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Mass segregation in young stellar clusters

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ABSTRACT

We investigate the evolutionary effect of dynamical mass segregation in young stellar clusters. Dynamical mass segregation acts on a time-scale of order the relaxation time of a cluster. Although some degree of mass segregation occurs earlier, the position of massive stars in rich young clusters generally reflects the cluster's initial conditions. In particular, the positions of the massive stars in the Trapezium cluster in Orion cannot be due to dynamical mass segregation, but indicate that they formed in, or near, the centre of the cluster. Implications of this for cluster formation and for the formation of high-mass stars are discussed.

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

1 INTRODUCTION

The advent of a new generation of detectors has significantly changed our perception of how stars form. The ability to penetrate deeper into star-forming regions using infrared cameras has led to improved observations, and has increased our catalogue of known young stellar objects. It is becoming increasingly clear that most stars do not form in isolation but are instead born in relatively rich clusters (Lada, Strom & Myers 1993; Zinnecker, McCaughrean & Wilking 1993). These clusters range from small associations of some tens of stars (e.g. Hillenbrand et al. 1995; Testi et al. 1997) to clusters of several hundreds of stars (Lada et al. 1991) and very rich dense clusters containing on the order of a thousand or more stars such as the Trapezium cluster in Orion (McCaughrean & Stauffer 1994; Hillenbrand 1997).

These clusters are typically found to have their most massive stars in the cluster centre (Zinnecker et al. 1993; Hillenbrand & Hartmann 1998). This segregation of the massive stars could be due to the initial conditions of the cluster, and thus reflect its formation scenario. Their mass is then unlikely to represent the Jeans mass when fragmentation occurred, as the stellar density implies a much lower mass (Zinnecker et al. 1993). One possibility is that stars acquired additional mass from subsequent accretion (e.g. Zinnecker 1982). In a cluster, the stars near the centre accrete the most material due to their location at the bottom of the cluster potential well (Bonnell et al. 1997).

Alternatively, mass segregation could be due to an evolutionary effect whereby the massive stars form elsewhere in the cluster but subsequently sink to the centre of the cluster through interactions with the much more numerous low-mass stars. This occurs as high-mass stars preferentially lose energy to low-mass stars through two-body encounters. We investigate this second possibility through numerical N-body simulations of young clusters, explicitly comparing the distribution of massive stars after a few crossing times with observations of the Trapezium cluster (Hillenbrand 1997; Hillenbrand & Hartmann 1998). Careful analysis of this cluster has ascertained that the Trapezium is the core of, and is thus dynamically linked to, the larger scale Orion nebula cluster (ONC) (Hillenbrand & Hartmann 1998). The aim of this paper is to investigate the time-scale necessary for mass segregation to occur, and thus to set constraints as to the probable initial distribution (i.e., sites of formation) of the massive stars within the cluster.

Realistic investigations of clusters containing a few hundred to a thousand stars and a spectrum of stellar masses have heretofore concentrated on their long-term evolution (Terlevich 1987; Kroupa 1995; de la Fuente Marcos 1995, 1997). Mass segregation in these clusters occurs before core-collapse, and is largely unchanged thereafter (Giersz & Heggie 1996). Here we are concerned with the onset of mass segregation. Specifically we are interested in the degree of mass segregation that occurs on time-scales of a few crossing times of the cluster.

Numerical simulations of the early dynamical evolution of model clusters are presented in Section 2. In Section 3 we discuss the effects on the mass-segregation time-scale of changing the initial conditions in these clusters. In Section 4 we consider whether mass-segregation is responsible for the location of the massive stars in the ONC. In Section 5 we consider the implications of our results for models of cluster formation. Our conclusions are presented in Section 6.

2 CALCULATIONS

In this paper we present numerical simulations of mass segregation in young clusters containing between 50 and 1500 stars, appropriate from observations of clustered star formation (Lada et al. 1993; Zinnecker et al. 1993). The calculations were performed with the NBODY2 code (Aarseth 1985, 1998). The stellar number density distribution is either uniform, or a Plummer distribution, or an isothermal sphere ($n \propto r^{-2}$). The stars are assumed to be single, although for the short time-scales followed here the effects of a primordial binary population should not be significant. The effect of gas present in the clusters is also neglected. Significant amounts of gas can only increase the time required for mass segregation (see Section 2.1). The time-scales for dynamical mass segregation that we find here are therefore lower limits for clusters that contain significant amounts of gas (e.g., $M_{\rm gas} \gtrsim M_{\rm stars}$).

The masses are chosen from a mass function given by Salpeter for stars greater than 1 $M_\odot$ and Kroupa, Tout & Gilmore (1990) for stars less than 1 $M_\odot$, i.e.,

$$f(m) = C_1 m^{-2.35}; \qquad m > 1\ M_\odot,$$

$$f(m) = C_2 m^{-2.2}; \qquad 0.5 < m < 1\ M_\odot,$$

$$f(m) = C_3 m^{-1.1}; \qquad m_{\rm min} < m < 0.5\ M_\odot.$$

The minimum mass, $m_{\rm min}$, is set to 0.1 $M_\odot$, while the maximum mass depends on the cluster size (as is expected from randomly sampling the mass function): $m_{\rm max} = 5\ M_\odot$ for clusters of 50 stars, $m_{\rm max} = 15\ M_\odot$ for clusters of 250 stars, $m_{\rm max} = 25\ M_\odot$ for clusters of 1000 stars, and $m_{\rm max} = 50\ M_\odot$ for clusters of 1500 stars (as is found in the Trapezium). A star of a given mass is assigned a position randomly within the stellar density distribution. In some cases, the most massive stars are assigned positions within specified radii, in order to investigate the effect of the initial distribution on subsequent segregation. The velocity dispersion is initially constant throughout the cluster, and is thus also independent of the stellar mass. The clusters are initially spherical and in global virial equilibrum. The dynamical evolution of clusters where these conditions are relaxed is discussed in Section 3.

A number of different realizations were run for each cluster considered, in order to establish the uncertainty in the quantitative conclusions we draw from the simulations. In each simulation we evolve the cluster for 15 crossing times, measuring the degree of mass segregation as a function of time. The crossing time, $t_{\rm cross}$, is the time it takes a star to cross the cluster ($t_{\rm cross} = 2R_{\rm hm}/v_{\rm disp}$, where $R_{\rm hm}$ is the radius that contains half the total cluster mass). A typical run is shown in Fig. 1. The massive stars, initially randomly placed within a number densty distribution, $n \propto r^{-2}$, preferentially sink to the centre of the cluster.

Measuring mass segregation can be done in a number of different ways. Unfortunately, there is no unique method for evaluating mass segregation, with different authors typically using different diagnostics. In this paper we use a variety of methods that are each designed to illustrate particular points and to facilitate comparison with existing and future observations.

The most obvious signature of mass segregation is the mean stellar mass of stars within some 'core radius'. This diagnostic is the easiest to determine observationally. However, caution must be exercised when using this diagnostic, as it depends critically on which stars are included to quantify the mean mass. It can also be severely biased by the presence of one very massive star. An example of the evolution of the mean stellar mass as a cluster undergoes mass segregation is illustrated in Fig. 2. The mean stellar mass is plotted as a function of time (in units of the crossing time) for clusters containing 250 and 1000 stars. The mean stellar mass is calculated for all stars contained within core radii of $0.25R_{\rm hm}$ and $0.5R_{\rm hm}$. The error bars are calculated as the standard error about the mean for the set of runs. From Fig. 2 it is clear that the mean stellar mass depends on the choice of core radius. It is also clear that although the time-scale for segregation depends on the number of stars in the cluster, some degree of mass segregation occurs very early on in all cases (within a few $t_{\rm cross}$).

Rather than consider the mean stellar mass inside a particular radius, one may consider the relative abundance of high-mass and low-mass stars, the characteristic radii of the massive stars (taken here to be the median radii), and the fraction of simulations producing concentrated subgroups of massive stars (as will be shown for the Trapezium in Section 4). The first two of these require a detailed knowledge of the stellar masses and their spatial distribution which is not always available observationally. The second diagnostic has the advantage that it traces directly the mas-

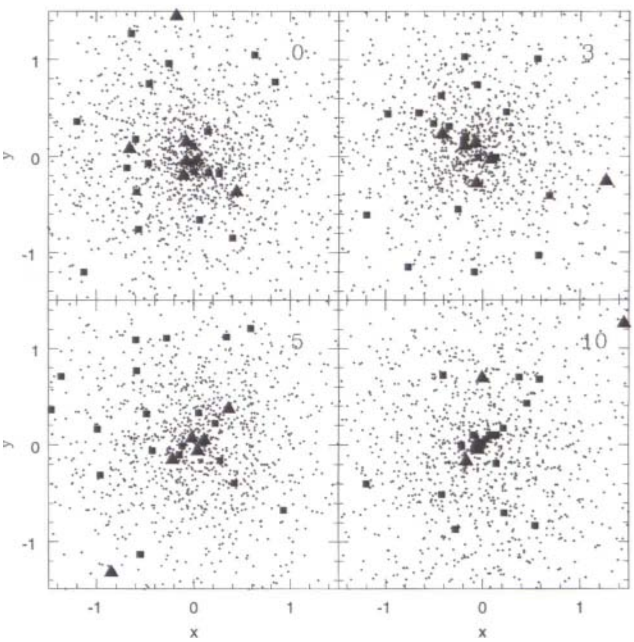

Figure 1. The evolutionary mass segregation in a cluster containing 1500 stars. The time in units of the crossing time is given in the top-right corner of each panel. The six most massive stars are indicated by the triangles, while the squares denote the next 24 massive stars. The massive stars are initially randomly placed within the number density distribution, $n \propto R^{-2}$.

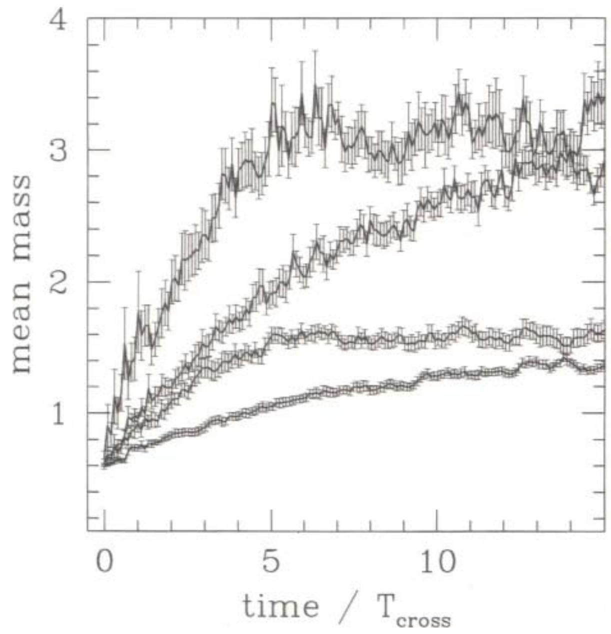

Figure 2. The mean stellar mass (in solar units) as a function of time in units of the crossing time. The four lines represent (from top to bottom): the mean mass in the inner quarter of the half-mass radius for a cluster of 250 stars, the mean mass in the inner quarter of the half-mass radius for a cluster of 1000 stars, the mean mass in the inner half of the half-mass radius for a cluster of 250 stars, and the mean mass in the inner half of the half-mass radius for a cluster of 1000 stars. The plotted error bars are the standard errors computed from the standard deviation of the mean calculated from all the realizations of a particular cluster.

sive stars. The last diagnostic is probably the easiest to use, but is obviously only computable in rich stellar systems containing a significant population of high-mass stars.

The centre of the cluster may be defined as the location of the deepest part of the gravitational potential, rather than the centre of mass. As such a definition is more closely related to observations, where the centre is defined as the region of highest surface brightness or the region containing the largest number of bright objects, we adopt this definition throughout the remainder of this paper. Typically this region contains the most massive star. Another advantage of this definition is that it eliminates any problem that may arise if the cluster contains an $m=1$ non-axisymmetric mode, such as may be present in the ONC where the Trapezium appears to be displaced from the centre of mass (Hillenbrand & Hartmann 1998).

2.1 Gas and mass segregation

Young stellar clusters are generally rich in gas, with typically a majority of the total mass in gas (Lada 1991). This gas can significantly affect the overall cluster evolution, determining whether the cluster is ultimately bound (Lada, Margulis & Dearborn 1984) and, through accretion, the masses of the individual stars (Bonnell et al. 1997). Although it can thus significantly affect the long-term evolution of a stellar cluster, it cannot, in the absence of accretion, aid in the dynamical mass-segregation process. The main effect of the gas is to increase the gravitational potential of the cluster, and thus increase the virialized stellar velocity dispersion. The time-scale for dynamical mass segregation corresponds to the time required for sufficient interactions to change a star's velocity, $\boldsymbol{v}$, by $|\delta \boldsymbol{v}| \approx |\boldsymbol{v}|$. Thus, if the velocity dispersion is higher, and the mass of the mean perturber has not changed, then a larger number of interactions, and hence time, is required.

The gas itself, if it is smoothly distributed, cannot be considered as an additional perturber. If the gas is clumpy, it can act as additional perturbers but, in order to have a significant effect, the clumps have to be smaller than the mean separation of two stars undergoing two-body relaxation. This implies a clump scale of $\lesssim 100$ au, which is not at all evident from any observations. Combined with a significant mass, the clump would almost certainly be gravitationally unstable, and thus collapse on a dynamical time-scale ($\lesssim 10^3$ yr) to form a star. Furthermore, they cannot be more massive than the stars that are supposed to segregate, or else it would be the clumps that segregate instead. Thus we are reduced to having a significant fraction of the total cluster mass in small objects that are not massive. This basically is equivalent to a large population of low-mass stars. Even in this extreme case, the result of an additional population of low-mass stars is to increase the mass-segregation time-scale (see Section 3.1) as the overall effect is to smooth out the cluster potential, decreasing the effects of two-body relaxation.

3 DEPENDENCE ON INITIAL CONDITIONS

There are a variety of potential initial conditions for a young stellar cluster. A cluster of stars will have formed through some sort of fragmentation (e.g. Monaghan & Lattanzio 1991; Boss 1996), possibly triggered by an external process (e.g. Pringle 1989; Chapman et al. 1992; Whitworth et al. 1994), and its initial conditions will be determined by this process. Additionally, the cluster will probably contain a significant amount of mass in the form of gas. This mass will affect the potential and the stellar dynamics, and even the stellar masses themselves (Bonnell et al. 1997). Any gas present in the cluster will act only to *increase* the mass-segregation time-scale (see Section 2.1).

We consider a number of different initial conditions which might affect the process of mass segregation. These include different stellar distributions, non-spherical clusters, deviations from virial equilibrium, and mass-dependent velocity dispersions. Mass segregation is evaluated in each case for clusters containing 250 stars. The stellar distributions considered are for a uniform distribution, a Plummer distribution, and an $n \propto r^{-2}$, isothermal sphere distribution. These cover the expected range of young clusters, as initially they might be near-uniform in stellar densities but will evolve towards centrally condensed distributions (e.g. Hillenbrand 1997). There is no significant qualitative difference observed between the outcomes of the simulations of the different clusters. The time-scale for mass segregation is largely unaffected by differences in the initial distribution. The same result is found for the non-spherical clusters. Flattened, oblate clusters with axis ratios of 2:1 and 5:1 evolve towards mass segregation on time-scales similar to those for spherical systems.

The initial conditions for cluster formation are unlikely to be those of a virialized system. The initial cluster will have a lower velocity dispersion than is required for stability, and will collapse until the velocity dispersion is increased sufficiently to support the cluster. Clusters significantly out of virial equilibrium ($E_{\rm kinetic}=0.1|E_{\rm potential}|$) are therefore considered to see if this process of violent relaxation aids in the mass segregation. We find that the time-scale for mass segregation in these clustes, in terms of the crossing time for the eventual virialized system, is the same as for the initially virialized systems. We therefore conclude that initially collapsing clusters do not undergo mass segregation on time-scales that are significantly shorter than similar systems that are initially virialized.

Mass-dependent velocity dispersions have a major effect on the mass-segregation time-scale. Observations show that the velocity dispersion in young clusters is largely mass-independent (Jones & Walker 1988), which is what one would expect from a cluster that has recently formed and probably undergone a violent relaxation (Binney & Tremaine 1987), hence our choice of initial conditions in Section 2. In this section we also consider clusters where the velocity dispersion, $v_{\rm disp}\propto m^{-1}$ and $v_{\rm disp}\propto m^{-1/2}$. In both these cases, the massive stars quickly sink to the centre of the cluster, on the time-scale of a single crossing time. In this case, the process of mass segregation, by which the massive stars lose kinetic energy to less massive stars and then sink to the centre, is unnecessary, as the massive stars do not need to lose the kinetic energy but just need the time to fall to the centre of the cluster. Such systems are already mass-segregated in terms of specific energy if not location, and this quickly leads to spatial mass segregation. If such a cluster is not initially in virial equilibrium, then the ensuing collapse and violent relaxation restores the mass-independent velocity dispersion such that these clusters then develop mass segregation on similar time-scales to clusters with uniform initial velocity dispersions.

3.1 Mass segregation versus cluster size

The time-scale of mass segregation is clearly dependent on the number of stars in a cluster. Mass segregation depends on the interaction of two stars and the resultant energy transfer from the more massive to the less massive star. This process results from the variable potential due to the motions of the stars. Thus, the smoother the potential, the less efficient is mass segregation. Larger clusters are inherently smoother (less grainy), and mass segregation is slower than in smaller clusters with a grainier stellar distribution. The different time-scales for mass segregation for clusters containing different numbers of stars are illustrated in Fig. 3 where we plot the fraction of high-mass stars contained in the inner half of the half-mass radius as a function of time. It is clear from this figure that although clusters of 50 stars are significantly mass-segregated by a few $t_{\rm cross}$, clusters of 1000 stars require $>10t_{\rm cross}$. The right-hand panel of Fig. 3 shows the same cluster evolutions but, instead of the clusters' crossing times, the fraction of high-mass stars is plotted as a function of the clusters' relaxation times. The relaxation time is the time-scale required for two-body relaxation, and it is a function of the cluster's size and the cluster's crossing time (Binny & Tremaine 1987),

$$t_{\rm relax}\approx \frac{N}{8\ \ln N}\, t_{\rm cross},$$

where N is the number of stars contained in the cluster. It is apparent from Fig. 3 that the time-scale for mass segregation is well fitted by the cluster's relaxation time, $t_{\rm relax}$. This is the same result as is found for systems with three mass components (Spitzer & Shull 1975). Thus systems younger than $t_{\rm relax}$ are not fully mass-segregated, although some degree of mass segregation occurs very early in the evolution.

4 ORION NEBULA CLUSTER

The best studied of the young stellar clusters is the Orion nebula cluster (ONC). Recent work has given an unprecedented understanding of the present composition of this cluster (Jones & Walker 1988; McCaughrean & Stauffer 1994; Hillenbrand 1997; Hillenbrand & Hartmann 1998).

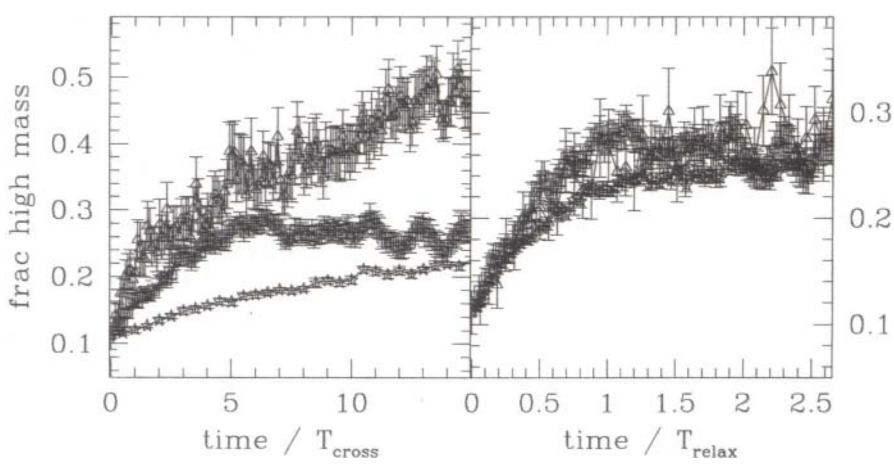

Figure 3. The fraction of stars in the inner half of a half-mass radius having a high mass ($M>1\ {\rm M}_\odot$) versus time for (from top to bottom) clusters with 50, 250 and 1000 stars. The right-hand panel shows the same curves, where now time is given in units of the relaxation time for each cluster.

Although the Trapezium cluster is often assumed to be a distinct entity from the ONC, recent work has shown that the stellar distribution of the ONC and Trapezium is well fitted by an isothermal cluster model, with the Trapezium comprising the core of the larger cluster. It also appears to be near global virial equilibrium, reaffirming the observation that the two are dynamically linked.

This knowledge of the ONC gives us a unique opportunity to constrain models of the initial conditions of such clusters through the numerical simulations presented here. Of particular interest is the definite bias towards high-mass stars present in the centre of the ONC, the so-called Trapezium cluster. The presence of the massive OB stars and other relatively high-mass stars at the centre of this cluster containing in excess of 1000 stars acts as a definite constraint to the models. This high mean stellar mass (≈ 5 $M_\odot$; Hillenbrand & Hartmann 1998) and large fraction of high-mass stars (the majority of stars are more massive than the Sun) have often been taken as an indication that star formation is bimodal, with high-mass stars, such as those in the Trapezium, forming in a radically different way from low-mass stars. In fact, the young stellar population in the ONC is not biased towards high-mass stars as long as the cluster is taken as a whole (Hillenbrand 1997). It is only in the central regions where the massive stars are segregated that the young population is biased towards high-mass stars. The question that arises from this is whether or not the present location of the massive stars is an indication of where they formed, or whether it is due to the subsequent dynamical evolution. Here we try to constrain their probable point of origin through the N-body simulations. In order to do this, we need an estimate of the dynamical age of the cluster.

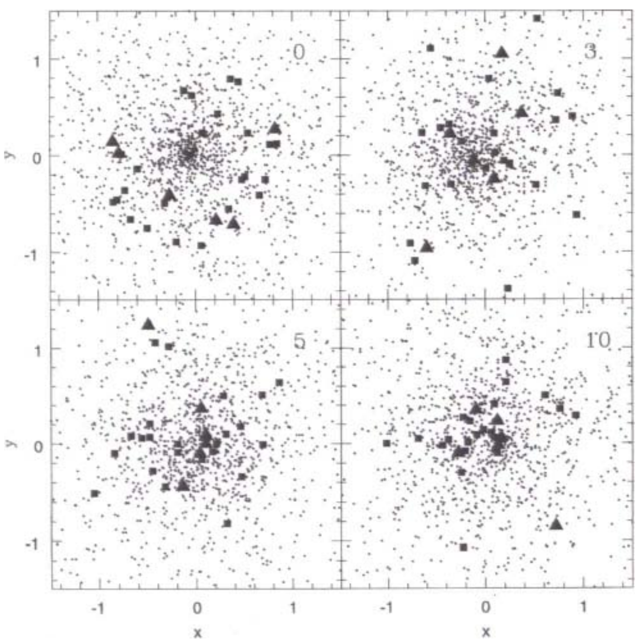

Figure 4. The evolutionary mass segregation in a cluster containing 1500 stars with a number density distribution $n \propto r^{-2}$. The time, in units of the crossing time, is given in the top-right corner of each panel. The six most massive stars are indicated by the triangles, while the squares denote the next 24 massive stars. The massive stars are initially placed near the cluster's half-mass radius.

Hillenbrand (1997) finds that the mean stellar age of the cluster is less than a million years. Jones & Walker (1988) find that the velocity dispersion is approximately 2.5 km s^{-1}. Combining this with an estimate of the half-mass radius of ≈ 0.5 pc, the cluster age is probably $\approx 3t_{\rm cross}$. Even with a smaller estimate of the half-mass radius, it is unlikely that the cluster is older than $5t_{\rm cross}$.

4.1 Mass segregation in the ONC

In order to constrain where the massive stars formed, we assign them specific initial locations within the cluster. This is done by assigning positions to all stars in accordance with the r^{-2} distribution, and then allocating the highest masses to those stars within the chosen radii. The rest are given masses randomly from the mass function. In this way, the most massive 2 per cent of the stars (30 in a cluster of 1500) are given initial locations at radii containing a specified fraction of the cluster's stars. These radii are chosen to contain 2 per cent (the 30 most massive stars for a cluster of 1500 stars), and also 10, 20, 30, 40, 50, 60 and 80 per cent of the stars in the cluster. Note that a radius containing 50 per cent of the stars corresponds roughly to the half-mass radius of the cluster. We also performed the same procedure but with the most massive 10 per cent of the stars for clusters of 1000 stars. The only significant differences in these simulations is a lower mean stellar mass due to the lower maximum mass.

In order to get a good measure of the mean stellar mass in the central regions of the cluster, we use the innermost 25 stars, in projection (which corresponds roughly to a radius $\approx 0.1 R_{\rm hm}$). The evolution of the mean stellar mass for these stars is plotted in the upper panel of Fig. 5. The four curves correspond to different initial locations for the 30 most massive stars. They range from placing the most massive stars at Lagrangian radii corresponding to 10, 20, 30 and 50 per cent of the stellar population. Placing the massive stars further out in the cluster gives lower values for the central mean stellar mass. Note that the centre of the cluster is determined by the deepest gravitational potential such that it is typically near the most massive star; thus the mean stellar mass is rarely below 2 $M_\odot$. The dispersion around the mean denoted by these curves is typically of the order of the noise in each curve (on time-scales $\lesssim t_{\rm cross}$). Note that the mean stellar mass observed in the centre of the Trapezium (≈ 5 $M_\odot$) is recovered if the massive stars are initially placed at radii containing 10 per cent of stars ($R \approx 0.3 R_{\rm hm} \approx 3 R_{\rm Trap}$) for ages $\gtrsim 3t_{\rm cross}$, and for ages $\gtrsim 5t_{\rm cross}$ when the massive stars are initially placed in the innermost 20 per cent of stars ($R \approx 0.6 R_{\rm hm} \approx 6 R_{\rm Trap}$). The necessary ages become $8t_{\rm cross}$ and $10t_{\rm cross}$ when the massive stars are initially placed at radii containing 30 and 50 per cent of the stars ($R \approx R_{\rm hm} \approx 10 R_{\rm Trap}$).

The lower panel of Fig. 5 plots the percentage of stars within the central region that are high-mass (defined as $M \geq 1$ $M_\odot$). In order that half of the central stars (the innermost 25 in projection) have masses larger than 1 $M_\odot$ (Hillenbrand 1997), the most massive 30 stars need to be initially located within the central 10 per cent of all stars, even if the cluster is as old as $6t_{\rm cross}$. This is barely sufficient, and the agreement is better if the massive stars are well placed at the centre of the cluster (Fig. 6). Fig. 6 plots the ratio of high-

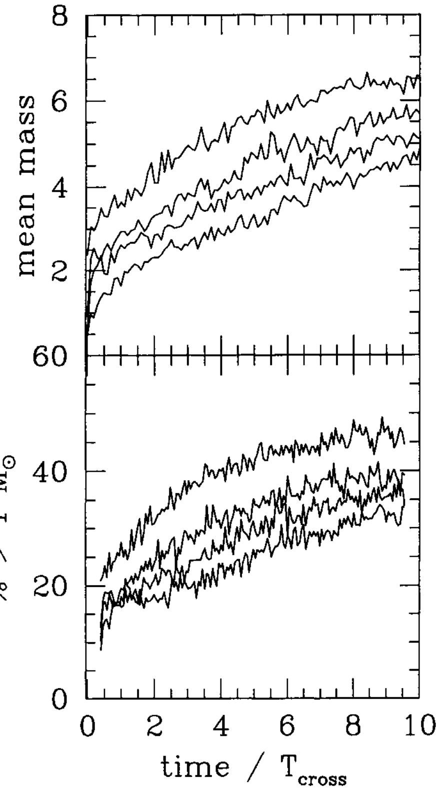

Figure 5. The mean stellar mass (top panel) and the percentage of stars greater than $M_\odot$ (bottom panel) as a function of time in units of the crossing time of clusters of 1500 stars following a number density distribution $n \propto r^{-2}$. The four lines represent the innermost 25 stars (in projection) for cases when the 30 most massive stars are placed (from top to bottom) at Lagrangian radii containing 10, 20, 30 and 50 per cent of the stars in the cluster.

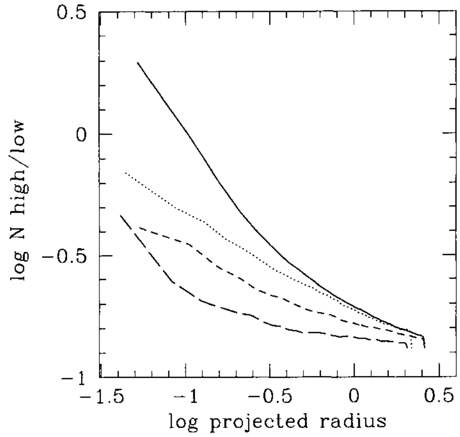

Figure 6. The log of the ratio of high-mass ($M > 1\ M_\odot$) to low-mass ($M < 1\ M_\odot$) stars as a cumulative function of the log of the projected radius (in units of the half-mass radius) after three crossing times. The four lines represent the cases when the 30 most massive stars are placed (from top to bottom) at Lagrangian radii containing 2 per cent (the 30 massive stars), 10, 30 and 50 per cent of the stars in the cluster.

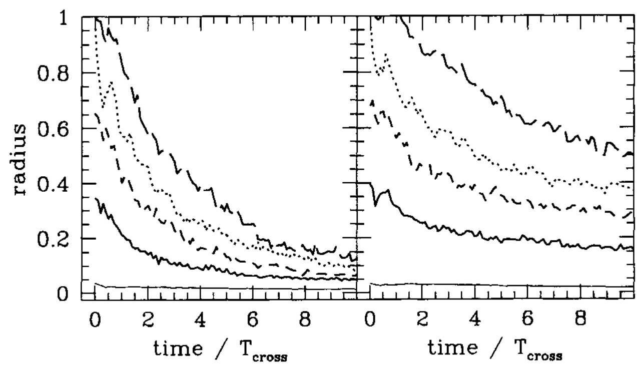

Figure 7. The median radius, in unis of the half-mass radius, of the six (left-hand) and 20 (right-hand panel) most massive stars. The five curves represent cases when the 30 most massive stars are placed (from bottom to top) at Lagrangian radii containing 2 per cent (the 30 massive stars), 10, 20, 30 and 50 per cent of the stars in the cluster.

mass to low-mass stars as a cumulative function of the projected radius (in terms of the half-mass radius). The plot is taken at $3t_{cross}$. The large number of high-mass stars relative to low-mass stars is approached only when the massive stars are initially in the centre. Larger ratios of high- to low-mass stars may indicate that more than just the 30 most massive stars originated near the centre.

4.2 Trapezium-like systems

In the above section we have seen that in order to reproduce the present observed conditions within time-scales of $3t_{cross}$ to $5t_{cross}$, the ONC must have been somewhat mass-segregated when it formed. Next, we try to place some definite constraints on where the most massive stars could have formed.

The central Trapezium Cluster is the most prominent feature of the ONC. This congregation of massive stars includes a fair proportion of the cluster's most massive constituents (three of the six stars with $M > 10\ M_\odot$, four of the eight stars with $M > 8\ M_\odot$, and five of the most massive 15 stars), and thus provides us with a definitive measure with which to evaluate the degree of mass segregation in our simulated clusters.

The effect of mass segregation on the positions of the most massive stars is shown in Fig. 7, where we plot the median radius of the six and 20 most massive stars, as a function of time for various initial distributions. Three of the six most massive stars are needed to compose the Trapezium which resides within $\approx 0.1 R_{hm}$ (0.05 pc). With this constraint, these stars need to have originated within the innermost 10 per cent of the stellar population if they are to form a Trapezium-like object on a time-scale $\lesssim 3t_{cross}$. Clusters with the massive stars originating further from the centre do not satisfy this criterion. The median radii of the 20 most massive stars do not decrease as quickly as a function of time; the moderately massive stars are supported to some degree by the energy that they gain by interacting with the most massive stars that are closer to the cluster centre. This can be used as a further constraint on the original positions of these stars.

Although the above results do show that the massive stars most probably formed near the centre of the cluster, it is still

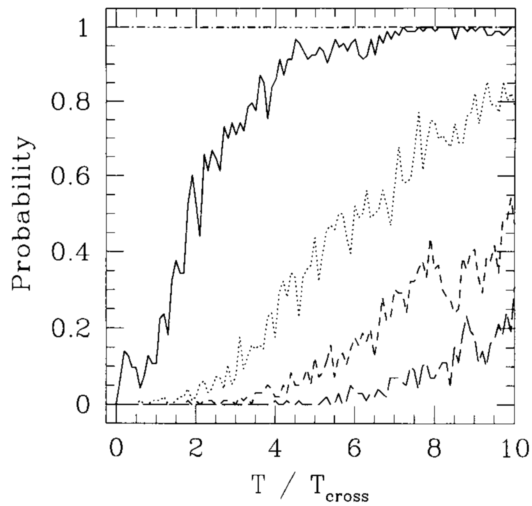

Figure 8. The probability of observing a Trapezium-like system at the centre of the cluster. The five lines represent the cases when the 30 most massive stars are placed (from top to bottom) at Lagrangian radii containing 2 per cent (the 30 massive stars), 10, 20, 30 and 50 per cent of the stars in the cluster.

possible that the Trapezium is a chance, transitory, occurrence or a projection effect, and not a real subsystem. In order to measure the probability of a Trapezium forming from different initial conditions, we have calculated the frequency of Trapezium-like systems, including projection effects, as a function of the evolutionary time and the initial placement of the massive stars. A cluster is said to contain a Trapezium-like system when at least N_2 of the most massive N_1 stars have at least N_3 neighbours, within $0.1R_{\rm hm}$, from amongst the N_1 most massive stars. Fig. 8 plots the results for systems consisting of $N_2 \geq 3$ stars with $N_3 \geq 4$ neighbours, all amongst the most massive $N_1 = 15$ stars. Similar groupings of the most massive $N_1 = 6$ and 12 stars give similar results. From Fig. 8 we can set concrete constraints as to the initial locations of the massive stars that make up the Trapezium. For a time of $3t_{\rm cross}$, there is a 70 per cent probability of forming the Trapezium if the massive stars are initially within the innermost 10 per cent of the stellar distribution, a 10 per cent chance if the massive stars form within the innermost 20 per cent of the population, and virtually no chance otherwise. If we assume a greater age for the ONC of $5t_{\rm cross}$, there is still only a 10 per cent chance of forming a Trapezium-like system if the massive stars originate at radii containing 30 per cent of all cluster stars. Note that at all times a Trapezium-like system is found if the massive stars originate at the centre of the cluster. From this we can conclude that it is very unlikely that the massive stars originated further out than the innermost 20 per cent of the cluster stars, and in all probability they were formed within the innermost 10 per cent of the ONC stars.

5 IMPLICATIONS FOR CLUSTER FORMATION

The primary result of this paper is that the massive stars that are found in the centre of very young clusters like the ONC cannot have formed in their outer regions. This implies that the mass of a star is to some degree a function of its initial position within a cluster, the more centrally located stars tending to have larger masses.

A star's mass is determined not only by the mass of the protostellar core at the time it fragments out of the general cluster background but also by the amount of material it is able to accrete thereafter. At the time of fragmentation, a fragment's mass is typically the Jeans mass,

$$M_{\rm J} = \left(\frac{5R_{\rm g}T}{2G\mu}\right)^{3/2}\left(\frac{4}{3}\,\pi\rho\right)^{-1/2},$$

smaller masses being non-self-gravitating, while objects with larger masses should be susceptible to further fragmentation. It is hard to imagine a scenario where once fragmentation is initiated, it will be halted before proceeding to form fragments of approximately one Jeans mass. The minimum separation of fragments needs to be greater than the Jeans radius,

$$R_{\rm J} = \left(\frac{5R_{\rm g}T}{2G\mu}\right)^{1/2}\left(\frac{4}{3}\,\pi\rho\right)^{-1/2}.$$

Now, assuming that the temperature is nearly constant, the conditions in the centre of the ONC imply that the density had to be very high in order that the Jeans radius is less than the stellar separation. This in turn means that the Jeans mass should be lower in the centre than elsewhere, with typical values of $M_{\rm J} < 1$ $\rm M_{\odot}$ even if the fragments are initially touching (Zinnecker et al. 1993). One possible alternative is a temperature gradient where the central regions are hotter than the outside. If we assume that the protocluster initially has near-uniform density, then a contrast of 50:0.1 in Jeans mass implies a temperature contrast of 63:1. If the protocluster is initially centrally condensed, then the required temperature contrast will be significantly greater ($>$450:1 for an r^{-2} density profile). Such temperature contrasts are not observed and, in general, considering cooling and self-shielding of cosmic rays, the inside should, if anything, be colder (e.g. Nelson & Langer 1997). Feedback from a massive star as a mechanism to heat the central regions can be ruled out by the coevality of the stars in the central regions. Furthermore, even if feedback were important, it required at least one massive star to have formed in regions with a small Jeans mass.

It seems unlikely that when fragmentation occurred, the Jeans mass in the centre of the cluster was much larger than elsewhere. We are therefore then left with the alternative that initially all protostellar clumps had similar masses, and that those in the centre grew by some mechanism into the present high-mass stars. There are two alternatives for this scenario: the fragments grew either through accretion from the residual gas or through coagulation with other fragments. For coagulation to work in the case of the Trapezium Cluster, the time-scale for collisions has to be sufficiently short to allow some 50 to 500 fragments of one Jeans mass to coalesce into the highest mass star, θ^1C. Assuming that the Trapezium Cluster initially contained ≈ 100 $\rm M_{\odot}$ within 0.05 pc of its centre, and that each fragment collapsed to densities where it became optically thick, $\rho \approx 10^{-13}$ g cm^{-3}, before collisions could occur, then the collisional time-scale is of the order of 3 crossing times of this central region or

$\approx 1/3$ of the cluster t_{cross}. Thus ≈ 50 collisions will occur in $\approx 15\ t_{\mathrm{cross}}$, which is significantly older than the present Trapezium. We therefore conclude that subsequent accretion of the residual gas present in the cluster is more likely to have produced the observed range of stellar masses. Observations of young clusters tell us that they typically contain more mass in gas than in stars (Lada 1991). This must be a lower limit on the amount of gas initially present in the cluster. Models of accretion in small stellar clusters show how the accretion rate depends primarily on each star's position in the cluster, with the stars near the centre having the highest accretion rates (Bonnell et al. 1997). Thus the subsequent accretion of material naturally produces the most massive stars in the centre of a cluster. Furthermore, the accretion of predominantly low-momentum matter helps to ensure that these stars remain in the centre, as it lowers their specific kinetic energy.

6 CONCLUSIONS

In this paper we have shown that dynamical mass segregation occurs on approximately the cluster relaxation time. Clusters that have ages $t \gtrsim t_{\mathrm{relax}}$ have thus lost all traces of their initial conditions. Dynamical mass segregation is independent of most possible initial cluster conditions. The exception to this is clusters with mass-dependent velocity distributions. These clusters are already mass-segregated in terms of specific energy which quickly leads to spatial mass segregation. Such initial conditions are not expected for any cluster that undergoes a collapse and violent relaxation.

The main result of this study is that the position of massive stars in the centre of rich young clusters ($t \ll t_{\mathrm{relax}}$) cannot be due to dynamical mass segregation. Instead, the positions of the massive stars indicate where they formed. In particular, the position of the Trapezium at the centre of the Orion nebula cluster implies that the vast majority of the most massive 2 per cent of the stars formed within the central 10 per cent of the cluster population, corresponding to $\approx 0.3 R_{\mathrm{hm}}$ or three times that of the present-day Trapezium. Any gas content in these clusters decreases the efficiency of mass segregation and thus strengthens the conclusions reached here. The constraints put on the location of the massive stars by these results imply that they most probably formed through the accretion of residual gas on to relatively low-mass protostellar cores (e.g. Bonnell et al. 1997).

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