue to their formation is that they are generally found in the dense cores of young stellar clusters (Hillenbrand 1997; Carpenter & Sanders 1998; Clarke, Bonnell & Hillenbrand 2000; Mermilliod & Garcia 2001; Zinnecker, McCaughrean & Wilking 1993). Their location in these very young systems cannot generally be explained by dynamical mass segregation (Bonnell & Davies 1998). Higher than observed primordial core densities (Kroupa 2002; Kroupa, Aarseth & Hurley 2001) can cause rapid mass segregation in the core region.

The central location of massive stars must tell us something about their birth. One possibility is that the accretion rates in the centre of the cluster are higher due to the deeper potential wells (Bonnell et al. 2001; Bonnell & Bate 2002) and that therefore the protostars that are present in the core are able to accrete up to a high mass (e.g. Behrend & Maeder 2001; Klessen 2001). An additional possibility is that as the stars in the core accrete, the core contracts due to the increase in the potential energy. The increase in stellar density may then be sufficient such that collisions between intermediate mass stars occur to form the massive stars (Bonnell, Bate & Zinnecker 1998; Bonnell & Bate 2002). One of the successes of these models is that they naturally account for the formation of massive stars in the centres of stellar clusters. These models predict the location of massive stars at the end of the accretion, mass build-up phase. At this point the cluster contains significant mass in gas which can still affect the cluster dynamics.

Once a massive star has formed in a cluster, it can have dramatic effects on its surroundings. The strong winds and ionizing photons inject significant energy into the surrounding gas which will begin to expand, eventually being cleared from the cluster. This gas removal has two effects: first, it halts any residual accretion or star formation; secondly, if the gas still comprises a significant fraction of the total mass, the cluster will expand to reflect the new, lower potential. Simulations of this process (Geyer & Burkert 2001; Kroupa et al. 2001; Boily & Kroupa 2003) have concentrated on the global evolution of the cluster as the gas is removed. They find that if the gas is a small fraction of the total mass, or if it is removed slowly relative to the dynamical time-scale, then the cluster can retain significant fraction of its initial stars. Kroupa et al. (2001) suggests that early dynamical mass segregation of the most massive stars can survive during and after a gas expulsion phase. Kroupa (2000) has presented results specifically for models of the Orion Nebula Cluster (ONC) including the gas expulsion scenario reflecting the situation we model here, but without primordial mass segregation.

In this paper, we are concerned with the dynamical evolution of the cluster core when the gas is removed. Gas removal occurs from inside out as the massive stars inject energy into their environment. The core of the cluster will be cleared first and the core stars will be affected by the gas removal before the rest of the cluster. This has serious implications for the dynamics of the massive stars, their location in the cluster, or even their possible ejection from the cluster. We address these questions using the numerical simulations presented below.

*E-mail: sgv@st-andrews.ac.uk

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2 GAS EXPULSION FROM CORE

Gas removal occurs as a result of the injection of energy from the massive stars in the core. The energy produced by these O- and B-type stars can take the form of strong stellar winds of up to a few \( \times 1000 \text{ km s}^{-1} \) (Churchwell 1999) or the formation of an expanding \( \text{H II} \) region (\( t_{\text{HII}} \approx 10 \text{ km s}^{-1} \)). In both cases, the expansion velocity is significantly higher than the velocity dispersion seen in young stellar clusters due to the higher initial density. If the core of the cluster is about 0.1 pc, this means that the crossing time for the core (\( t_{\text{cross}} \approx 5 \times 10^4 \text{ yr} \)) is at least an order of magnitude larger than the gas expulsion time. We may then assume that the period of gas expulsion has negligible effect on the dynamics of the constituent stars in the core, and so we assume instantaneous gas expulsion. Thus we incorporate an initial surplus of kinetic energy into the core stars which results in their being no longer in virial equilibrium. This implies that the gas is only removed from the core as stars further out remain in virial equilibrium. The time-scales (\( \approx 10^5 \text{ yr} \)) and radial extent (\( \approx 0.1 \) pc) reflect the situation in an ultra-compact \( \text{H II} \) region where a stellar wind has evacuated a small inner region before stalling due to mass loading (Lizano et al. 1996), ram pressure of the infalling gas (Wood & Churchwell 1989), or other possible mechanisms (Churchwell 1999).

3 NUMERICAL SIMULATIONS

Over the time-scales involved it is only gravitational forces which play a significant role in the subsequent evolution. Thus the system is sufficiently modelled with a pure \( N \)-body simulation. The numerical simulations reported here were performed using the \textsc{nbody2} code (Aarseth 2001). This code is extremely efficient and accurate at following a stellar dynamical system for tens to a hundred dynamical times. It includes the AC neighbour scheme (Ahmad & Cohen 1973) and a softened potential (here \( r_{\text{soft}} \lesssim 0.1 r_{\text{core}} \)) which minimizes computational expense at the cost of not following any (close) binary systems. As we are following the stellar dynamics over only a few local dynamical times where distant interactions dominate, \textsc{nbody2} is sufficient for our needs.

Our cluster is assumed to be in a virialized state prior to gas expulsion; from arguments of the star formation time-scale compared to the crossing times, typical systems may indeed be near to virial equilibrium (Boily & Kroupa 2003). The stellar system consists of 1500 massive stars in the core region (\( t_{\text{HII}} \approx 10 \text{ km s}^{-1} \)). In both cases, the expansion velocity is significantly higher than the velocity dispersion seen in young stellar clusters due to the higher initial density. If the core of the cluster is about 0.1 pc, this means that the crossing time for the core (\( t_{\text{core}} \approx 5 \times 10^4 \text{ yr} \)) is at least an order of magnitude larger than the gas expulsion time. We may then assume that the period of gas expulsion has negligible effect on the dynamics of the constituent stars in the core, and so we assume instantaneous gas expulsion. Thus we incorporate an initial surplus of kinetic energy into the core stars which results in their being no longer in virial equilibrium. This implies that the gas is only removed from the core as stars further out remain in virial equilibrium. The time-scales (\( \approx 10^5 \text{ yr} \)) and radial extent (\( \approx 0.1 \) pc) reflect the situation in an ultra-compact \( \text{H II} \) region where a stellar wind has evacuated a small inner region before stalling due to mass loading (Lizano et al. 1996), ram pressure of the infalling gas (Wood & Churchwell 1989), or other possible mechanisms (Churchwell 1999).

The half-mass radius of the cluster, \( r_{\text{half}} = 0.8 \) pc. We choose the core radius to be \( r_{\text{core}} = 0.08 \) pc, which is 0.1 times the half-mass radius; it is this region within \( r_{\text{core}} \) in which we consider the gas expulsion to be effective. The mass of our cluster is 1200 \( M_{\odot} \), and \( N = 1500 \) so that the mean stellar mass, \( M_{\star} = 0.8 \) \( M_{\odot} \). Finally, we follow the evolution of the core of the cluster to \( t \gtrsim 1.0 \) Myr (~20 \( t_{\text{cross}} \)), by which time the dynamical evolution that we are interested in will have occurred.

4 RUN PARAMETERS

The effect of gas removal is included by way of a super-virial distribution of the stellar velocities inside the core of the cluster. The kinetic energy of these stars is taken to be that required to balance the energy produced by these O- and B-type stars can take the form of strong stellar winds of up to a few \( \times 1000 \text{ km s}^{-1} \) (Churchwell 1999) or the formation of an expanding \( \text{H II} \) region (\( t_{\text{HII}} \approx 10 \text{ km s}^{-1} \)). In both cases, the expansion velocity is significantly higher than the velocity dispersion seen in young stellar clusters due to the higher initial density. If the core of the cluster is about 0.1 pc, this means that the crossing time for the core (\( t_{\text{cross}} \approx 5 \times 10^4 \text{ yr} \)) is at least an order of magnitude larger than the gas expulsion time. We may then assume that the period of gas expulsion has negligible effect on the dynamics of the constituent stars in the core, and so we assume instantaneous gas expulsion. Thus we incorporate an initial surplus of kinetic energy into the core stars which results in their being no longer in virial equilibrium. This implies that the gas is only removed from the core as stars further out remain in virial equilibrium. The time-scales (\( \approx 10^5 \text{ yr} \)) and radial extent (\( \approx 0.1 \) pc) reflect the situation in an ultra-compact \( \text{H II} \) region where a stellar wind has evacuated a small inner region before stalling due to mass loading (Lizano et al. 1996), ram pressure of the infalling gas (Wood & Churchwell 1989), or other possible mechanisms (Churchwell 1999).

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In practice, we take our initial system as described above and increase the kinetic energies of the stars in the core by the following energy argument:

\[
[M_{\text{gas}} + M_{\text{stars}}]v_{\text{old}}^2 = M_{\text{stars}}v_{\text{new}}^2,
\]

Table 1. Values of the initial gas ratio parameter used, and the equivalent star formation efficiency, \( \epsilon \).

| \( M_{\text{gas}} \) \( M_{\text{stars}} \) | \( \epsilon \) (per cent) |
|----------------|------------------|
| 0.25 | 80 (per cent) |
| 1.0  | 50 (per cent)  |
| 2.0  | 33 (per cent)  |
| 3.0  | 25 (per cent)  |
| 4.0  | 20 (per cent)  |
| 5.0  | 17 (per cent)  |
we can then directly scale the core velocities such that

\[ v_{\text{core}}^2 = \frac{v_{\text{rad}}^2}{\epsilon} \]  

(2)

where we have introduced the star formation efficiency, in terms of the gas ratio, as

\[ \epsilon = 1 - \left(1 + \frac{M_{\text{gas}}}{M_{\text{stars}}}ight) \]  

(3)

For each value of the initial parameter, \( M_{\text{gas}}/M_{\text{stars}} \), eight initial realizations were constructed using a different random seed for each. This helps to extract the mean behaviour of the massive stars in the clusters and not individual fluctuations, due to their small numbers.

5 RESULTS

The purpose of our investigation is to discover whether a mass-segregated core will survive after a gas expulsion phase, and also to gain general insight to the subsequent motions of the massive stars. The following results examine properties of the core: mass segregation, average mass within the core, fraction of stars remaining in the core, and core survivability. We also look at the phase-space evolution of the individual massive stars by examining their radial evolution and their angular momentum.

5.1 Mass segregation

We investigate the evolution of mass segregation in the core, which, in this case, amounts to the survival of the most massive stars in the core.

After 0.62 Myr (~12\( t_{\text{cross}} \)) we take the ratio of the number of stars within \( r \) to the number initially contained within a given radii \( (R_{\text{core}} \text{ and } 2R_{\text{core}}) \). This cumulative number ratio is calculated independently for three stellar mass ranges: \( M_* \leq 1.08 M_\odot \): 1.08 < \( M_* \leq 5.4 M_\odot \); and 5.4 \( M_\odot \leq M_* \), shown as a thin line, a medium line and a thick line, respectively, in Figs 2(a)–(d). These figures show the cumulative number ratio for a \( M_{\text{gas}}/M_{\text{stars}} \) parameter of (a) 0.25, (b) 1.0, (c) 3.0, and (d) 5.0. The top and bottom panels in each figure show the cumulative number ratio normalized to \( 2R_{\text{core}} \) and \( R_{\text{core}} \) respectively. The initial state of the system at \( t = 0 \) is shown as a dashed line in each figure. These figures are the combined results of all realizations for each particular \( M_{\text{gas}}/M_{\text{stars}} \).

In particular, we are interested in the highest mass range, which we consider to represent the OB type stars in the cluster. Clusters with lower values of \( M_{\text{gas}}/M_{\text{stars}} \) (Figs 2a and b) show little significant change in the distribution of the massive stars, in fact the lower mass stars decrease in number more than the massive stars, making the core slightly more segregated. However, as soon as the effective kick to the core stars becomes large enough to boot out the massive stars we see a dramatic decrease in all the stellar numbers. Figs 2(c) and (d) show a decrease in the actual massive star numbers by 20 and 70 per cent, respectively.

An alternative and perhaps more intuitive way of looking at the mass segregation is to look at the average stellar mass within a certain radius, or, as we do in this case, the 100 stars nearest to the centre of mass. Fig. 3 shows that there is an almost linear decrease in \( \overline{M_{\text{gas}}} \) for each value of the \( M_{\text{gas}}/M_{\text{stars}} \) parameter after \( M_{\text{gas}}/M_{\text{stars}} = 1.0 \). Also shown, as a vertical bar on each point, is the range due to the variation in the initial realizations for each parameter. This clearly shows that as the stars are ejected out into the rest of the cluster, the massive stars are less of a characteristic of the central cluster regions. Although the mean stellar mass is slightly greater than the cluster mean \( \langle M_* \rangle = 0.8 M_\odot \), at \( M_{\text{gas}}/M_{\text{stars}} = 5.0 \) the mass segregation is much less significant.

5.2 Radial evolution of massive stars

The question now arises of what becomes of the massive stars which the core has ejected. For comparison with observed clusters, we would like an idea of where the stars are located in our simulations. We examine the radial distances of the most massive stars from the centre of mass with respect to time. Typical examples are shown in Fig. 4.

These figures illustrate typical evolution of the 10 most massive stars which were initially in the cluster core, each figure showing one realization for each value of the parameter \( M_{\text{gas}}/M_{\text{stars}} \). As we have seen in the previous section, for a larger \( M_{\text{gas}}/M_{\text{stars}} \), a greater number of massive stars leave the core. Fig. 4 shows this trend explicitly and we can see the subsequent radial motion of the stars after gas expulsion. The grey region in the panels is the initial core in which the gas is assumed to have been removed. The half-mass radius, \( R_{\text{half}} \), is also shown as a solid line at 0.8 pc.

For a \( M_{\text{gas}}/M_{\text{stars}} = 0.25 \), the panel shown at the top left in Fig. 4 is typical for all realizations, and similar results are seen for \( M_{\text{gas}}/M_{\text{stars}} = 1.0 \) (top middle). For \( M_{\text{gas}}/M_{\text{stars}} = 2.0 \) (top right) it is more typical to see a couple of the stars ejected from the core but within the half mass radius. For \( M_{\text{gas}}/M_{\text{stars}} = 3.0 \), 2 to 4 stars are ejected beyond \( R_{\text{half}} \) and another couple beyond \( R_{\text{core}} \) (bottom left). Fig. 5 shows a resulting configuration in the \( x-y \) plane. There is a resemblance to the configuration of the massive stars in the ONC, showing that this is a possible mechanism leading to ONC-type structures, where some of the massive stars are located a significant distance from the core. However, without observational velocities we cannot say how likely it is.

The tendency when \( M_{\text{gas}}/M_{\text{stars}} = 4.0 \) (bottom middle panel of Fig. 4) is for more massive stars to be completely ejected and still two or so to be found between \( R_{\text{core}} \) and \( R_{\text{half}} \). It is likely that most stars are ejected from the core for \( M_{\text{gas}}/M_{\text{stars}} = 5.0 \) and also beyond \( R_{\text{half}} \) (Fig. 4, bottom right).

5.3 Velocity evolution

Observational measurements of velocities (proper motions as well as line-of-sight velocities) are now feasible with space-borne instruments; such velocities may provide strong evidence to decide on the spatial origin of the stars. It is therefore of interest to explore the kinematics that result from gas expulsion and the ejection of massive stars from the core of the cluster.

The expectation is that stars which receive significant velocity increases escape the cluster on near-radial orbits. Instead, we show below that these stars generally have more tangential than radial motions. This can be explained by the interactions that occur as a result of the discrete nature of the stellar cluster. We can suppose that the orbits of these stars will encounter a great range of stars on highly varied orbits, its velocity signature will vary greatly, leaving the angular momentum measured with respect to the centre of the core density peak, \( |L_z|/|L_x| \), as the most robust general measure of the subsequent evolution of the stars. This measure of angular momentum is not affected by the motion of the core over the duration of these simulations.

Fig. 6 shows the ratio of the angular momentum at time \( t = 0.62 \) Myr (12\( t_{\text{cross}} \)) to the initial value immediately after the velocity kick \( |L_z|/|L_x| \). All stars over 5 \( M_\odot \), in all realizations of the parameter \( M_{\text{gas}}/M_{\text{stars}} \), are shown. We have distinguished the stars...
Figure 2. Cumulative number ratio for different mass ranges of stars, and different initial gas ratios averaged over all realizations. The vertical axis shows the cumulative numbers of stars divided by the total number contained within the region of interest. Radius is shown along the horizontal axis. Three mass ranges are shown, indicated by a thick line \( M_\ast \geq 5.4 \, M_\odot \), a medium line \( 5.4 > M_\ast > 1.08 \, M_\odot \), and a thin line \( M_\ast \leq 1.08 \, M_\odot \). The dashed lines represent the initial state of the clusters for each mass range. The lower panel in each figure shows the cumulative number ratio normalized to the initial numbers of stars within \( R_{\text{core}} \), and the upper panel within \( 2R_{\text{core}} \). The upper figures, (a) \( M_{\text{gas}}/M_{\text{stars}} = 0.25 \) and (b) \( M_{\text{gas}}/M_{\text{stars}} = 1.0 \), show little evolution; figure (c) \( M_{\text{gas}}/M_{\text{stars}} = 3.0 \) shows significant numbers of stars lost from the core; and figure (d) \( M_{\text{gas}}/M_{\text{stars}} = 5.0 \) show 70 per cent of the massive stars are lost from within \( R_{\text{core}} \).

by their radial position at time \( t = 0.62 \) Myr: those within \( R_{\text{core}} \) are shown as small open circles, those beyond \( R_{\text{core}} \) shown as filled stars, and those beyond 5\( R_{\text{half}} \) (those which have left the cluster) are shown as open triangles. Each radial range is shifted slightly to left or right for clarity.

The first effect to notice is the increasing spread of angular momentum with increasing initial \( M_{\text{gas}}/M_{\text{stars}} \), such that for \( M_{\text{gas}}/M_{\text{stars}} = 5.0 \) the gain in \( |L| \) for some stars reaches \( \sim 1000 \). The other striking feature is the bimodality between stars that have stayed in the core and stars which have left it. Stars remaining in the core have angular momenta distributed around their initial values, although plenty of angular momentum exchange has occurred resulting in \( 100 > |L_T|/|L_0| > 0.01 \). The core escapers, however, almost exclusively increase their angular momenta such that \( 1000 > |L_T|/|L_0| > 1 \).

Such a result indicates that the higher velocity massive stars must have encountered a greater number of stars with a broader range of orbits on their journey outward through the cluster. A combination of their gain in \( |L| \) and high velocity puts many stars on large tangential orbits which do not pass through the core. This was seen in Fig. 4 as stars are ejected from the core but are seen to orbit beyond \( R_{\text{core}} \). As a consequence of this the velocities of the ejected...
Figure 3. The figure shows the average mass of the 100 stars nearest the centre of mass of the cluster for each value of $M_{\text{gas}}/M_{\text{stars}}$. The vertical bars show the resulting range within the 8 different realizations of each run. A roughly linear relation between $M_{\text{gas}}/M_{\text{stars}}$ and $M_{100}$ after $M_{\text{gas}}/M_{\text{stars}} = 1.0$.

Figure 4. Radial distance from density centre versus time for the 10 most massive stars initially found in the cluster core. These figures represent a single individual realization for each value of the parameter $M_{\text{gas}}/M_{\text{stars}}$. The grey area is the core region in which the initial velocity kick is given, and a solid line representing the initial $R_{\text{half}}$ is shown. The thickness of the individual lines relate to the mass of the star, thickest being most massive. The realizations have been chosen to illustrate the typical behaviour of the system for each $M_{\text{gas}}/M_{\text{stars}}$, where no stars leave the core for a value of 0.25 and all leave the core for $M_{\text{gas}}/M_{\text{stars}} = 5.0$. The apparent kink in the path of stars that leave the core is due to the time-sampling of the simulations and is not a physical affect. The value of the lower mass limit of stars shown is also indicated in each figure.

Figure 5. The $x-y$ plot of a typical realization with $M_{\text{gas}}/M_{\text{stars}} = 3$ after $t = 0.62$ Myr ($\sim 12 t_{\text{cross}}$). Here we notice two stars remain bound within $R_{\text{half}}$ (large dashed circle) and the rest forming a bound (but less dense) core shown in the inset.
massive stars will be seen to have predominantly tangential motions to the cluster core.

There is a further subset of stars which appear to leave the cluster entirely (a limit of \(5R_{\text{vir}}\) is used to identify cluster leavers); these are shown as open triangles in Fig. 6. The physical velocities of these stars range from 10 to 40 km s\(^{-1}\), a result which allows us to rule out the existence of observed high velocity stars (\(\sim 200\) km s\(^{-1}\)) as a consequence of the two-body interactions which occur in this scenario.

5.4 Core survival

To summarize the results in terms of the original question posed – how does gas expulsion from the core affect the core’s survival? – we have plotted (Fig. 7) the fraction of massive stars remaining in the core for each value of \(M_{\text{gas}}/M_{\text{stars}}\). It is perhaps a matter of definition as to what constitutes a surviving core, and in this case we take a value of 50 per cent of the original massive stars. More precisely, we say that if more than half the core (or rather its constituent massive stars) is dissipated subsequent to the gas expulsion phase then the core does not survive. This is supported by the fact that the actual number of massive stars in the core are of the order of a few; once half of these have left the system there may be only one or two left, which is not enough to constitute a core.

The relation between \(M_{\text{gas}}/M_{\text{stars}}\) and the core survivability is fairly smooth (Fig. 7). The core is relatively undisturbed up to \(M_{\text{gas}}/M_{\text{stars}} = 2.0\), then becomes proportionately more disrupted with greater \(M_{\text{gas}}/M_{\text{stars}}\) but survives (by our definition) to a \(M_{\text{gas}}/M_{\text{stars}}\) of over 4.0.

6 DISCUSSION

We have modelled the gas expulsion from the core of a stellar cluster via a rapid change in the stellar velocities and thus an effective change in the gravitational potential of the core. This is taken to mimic the evolutionary stages of a hyper- or ultra-compact H\(\text{II}\) region. Their evolution is likely to be driven by a stellar wind which stalls as mass-loading occurs in order to explain their relatively long lifetimes (\(\sim 10^5\) yr). Thus, we assume an instantaneous removal of gas from the core of the cluster but assume that the gas content of the rest of the cluster is for the most part unaffected during our simulation.

The formation of massive stars is largely an unsolved problem. What is certain is that they require high accretion rates in order to build the star up over time-scales of \(10^5\) to \(10^6\) yr. This is true whether they form just through accretion (Behrend & Maeder 2001; Bonnell & Bate 2002) or even through stellar mergers, which require high accretion rates to reach the necessary stellar density (Bonnell et al. 1998; Bonnell & Bate 2002). The most obvious way that high accretion rates can occur is by situating the forming massive star in the centre of a stellar cluster. In this way, the overall cluster potential funnels matter down to the protomassive star where it can preferentially accrete it due to its position and mass (Bonnell et al. 2001). This naturally results in a mass segregated stellar cluster even while deeply embedded.

The simulations reported here show that gas expulsion is unlikely to remove this ‘initial’ mass segregation unless the gas comprises more than 83 per cent of the total mass in the core. The core, being where the accretion rates are highest and the most massive stars are located, has therefore the lowest gas fraction of the system and is the most likely to be dominated by the mass in stars. Thus, the mass segregation which results from the cluster formation and gas accretion is likely to remain unaffected by the gas expulsion stage in the cluster.

In some young clusters such as the ONC, a few relatively massive stars are found to be some distance from the core of the cluster. If the above scenarios for the formation of massive stars are correct in that they form in the denser parts of the cluster, then we need to explain
how they could have moved from the core to, for example, the half-mass radius of the cluster. The numerical simulations reported here offer one possibility. The massive stars could have originated in the core but escaped from this region during the gas expulsion phase (Williams 2002). We see that for gas fractions of greater than 83 per cent, some of the massive stars do escape the core and can be found virtually anywhere in the cluster. They will of course sink back to the cluster core, but on longer time-scales than the age of the cluster (Bonnell & Davies 1998).

The difficulty in the above is that relatively high gas fractions are required which may not be present in the core of the cluster. An alternative mechanism to explain the location of the massive stars not in the core would be stellar interactions with a binary or multiple system which eject one or more of the stars. Some of these ejections could be the high-velocity OB runaways while those that do not garner such a large velocity boost remain in the cluster but outside the core. If that is the case, their dynamics should resemble the massive stars ejected from the core in the simulations reported here.

7 CONCLUSION

Using a series of N-body simulations we follow the dynamical evolution of massive stars which are assumed to be initially located in the core of the cluster. The stars undergo evolution because of very rapid gas expulsion (assumed to be instantaneous) which is parametrized by the ratio of gas mass to stellar mass in the core ($M_{\text{gas}}/M_{\text{stars}}$). This parameter is varied from 0.25 to 5.0 (equivalent to a star formation efficiency of 80 per cent down to 17 per cent).

We find that the initial mass segregation in the core is destroyed for an initial gas mass of greater than 4 times the stellar mass, or a star formation efficiency of less than 20 per cent. The initial conditions used are of a relaxed, mass-segregated cluster. The massive stars are therefore approximately in equipartition with low-mass stars in the core. Their lower velocities result in a lower probability of escaping the core once the gas too has been removed. This explains the relatively high value of $M_{\text{gas}}/M_{\text{stars}}$ required to dissolve the core. Otherwise, for star formation efficiencies of more than 20 per cent, but less than 50 per cent some massive stars will be ejected from the core and maybe beyond. However these ejected stars are found to have predominantly tangential motions, gaining angular momentum due to encounters along the way.

REFERENCES

Aarseth S. J., 2001, New Astron., 6, 277
Ahmad A., Cohen L., 1973, J. Comput. Phys., 12, 389
Behrend R., Maeder A., 2001, A&A, 373, 190
Boily C. M., Kroupa P., 2003, MNRAS, 338, 665
Bonnell I. A., Bate M. R., 2002, MNRAS, 336, 659
Bonnell I. A., Davies M. B., 1998, MNRAS, 295, 691
Bonnell I. A., Bate M. R., Zinnecker H., 1998, MNRAS, 298, 93
Bonnell I. A., Bate M. R., Clarke C. J., Pringle J. E., 2001, MNRAS, 323, 785
Carpenter J. M., Sanders D. B., 1998, AJ, 116, 1856
Churchwell E., 1999, in NATO ASIC Proc. 540, The Origin of Stars and Planetary Systems Massive Star Formation. Kluwer, Dordrecht, p. 515
Clarke C. J., Bonnell I. A., Hillenbrand L. A., 2000, Protostars and Planets IV. Univ. Arizona Press, Tucson, p. 151
Geyer M. P., Burkert A., 2001, MNRAS, 323, 988
Hillenbrand L. A., 1997, AJ, 113, 1733
Hillenbrand L. A., Hartmann L. W., 1998, ApJ, 492, 540
Klessen R. S., 2001, ApJ, 550, L77
Kroupa P., 2000, New Astron., 4, 615
Kroupa P., 2002, Sci, 295, 82
Kroupa P., Aarseth S., Hurley J., 2001, MNRAS, 321, 699
Lizano S., Canto J., Garay G., Hollenbach D., 1996, ApJ, 468, 739
Mermilliod J., García B., 2001, in IAU Symp. Vol. 200, Spectroscopic Binaries in Young Open Clusters. Astron. Soc. Pac., San Francisco, p. 191
Williams J., 2002, in Paul A. Crowther, ed., ASP Conf. Ser. Vol. 267, Hot Star Workshop III: The Earliest Stages of Massive Star Birth. Astron. Soc. Pac., San Francisco, p. 237
Wood D. O. S., Churchwell E., 1989, ApJS, 69, 831
Zinnecker H., McCaughrean M. J., Wilking B. A., 1993, in Protostars and Planets III The initial stellar population. Univ. Arizona Press, Tucson, p. 429

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