Abstract. A dense-enough gas-accumulation evolves, over a few Myr of intensifying star formation, to an embedded cluster. If it contains a sufficient amount of mass, O stars form and explosively expel the remaining gas, whereas poorer clusters reduce their embryonic gas content more gradually. The sudden expulsion of gas unbinds most of a rich cluster, but a significant fraction of it can condense by two-body interactions to become an open cluster despite a star-formation efficiency as low as 30 per cent. Poorer clusters survive their gradual mass loss more easily, but have short, relaxation-limited life-times. Pleiades-like clusters may thus form as nuclei of expanding OB associations, by filling their tidal radii and having large (1–2 pc) core-radii. A 'main-sequence' of clusters is thus established. Ultimately, a cluster dies an explosive death through the ever shortening relaxation time, and leaves a remnant that consists of about 4–10 stars arranged in a highly hierarchical and thus long-lived system. Dynamical mass segregation in very young clusters is extremely rapid, and heats a cluster substantially, which is partially off-set by the cooling from the disruption of primordial binaries.

1. Introduction

Star clusters fascinate because some are beautifully evident to the unaided eye, and because their birth, life and death remain mysterious. Wonderful examples 'magically' lying together in one quadrant on the summer sky (southern hemisphere) are M42 (the Orion Nebula Cluster, ONC), and the Pleiades and Hyades Clusters. Their ages are $\tau_{cl} \approx 1$ Myr, 100 Myr and 600 Myr, respectively, and latest research indicates they may form approximately one evolutionary sequence. Such clusters may be the origin of a significant proportion of Galactic-field (GF) stars, which is one reason why we want to understand their behaviour. In this contribution (KII), the aim is to convey some theoretical aspects concerning the birth, evolution and death of open clusters, but I stress that much remains to be worked out in this exciting field. Complementary texts are Kroupa (2000a, KI; 2000b, KIII).

A few quantities useful for roughly assessing the global state of a cluster are the half-mass diameter crossing-time [Myr],

$$t_{cx} = 4.2 \left( \frac{M_{st}}{(100 M_\odot)} \right)^{-1/2} \left( \frac{R_{0.5}}{1 \text{ pc}} \right)^{3/2} \text{,}$$

the median relaxation-time [Myr] for a purely stellar system (Binney & Tremaine 1987, BT)
the universal (GF) IMF (Kroupa 2000c) with stellar masses in the range 0.01–50 \( M_\odot \), and the forming proto-stellar clumps collide to form more massive star clusters (Bonnell, Bate & Zinnecker 1998; Stahler, Palla & Ho 2000), which is more or

Here, \( R_{0.5} \) is the half-mass radius, \( M_\text{tot} = M_g + M_\star \), \( M_g \) being the gas mass and \( \epsilon \) the star-formation (sf) efficiency, and \( \dot{M}_\text{tot} = N \overline{m} \) is the mass of the cluster containing \( N \) stars that have an average mass \( \overline{m} = 0.36 M_\odot \), assuming the universal (GF) IMF (Kroupa 2000c) with stellar masses in the range 0.01–50 \( M_\odot \), \( G = 4.49 \times 10^{-3} \text{ pc}^3/(M_\odot \text{ Myr}^2) \), and 1 pc/Myr \( \approx 1 \text{ km/s} \).

For one massive star with \( m = 10 (20) M_\odot \), the GF IMF implies \( N_{10(20)} = 371 (1155) \) stars with \( m \in [0.01, 10] (\{0.01, 20\}) M_\odot \). These numbers are useful for determining if an embedded cluster is likely to contain stars massive enough to remove the natal gas within a time \( \tau_g < t_{\text{cr}} \), i.e. “explosively”. In what follows, poor clusters contain \( N \lesssim 10^3 \) stars, whereas rich clusters contain \( N \gtrsim 10^3 \) stars.

Typical numbers for a few well-known clusters are \( \tau_{\text{cl}} \lesssim 1 \text{ Myr} \), \( N = 5000–10000, R_{0.5} \approx 0.45 \text{ pc} \) (ONC), \( \tau_{\text{cl}} \lesssim 1 \text{ Myr}, N \approx 200, R_{0.5} \approx 0.5 \text{ pc} \) (\( \rho \) Oph, still embedded in gas), \( \tau_{\text{cl}} \approx 100 \text{ Myr} \), \( N \approx 3000, R_{0.5} \approx 3 \text{ pc} \) (Pleiades), and \( \tau_{\text{cl}} \approx 600 \text{ Myr}, N \approx 2000, R_{0.5} \approx 4 \text{ pc} \) (Hyades).

2. Birth and Morphology

The birth of a cluster undoubtedly requires some relatively large gas mass (\( M_g \gtrsim 500 M_\odot \)) to be squeezed into a relatively small volume (\( R_{0.5} \lesssim 0.5 \text{ pc} \)). This is evident from many observational results (e.g. contributions in Lada & Kylafis 1999; Clarke, Bonnell & Hillenbrand 2000; these proceedings), but how a molecular cloud decides to do this remains to be understood theoretically. Calculations using the SPH-approximation to treat gas-dynamics during the earliest stages of the formation of a cluster (prior to stellar feedback) shows that it is heavily sub-structured (Klessen & Burkert 2000), which is also evident from observations (e.g. Kaas & Bontemps 2000). Observational evidence indicates that sf begins slowly and accelerates (Palla & Stahler 2000), probably owing to the increasing density and probably additional sf being triggered by feedback, with a characteristic duration, \( t_{\text{sf}} \), of a few–many Myr. The star-gas system probably contracts due to dynamical friction of the stars on the gas (Saiyadpour, Deiss & Kegel 1997), and/or the stars that ‘freeze-out’ of the gas fall towards the cluster centre if the turbulent length-scale is smaller than the region from which the stars condense (ie. small proto-star–proto-star velocity dispersion). As the proto-stars continue forming, their orbits in the cluster rapidly (within \( t_{\text{cr}} \)) virialise, so that the stellar system should always be close to virial equilibrium in the potential that is determined mostly by the mass-dominating gas. As a result of these processes, the sub-structure washes out on the global \( t_{\text{cr}} \) timescale. In subregions, in which \( t_{\text{cr,sub}} < t_{\text{sf}} \), where \( t_{\text{sf}} \approx 0.1 \text{ Myr} \) is the time for the formation of an individual proto-star (e.g. Wuchterl & Tscharnuter 2000), and \( t_{\text{cr,sub}} \ll t_{\text{cr}} \), the forming proto-stellar clumps collide to form more massive clumps that are more likely to collide, and can accrete even more radially in-flowing gas with low specific angular momentum, causing contraction of the subregion which speeds-up this process. It is thus in the localised density maxima that massive stars are expected to form through collisional accumulation (Bonnell, Bate & Zinnecker 1998; Stahler, Palla & Ho 2000), which is more or
less supported by observations (Megeath et al. 1996), but the growth of massive stars through accretion alone remains an important possibility (e.g. Norberg & Maeder 2000).

Termination of the sf process occurs abruptly through the devastating action of one or more O stars in rich embedded clusters. When the first O star 'ignites', an ultra-compact HII region (UCHII, radius $R \lesssim 0.1$ pc) develops which is stable and 'long-lived' (a few $10^5$ yr), being confined by the large pressure of the star-forming gas, before finally breaking out to become a compact HII region (CHII, $R \lesssim (0.1 - 0.3)$ pc) with complex gas structures, and finally an extended HII region (EHII, $R \gtrsim$ few pc) (García-Segura & Franco 1996). The evolution from the UCHII to an EHII region occurs rapidly, the heated ionised gas expanding with at least the sound velocity (about 12 km/s), but also being driven by the fast wind (a few 100 km/s, e.g. Lamers, Snow & Lindholm 1995) emanating from the hot surface of an O star. Even prior to the eruption of the UCHII, large quantities of the surrounding gas are removed through the massive outflows expelled from the region containing the massive stars (Churchwell 1997; 1999). Star-formation ceases more gradually by the removal of unused gas through less-massive outflows and winds powered by lower-mass stars in poor embedded clusters (Matzner & McKee 2000).

Observational evidence (section 6.2 in Matzner & McKee 2000 for an overview) suggests that $\epsilon < 0.4$ in embedded clusters. Matzner & McKee (2000) theoretically estimate that $0.30 < \epsilon_{MM} < 0.50$ for poor clusters, $\epsilon$ essentially being determined by the rate with which sf can continue as the increasing number of outflows collect and discard increasing amounts of unused gas. For rich embedded clusters, $\epsilon < \epsilon_{MM}$ because once the O star 'ignites', essentially all sf is terminated throughout the cluster, no transition time existing during which sf dies down.

The ONC is in the CHII→EHII phase, whereas $\rho$ Oph is still in the embedded phase but may never have O stars. The Pleiades and Hyades have evolved well beyond the EHII stage, and how they survived explosive gas expulsion was an unsolved problem until very recently.

3. Cluster Survival and Ultimate Death

Once an embedded cluster forms, three mass-loss mechanisms work over different time-scales towards unbinding it: (i) Expulsion of embryonic gas (approximately during first 0–5 Myr), (ii) mass loss from evolving stars (significant after about 3 Myr), and (iii) stellar-dynamical evaporation and ejections of stars (all times).

Gas-expulsion: It has been realised since a long time that the expulsion of significant amounts of gas from an embryonic cluster has serious implications for its survival. Hills (1980), Mathieu (1983), and Elmegreen (1983) provide groundbreaking analytical results, and the first $N$-body experiments ($N \leq 100$ stars) were performed by Lada, Margulis & Dearborn (1984). These pioneers arrived at the general result that if gas-expulsion occurred instantly (i.e. $t_g < t_{cr}$ essentially, so that the stellar orbits cannot adjust to the rapidly varying potential), as is the case in clusters with O stars, and if $\epsilon < 0.5$ then an unbound association results, although the $N$-body results indicated that $\epsilon \approx 0.4$ still allows a small part of the embedded cluster to 'hang-on' as an expanded but bound entity. A
contraction of the stellar system relative to the gas leads to higher effective $\epsilon$, allowing more of the embedded cluster to survive after gas expulsion. Further variations on the theme incorporate an initial cold collapse, in which however only a small fraction of the gas needs to be removed to lead to an unbound association, unless the removal occurs just at the beginning or after violent relaxation (and thus after a new, contracted virial equilibrium of the stellar system is achieved with a much higher effective $\epsilon$).

The particularly noteworthy result emerged that open clusters, such as the Pleiades, could not have formed with O stars and $\epsilon \lesssim 0.5$. Since $\epsilon > 0.5$ was never observed, the implication is that Galactic clusters can only form with stellar IMFs that are truncated near $m \approx 5 - 10 M_\odot$. In this respect, the future fate of the ONC, which contains OB stars that clearly rapidly drove out the unused gas some time ago, is interesting, in as much as it has a velocity dispersion that is too large for virial equilibrium of the stellar system (e.g. Hillenbrand & Hartmann 1998).

In clusters without O stars, the gas is expelled over a time comparable to the duration of the most intense sf period, i.e. $\tau_g \approx t_{sf}$ (a few Myr), since the stars that go 'on-line' immediately add their outflows to the general erosive commotion. The above-mentioned pioneering work established that under these conditions, the stellar system expands, but because it has enough time to adjust to the varying potential, roughly half of it can relax to form a bound cluster filling its tidal radius.

More recent numerical experiments (e.g. Goodwin 1997; Geyer & Burkert 2000) confirm the above results, and Adams (2000; also these proceedings) analytically estimates the fraction of stars that have velocities below the escape velocity after gas and the unbound stars escape, assuming, however, that the stellar system is more concentrated than the gas, implying an effective $\epsilon \approx 0.9$, as noted by Geyer & Burkert (2000). It is thus not surprising that Adams finds that substantial clusters form despite an assumed $\epsilon < 0.4$ (overall for gas + stars). The above results were obtained under simplifying assumptions, such as neglecting the Galactic tidal field and mass loss from evolving stars, both of which further increase the critical $\epsilon$ required for a bound Galactic cluster, probably well above $\epsilon = 0.4$, so that the formation of a Pleiades-like cluster continued to remain a mystery.

All of the research summarised above assumed that the stellar system can be treated as collision-less, i.e. that near-neighbour encounters can be neglected while the gas is being expelled. The assumption appears reasonable, but a detailed look uncovers that this is flawed. Very recently, Aarseth’s (1999) code \textsc{Nbody6}, which treats close stellar encounters accurately and computationally efficiently using special mathematical transformations, has been augmented by a rapidly varying back-ground potential (Kroupa, Aarseth & Hurley 2000, KAH). The resulting code \textsc{GasEx} has already been used in a study of the future evolution of the ONC under the assumption that $\epsilon = 0.3$, and that it was in virial equilibrium for 0.6 Myr (to model the UCHII phase) when the O stars removed the surplus gas explosively. A local Galactic tidal field, and state-of-the art stellar evolution (Hurley, Pols & Tout 2000) is treated, and the (surprising) result is that a Pleiades-like cluster readily condenses from the radially expanding flow.
About 1/3 of the initial number of stars condense, which is substantially more than implied under similar conditions by the above mentioned research.

Thus, the Pleiades most probably formed from an ONC-like object, and the mechanism for this must be two-body encounters that allow density differences to grow as the system expands, causing a part of the radial flow to be re-directed into orbital motions about the centre of expansion thus forming a substantial bound cluster. Clearly, this is an exciting field of research, and details still have to be worked out, but the results available so far suggest that Galactic clusters form with large core radii ($\approx 1 - 2$ pc) and filling their tidal radii, as a result of the expansion after gas loss. Binary disruption is very efficient during the embedded epoch, and the surviving binaries are always hard when the cluster reaches a relaxed state in the Galactic tidal field, which may be called a cluster main sequence, since global evolution thereafter depends only on the number of stars within the tidal radius (fig. 1 in K3), assuming everything else (IMF, primordial binaries) is universal. Any initial mass segregation, imposed either as a result of cluster formation or through rapid dynamical mass segregation (see below), will be much reduced after the expansion, but some memory of it remains. A new epoch of mass segregation begins as soon as the 'cluster main sequence' is reached (KAH). A notable example of a very young and very massive open/globular cluster, that is just at the stage of having expanded to fill it’s tidal radius, may be Cygnus OB2 (Knödlseder 2000). Each Galactic cluster should thus be associated with an expanding population of co-eval stars which amounts to about 2/3 of the total number of stars formed in the one event, and these extended moving groups will be identifiable with the upcoming astrometric satellite missions DIVA (Röser 1999) and GAIA (Gilmore et al. 1998).

Finally, the Pleiades will appear similar to the Hyades when 600 Myr old (Portegies Zwart et al. 2000).

**Mass-loss from evolving stars:** Stars with $m \gtrsim 8 M_\odot$ explode as supernovae (sn), their remnants having $1 - 2 M_\odot$, but usually being lost from the cluster owing to the sn kick (> 10 km/s, e.g. Portegies Zwart, Kouwenhoven & Reynolds 1997). The last sn ($\approx 8 M_\odot$ star) occurs at an age of about 40 Myr. Thereafter mass-loss occurs via planetary nebulae leaving white dwarf remnants with masses in the range 0.5 $-$ 1.2 $M_\odot$ (Weidemann 1990).

The ratio of the mass lost from a cluster to the initial stellar mass is, for the universal GF IMF (Kroupa 2000c, eq. 2),

$$\frac{\Delta M}{M_{\text{st.init}}} = 0.733 m_{\text{to}}^{-0.3} - 0.169 m_{\text{to}}^{-1.3} - 0.215,$$

assuming $m \gtrsim 8 M_\odot$ stars kick out their remnants, and that for less massive stars the remnants have a mass of about 1 $M_\odot$ and are retained in the cluster. Thus, within 40 Myr a cluster looses about 17 per cent of its mass (sn explosions), within 100 Myr (turn-off mass $m_{\text{to}} \approx 5 M_\odot$) about 23 per cent is lost, within 600 Myr ($m_{\text{to}} \approx 2 M_\odot$) 31 per cent is lost, and within about 14 Gyr ($m_{\text{to}} \approx 0.9 M_\odot$) a cluster would loose in total about 35 per cent of its initial mass owing to stellar evolution alone (stellar evolution times are from Hurley, Pols & Tout 2000). A cluster thus suffers under the significant mass loss from evolving stars (e.g. de la Fuente Marcos 1997). However, less mass is lost over progressively longer time-intervals, so that it ultimately becomes negligible compared to dynamical 'evaporation'.

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Stellar-dynamical evaporation and ejection: Stars in a 'main-sequence cluster' suffer many weak, long-distance 'encounters' with other cluster stars, so that the kinetic and potential energies are constantly being re-arranged among cluster members (two-body relaxation, e.g. Lee & Goodman 1995). Energy equipartition in the cluster potential leads to the less massive stars gaining kinetic energy and the heavier ones gaining potential energy, thus sinking towards the cluster centre. After many such two-body encounters, a low-mass star may find itself with a positive energy relative to the cluster. It is lost from the cluster, typically after one Galactic orbit usually by exiting through one of the Lagrange points (e.g. Portegies Zwart et al. 2000), but on rare occasions it may suffer an encounter while traversing the cluster and may be scattered back into membership. Estimates based on simplified model clusters (single stars of equal mass) suggest that a cluster evaporates within

\[ t_{\text{life}} \approx 20 t_{\text{rel}} \]  

(e.g. BT, section 8.4), but this estimate breaks down for a young cluster that does not fill it's tidal radius. This is evident in models that have the same \( N \) but different \( R_{0.5} \), and thus very different initial \( t_{\text{rel}} \), leading to the same \( t_{\text{life}} \) (Kroupa 1995b, K3). The above equation may be used only when the cluster is relaxed in the tidal field. Thus, a poor cluster with typically \( N \approx 200 \) after gas expulsion and \( R_{0.5} \approx 2 \) pc has \( t_{\text{life}} \approx 0.6 \) Gyr, whereas for the Pleiades \( t_{\text{life}} \approx 3 \) Gyr.

Rare, close encounters between single stars can lead to the ejection of stars with relatively large velocities at the expense of the more massive stars that gain binding energy in the cluster. These processes are, however, much rarer than the loss through evaporation (BT and references therein). However, the large abundance of primordial binaries in realistic clusters increases the ejection rate and ejection velocities substantially. The models of K3 show that about \( 4 - 5 \) times as many stars are ejected with velocities \( v_{\text{ej}} \gtrsim 5 \) km/s in clusters with primordial binaries than in clusters without binaries. The models also demonstrate that initially more concentrated clusters loose a larger percentage of their stars through energetic ejection events. Binary-star encounters are not very significant for expelling stars as a cluster ages (also pointed out by de la Fuente Marcos 1997), because the surviving binaries are hard with small interaction cross sections (see above). Overall, this channel for loosing stars from a cluster amounts to less than \( 10 \) per cent of the initial stellar population of the 'main-sequence cluster' (K3), and since a cluster ultimately dissolves completely, evaporation, driven by cluster expansion through mass loss from evolving stars, remains the dominant mechanism for stellar loss. It is clear though that the velocity distribution of ejected stars contains information about the typical birth configuration, for example of massive stars (see KIII).

Owing to the preferred loss of the least massive and single stars, a Galactic cluster approaches an idealised state, being composed predominantly of stars with similar masses around \( m_{\text{to}} \) and an enhanced proportion of hard binaries. At late evolutionary times, the binary proportion can achieve levels as high as \( 80 \) per cent (K3), even if the primordial proportion was only \( 1/3 \) (de la Fuente Marcos 1997).

Death: As a consequence of mass loss, the tidal radius,

\[ R_{\text{tide}} \approx (M_{\text{st}}(t)/(3 M_{\text{gal}}))^{1/3} R_{\text{GC}}, \]  

where

where $M_{\text{gal}} \approx 5 \times 10^{10} M_{\odot}$ is the Galactic mass within the solar radius $R_{\text{GC}} \approx 8.5$ kpc, contracts, the density within remaining approximately constant. However, $R_{0.5}$ need not decrease monotonically as a consequence. It may increase intermittently if a core forms that contracts thus heating the rest of the cluster. This is the case for rich clusters, but details on the evolution along the putative cluster main sequence remain to be worked out. The contracting $R_{\text{tide}}$ implies a decrease of $t_{\text{rel}}$, so that the cluster’s dynamical evolution speeds up. Open clusters thus die, in a sense, explosively, their population dwindling at an ever increasing rate. This can be seen in the evolutionary curves in fig. 1 of K3, as well as in the models of de la Fuente Marcos (1997). The very final stage in a cluster’s life sees the formation of a stable few-body system, the *cluster remnant*. Such a remnant consists of only a few ($4 \lesssim N_{\text{rem}} \lesssim 10$) stars that are arranged in a stable, strongly hierarchical multiple system (de la Fuente Marcos 1997; de la Fuente Marcos 1998). Individual tight binaries in it need not be primordial. Such an object can be very long-lived and difficult to find, but a complete census of all strongly hierarchical systems would give insights into the number of Galactic clusters ever born in our neighbourhood.

An ‘unnatural’ but not unlikely death of a star cluster can occur if it encounters a molecular cloud (Theuns 1992).

4. Primordial Binaries: Cooling

Changing to a more fundamental topic: in order to assess the role of realistic primordial binary systems as heating and cooling sources, and to study early mass segregation, a library of clusters has been generated (table 1 in KI). These have $N = 800, 30000, 10000$, the same initial central ONC density, the same $t_{\text{cr}}$, assume different primordial binary populations, but no initial mass segregation. These models are set-up in theoretical virial equilibrium (Aarseth, Hénon & Wielen 1974). Here focus is on the models with Taurus–Auriga-like primordial binary-orbital parameters of Kroupa (1995a, K2) having a primordial binary proportion $f_{\text{tot}} = 1$.

As discussed in KI and KIII, soft binaries are typically disrupted on a crossing-time scale (fig. 2 in KI), whereas hard ones harden thereby injecting energy into the cluster which consequently heats up and expands. Disruption of binaries requires energy, cooling a cluster. How significant cooling and binary heating is for very young clusters can be estimated from the total binding energy in ‘soft’ binaries, $E_{\text{bs}} = \sum |e_{\text{bs,i}}|$, such that $|e_{\text{bs,i}}| < e_k$, $e_k = 0.5 \bar{m} \sigma_{3D}^2$ being the average kinetic energy, with $\bar{m}$ the average stellar mass and $\sigma_{3D}$ the three-dimensional velocity dispersion. ‘Active’ binaries have $E_{\text{ba}} = \sum |e_{\text{ba,i}}|$, such that $e_k \leq |e_{\text{ba,i}}| \leq 100 e_k$. The evolution of $\Delta E_{\text{s}} \equiv (E_{\text{bs}}(0) - E_{\text{bs}}(t))/E_{k}(0)$ and $\Delta E_{\text{a}} \equiv (E_{\text{ba}}(0) - E_{\text{ba}}(t))/E_{k}(0)$, where $E_{k}(0) = 0.5 N \bar{m} \sigma_{3D}$ is the approximate total kinetic energy content of the cluster, is shown in Fig. [ ].

Thus, $\Delta E(t) < 0$ (i.e. *cluster cooling*) in all cases except for active binaries which heat for very brief times. The energy input into the cluster is negligible though. What is interesting (and somewhat surprising) is that the active binaries are efficient cooling agents, especially for clusters with $N \lesssim 1000$. For these, the energy ‘soaked up’ by the binaries amounts to about 12 per cent of the initial kinetic energy. Soft binaries take $\lesssim 0.01 E_{k}$ out of the field, and are thus
negligible cooling agents. Models with a log-normal GF period distribution and $f_{\text{tot}} = 0.6$ always have smaller $\Delta E$ than the models shown here that assume the 'K2 binary population'. The cooling of the clusters is the reason why the central density remains higher than in clusters containing initially fewer or no binaries (fig. 4 in KI; fig. 2 in Kroupa, Petr & McCaughrean 1999).

The above is a preliminary account of a 'dash in this direction', and more details concerning the energy transfer from active to hard binaries (i.e. hardening of 'actives' to $|e_b| > 100 e_k$) need to be worked out. That hard binaries can have a substantial influence on the long-term evolution of a cluster by being energy sources that counteract core-collapse in massive clusters has been realised for a long time (e.g. Giannone & Molteni 1985; Giersz & Spurzem 2000).

5. Mass Segregation

Massive systems sink towards the centre thereby gaining potential energy which heats the cluster. This is a consequence of energy equipartition, as described above. The consequences of this are seen in fig. 4 in KI, which shows that the central density decreases for a wide range of very young clusters. That this is not due to binary-star heating alone is evident from the expansion of the single-star clusters. The observational consequences of this are an expanding halo of BDs and M dwarfs (Fig. 2).

The time-scale for mass-segregation to complete is not very well known, this being an active area of research (e.g. Bonnell & Davies 1998, who however employed a collision-less code to a collisional problem), especially because of the need to understand trapezium-type sub-systems in star clusters (Mermilliod 2000), and the associated implications for the formation mechanisms of massive
Figure 2. The average radius of stars with \( m \geq 8 M_\odot \) (solid lines), \( 1 \leq m < 8 M_\odot \) (dashed lines) and BDs \( (0.01 \leq m \leq 0.08 M_\odot, \text{dotted lines}) \). In decreasing curve thickness: \( f_{\text{tot}} = 1, 0.6, 0 \) (same models as in Section 4).

Table 1 in KI is augmented here by the models 100f10, 100f06 and 100f00 (lower left panel) which have the same GF IMF (Kroupa 2000c) as the other models displayed here.

stars (Bonnell et al. 1998). An analytical estimate for the time-scale for mass-segregation (more precisely, for the equipartition time-scale) was obtained by Spitzer (1987, p.74),

\[
t_{\text{equ}} \approx (\overline{m}/m_h) t_{\text{rel}},
\]

where \( \overline{m}, m_h \) are the average and heavy-star mass, respectively. Thus, for the examples shown in Fig. 2 (\( \overline{m} = 0.36 M_\odot, m_h \approx 20 M_\odot \)) one obtains \( t_{\text{equ}} = 0.02 t_{\text{rel}} < 0.3 \) Myr in all cases. However, this estimate breaks down as soon as the density structure of the cluster has changed significantly, with further evolution slowing. Fig. 2 suggests that mass segregation completes by about 1 Myr in all models. Note also that only the massive stellar sub-system contracts.

The increase with time of the average stellar mass near the cluster centre is shown in Fig. 3. Note that the increase is linear until the core disrupts (massive stars are ejected), as is evident in Fig. 2. The slope of \( \overline{m}(t) \) depends on the IMF (here Salpeter, eq. 2 in Kroupa 2000c), and additional computations show a less rapid increase for a steeper IMF for massive stars. In the present models, the average mass in the centre of the cluster increases by a factor of about 10 within 3 Myr.

Heating: that the cluster is heated through mass segregation is evident in figs. 4, and 5 in KI by a decreasing central density and increasing \( R_{0.5} \), and by increasing average radii (Fig. 2), even for clusters without primordial binaries. A very rough estimate of the significance of this heating source can be attempted by comparing the change in binding energy of the massive stars, \( \Delta E_{b,m} = \)
$G M_m^2 / (4 R_m^2)$, where $R_m$ is the average radius of $m \geq 8 M_\odot$ stars at maximum contraction (Fig. 2), to the cluster binding energy, $E_{cl} = -G M_{st}^2 / (2 R_{st})$, where $R_{st}$ is the initial average radius of all stars (Fig. 2).

$$\Delta E_{b,m}/E_{cl} = (M_m/M_{st})^2 R_{st} / (2 R_m^2),$$

where $M_m/M_{st} = 0.17$ (Kroupa 2000c). One obtains $\Delta E_{b,m}/E_{cl} = 0.14, 0.22, 0.22$ ($N = 800, f_{tot} = 1.0, 0.6, 0$), 0.11, 0.09, 0.06 ($N = 3000, f_{tot} = 1.0, 0.6, 0$), and 0.04, 0.05, 0.04 ($N = 10^4, f_{tot} = 1.0, 0.6, 0$).

Heating through initial mass segregation is thus a larger contribution to the energy budget of a cluster than is cooling through the disruption of active binaries for $N \lesssim 1000$, but comparable for $N \gtrsim 3000$.

Massive sub-system: Once the massive stars assemble near the cluster core, they more or less decouple from the rest of the cluster (Hills 1975), because their velocity dispersion is significantly smaller than that of the less massive stars, which pass through the core too rapidly to interact significantly. The massive stars interact, exchanging companions for more massive contemporaries, ejecting the divorced partners, and being ejected themselves when one of the involved systems hardens sufficiently (Fig. 2). Under rare circumstances the stars may collide and form even more massive rejuvenated exotic stars which may continue interacting in the core or briefly roam Galactic space if ejected, as studied in detail by Portegies Zwart et al. (1999).

The relaxation time of the core with radius $R_c$ containing $N_c$ massive stars, $t_{rel,c} \approx 0.1 (N_c/\ln N_c) t_{cr,c}$ (BT), so that the core will relax, or significantly change its energy, within about one crossing time, $t_{cr,c}$, if $N_c \lesssim 50$. In the core, massive stars pair-up to binaries, if they are not already with massive partners. Such a binary can have a significant impact on the energy of the core if it’s
binding energy, \( e_b = -G \overline{m}^2 / (2 a_{\text{int}}) \), is comparable to the binding energy of a massive star to the core, \( E_{b,m} \approx -G N_c \overline{m}^2 / (2 R_c) \), where \( \overline{m} \) is the average stellar mass in the core, and if the cross section for encounters is sufficiently large. The former condition can be written \( \gamma \equiv E_{b,m} / e_b = (2 N_c / \beta)^{1/2} \), and the latter requires the binary-star semi-major axis to be comparable to the cross-section for one encounter per \( \beta \) crossing times in the core. From the core surface density, one obtains \( a_{\text{int}} \approx \sqrt{2R_c / (N_c \beta)} \). Thus, \( \gamma \approx 10 \) if \( N_c \approx 50 \), the massive stars being in the core for \( \beta \approx 1 t_{\text{cr,c}} \). The ejection of massive stars is very efficient under these conditions since an encounter is likely to liberate an amount of kinetic energy comparable to \( -e_b \). On the other hand, a cluster that contains \( N_c > 100 \) OB stars is less efficient in ejecting its members (\( \gamma > 10 \)).

The life-time of such a decoupled core is thus short. This can also be seen in Fig. 2, where \( N_c \approx 37 \) for all models. Thus, the “Trapezium” \( (N_c \approx 5) \), each with a mass of \( \approx 20 M_{\odot} \), and \( R_c \approx 0.05 \) pc, giving \( t_{\text{e,j,c}} \approx 0.017 \) Myr) in the core of the ONC is probably in the final stage of its decay.

**Ejection of massive stars:** The decay of the core implies the ejection of OB stars, which is dealt with in more detail in KIII.

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