Conference summary: Mass loss from stellar clusters

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1. Introduction: topics on this conference

This conference dealt with the mass loss from stars and from stellar clusters. In this summary of the cluster section of the conference, I highlight some of the results on the formation and the fundamental properties of star clusters (§2), the early stages of their evolution (§3) and go into more detail on the subsequent mass evolution of clusters (§4). A discussion on how this may, or may not, depend on mass is given in §5. Obviously, there will be a bias towards the topics where Henny Lamers has contributed. Some of the contributions to these proceedings have already reviewed extensively the topics of clusters mass loss and disruption, so I will try to fit these in a general framework as much as possible.

2. Cluster formation and fundamental properties

Star clusters are considered to be the lowest step in the hierarchical star formation scenario (see Elmegreen in these proceedings). This hierarchy is thought to result from a combination of (gravitational) fragmentation and turbulent compression in the interstellar medium (ISM), resulting in scale-free power spectra. These have been observed for the Milky Way ISM (Dickey et al. 2001) and seem also to exist for young star fields in M33 (Elmegreen et al. 2003) and NGC 628 (Elmegreen et al. 2006). Fragmentation in a turbulent medium yields power-law distributions at all scales for the mass and radius distributions. Power-law mass functions are found for the stellar mass function (e.g. Salpeter 1955) and for the cluster initial mass function (CIMF) (Battinelli et al. 1994; Zhang & Fall 1999; de Grijs et al. 2003; Bik et al. 2003), with some evidence for an upper-mass truncation (Gieles et al. 2006a; Dowell et al. 2006 and Haas et al. in these proceedings). A truncation is also found for the mass function of giant molecular clouds (Williams & McKee 1997; Rosolowsky 2005), but a solid theoretical understanding of the top end of the CIMF is still lacking. When extrapolating the cluster mass function to $N = 1$, de Wit et al. (2005) show that 4% of the O stars should form in isolation, which is in agreement with their observations. On a larger scale, complexes of stars and clusters are also characterized by scale-free power-law distributions for luminosity and radius (Ivanov 2005; Bastian et al. 2005a).

The radius distribution of clusters in M51 is well described by a power-law (Bastian et al. 2005b). For the interstellar gas clouds there is a clear relation
between radius and mass of the form $M \propto R^{-2}$, which is found back for stellar complexes (Elmegreen et al. 2001; Bastian et al. 2005a). This relation breaks down at the level of individual clusters, for which observations are more consistent with no relation between mass and radius at all (e.g. Zepf et al. 1999; Larsen 2004). For the embedded clusters in the Milky Way this relation is still present (Allen et al. 2007), suggesting that the relation gets wiped out by a combination of effects in the early stages of evolution (e.g. gas removal, dynamical mixing, tidal truncation etc.). However, the range of masses of these clusters span only a few orders of magnitude, which makes it dangerous to extrapolate this result to all masses. Several scenarios have been introduced to explain the scatter relation between cluster radius and mass, involving a mass dependent star formation efficiency (Ashman & Zepf 2001) or the early evolution were gas expulsion plays a role (Goodwin & Bastian 2006). Still, a concluding explanation can not be given yet.

Star clusters with masses in excess of a few times $10^6 \, M_\odot$ tend to be slightly larger than the typical radii found for young clusters and globular clusters ($\sim 3$ pc). The mass-radius relation for these super massive clusters is well described by the Faber-Jackson relation for elliptical galaxies, when extrapolated down to these masses (Haøgan et al. 2005; Kissler-Patig et al. 2006 and in these proceedings). When clusters form through merging of multiple clusters into a single massive object, the final radius is somewhat larger than the typical radii ($\sim 3$ pc) of clusters of lower mass (Fellhauer & Kroupa 2005). This points at a difference between the formation process of clusters with $M \lesssim 10^6 - 10^7 \, M_\odot$ and those with $M \gtrsim 10^6 - 10^7 \, M_\odot$ (Kissler-Patig et al. 2006).

3. Early evolution

The early evolution (first $\sim 10$ Myr) of clusters is dictated predominantly by the removal of left-over gas (not used for star formation) by stellar winds from early-type stars. This removes a significant fraction of the binding energy of the embedded cluster on a time-scale shorter than, or comparable to, the crossing time of stars in the cluster. This causes the cluster to expand, lose mass or even completely dissolve (e.g. Hills 1980; Goodwin 1997; Kroupa et al. 2001; Geyer & Burkert 2001). The simulations of clusters including residual gas expulsion generally assume a spherically symmetric gas configuration and instantaneous gas removal, resulting in an unbound cluster whenever the star formation efficiency is less than 50%, i.e. when the total gas mass that is expelled equals the mass of the stars. Detailed hydrodynamic calculations, taking into account the clumpiness of the gas, show that only a small fraction of the gas is accelerated to high velocities, escaping through irregular outflow channels, causing a larger fraction of stars to remain bound (Dale et al. 2005 and Clarke in these proceedings). From observations it appears that some clusters remove their primordial gas more efficiently than others. For example, the extremely young (1 ± 1 Myr, Stolte et al. 2004) Galactic cluster NGC 3603 has cleared its inner region, while NGC 346 in the Small Magellanic Cloud is still surrounded by gas, even in its core, whereas its age is 3 ± 1 Myr (Sabbi et al. 2007 and Nota in these proceedings).
Rapidly expanding clusters have a wide range of implications on the evolution of galactic discs (Kroupa 2005), the CIMF (Boily & Kroupa 2003) and the early disruption, or infant mortality, of clusters (Lada & Lada 2003). In addition, estimates of dynamical masses at young ages ($\lesssim 30$ Myr) are affected, since these rely on the assumption that the cluster is in virial equilibrium, which is not the case right after gas expulsion (Goodwin & Bastian 2006).

Several observational confirmations of the infant mortality scenario have become available recently. The most direct one comes from the age distribution ($dN/dt$) of (young) clusters. For the solar neighbourhood Lada & Lada (2003) find that there is a steep drop in $dN/dt$ going from the embedded ($\lesssim 3$ Myr) clusters to the young clusters that have expelled their gas ($\gtrsim 3$ Myr), corresponding to $\sim 90\%$ infant mortality. This value was confirmed independently, by determining the mean formation rate of bound clusters in the last few Gyrs, correcting for various disruption processes, and comparing this to the total star formation rate following from field stars (Lamers & Gieles 2006 and in these proceedings).

Fall et al. (2005) and Bastian et al. (2005a) derive similar values for the infant mortality rates for the clusters in the Antennae galaxies and M51, respectively. A novel approach is presented by Pellerin et al. (2007) (also in these proceedings). They study groupings of individual stars of different spectral type in nearby (few Mpc) spiral galaxies using HST/ACS data. The O stars are strongly clustered, while the B stars are more equally spread out over the disc, suggesting that infant mortality works on time-scales comparable to the life-time of O stars. From the surface brightness profiles of slightly resolved clusters, Bastian & Goodwin (2006) find evidence of escaping stars in the outer halo of young (few Myrs) clusters from high resolution HST/HRC imaging.

4. The evolution of the (globular) cluster mass function

Larsen (in these proceedings) highlights some of the standing problems in our understanding of the globular cluster mass function (GCMF). The general picture is that clusters form from a universal power-law CIMF with index $-\alpha = -2$, as is observed for young clusters in several galaxies (e.g. Zhang & Fall 1999; de Grijs et al. 2003; Bik et al. 2003). Through dynamical evolution, the low-mass clusters are preferentially destroyed, causing the GCMF to turn-over (e.g. Chernoff & Weinberg 1990; Fall & Zhang 2001). Although the general idea is quite established, there are still several issues to be resolved. First, if dynamical evolution removes low-mass clusters, then the location of the turn-over in the GCMF, i.e. the turn-over mass, will depend on the strength of the tidal field. This implies a decrease of the turn-over mass with galactocentric distance ($R_G$), because the strength of the tidal field decreases with $R_G$.

However, from observations it follows that the turn-over mass is almost universal among different galaxy types and independent of $R_G$ (e.g. Richtler 2003). Solutions to overcome this problem have been introduced in analytical models, such as including a strongly increasing velocity anisotropy with $R_G$ (Fall & Zhang 2001). Observations of globular cluster kinematics have shown
that these assumptions are not realistic (e.g. Côté et al. 2001 for the M87 clusters).

The term “turn-over” can be misleading. The $dN/d\log M$ distribution, or the magnitude distribution (since the magnitude scales with the logarithm of the mass, assuming a constant $M/L$-ratio), is peaked. A $dN/dM$ representation of the GCMF is flat on the low-mass end and on the high-mass end it approaches the (initial?) power-law distribution with index $-2$ (see Fig. 2 of Larsen in these proceedings).

If the disruption time of clusters ($t_{\text{dis}}$) depends on their mass as a power-law with index $\gamma$, then the low-mass end of a single-age population evolves to a power-law with index $1 - \gamma$ (Lamers et al. 2005a). A flat $dN/dM$ distribution is thus achieved when $\gamma = 1$. It is worth noting that the final index is independent of the initial index $\alpha$, implying that the low-mass end of the globular cluster MF reflects only disruption and not formation. This holds of course only if the initial index $-\alpha$ is smaller than $1 - \gamma$. The evolution of GCMFs that are bell-shaped initially are discussed by Vesperini (2000).

For a multi-age population which has formed with a continuous rate and for which the age spread is much larger than the typical $t_{\text{dis}}$, the index of the $dN/dM$ distribution approaches a value of $\gamma - \alpha$ (Boutloukos & Lamers 2003) (BL03), which is $-1$ in the case of $-\alpha = -2$ and $\gamma = 1$, i.e. steeper by an index 1 as compared to the single-age case. This type of multi-age populations were studied by BL03 and they find a mean index of the mass function of $\simeq -1.4$, implying $\gamma \simeq 0.6$, for the cluster populations in the SMC, M33, M51 and the solar neighbourhood.

5. Some notes on $\gamma$

The value of $\gamma = 1$ is needed to get the flat $dN/dM$ distribution of the GCMF on the low-mass end, while BL03 find $\gamma \simeq 0.6$ from the $dN/dM$ distribution of clusters with ages up to a few Gyr. Did globular clusters evolve differently than their younger counterparts? Or did globular clusters not form with the same initial mass function as clusters now?

There is theoretical support for a value of $\gamma = 0.6$. The arguments are as follows: Baumgardt (2001) showed that $t_{\text{dis}}$ depends on the relaxation time ($t_{\text{rh}}$) and the crossing time ($t_{\text{cr}}$) of stars in the cluster as $t_{\text{dis}} \simeq t_{\text{rh}}^x t_{\text{cr}}^{-x}$ which, with the expressions for $t_{\text{rh}}$ and $t_{\text{cr}}$ from Spitzer (1987), can be reduced to

$$t_{\text{dis}} \propto \left[ \frac{N}{\ln \Lambda} \right]^x \left[ \frac{r_h}{M} \right]^{3/2},$$

(1)

with $\Lambda$ the Coulomb logarithm which scales with $N$ as $\Lambda \simeq 0.1 N$ (Spitzer 1987) and $r_h$ the half-mass radius of the cluster. Baumgardt & Makino (2003) verified this relation using detailed $N$-body simulations of clusters dissolving in the Galactic tidal field and they found that $x \simeq 0.75$. They assumed that clusters are initially in tidal equilibrium with the Galaxy, implying a constant cluster density, i.e. $r_h \propto M^{1/3}$ with $\lambda = 1/3$, at a given galactocentric distance. This reduces Eq. 1 to $t_{\text{dis}} \propto \left[ N/\ln \Lambda \right]^{0.75}$. The same scaling of $t_{\text{dis}}$ with $N$ was found by Vesperini & Heggie (1997). Lamers et al. (2005a) showed that this relation
can be well approximated by \( t_{\text{dis}} \propto N^{0.6} \), agreeing with the empirical findings of BL03. The scaling of \( \Lambda \) with \( N \) is often ignored by taking \( \ln \Lambda \) constant (e.g. Fall & Zhang 2001). Combined with the assumption of a constant cluster density, i.e. \( \lambda = 1/3 \), then this results in a linear scaling of \( t_{\text{dis}} \) with \( N \) (Eq. 1), equivalent to \( \gamma = 1 \), which is required to model the low-mass end of the GCMF (Waters et al. 2006). However, this value of \( \gamma \) does not follow from recent \( N \)-body simulations, but from the assumptions that \( t_{\text{dis}} \) scales linearly with \( t_{\text{rh}} \), a constant \( \Lambda \) and a constant cluster density.

The assumption of Baumgardt & Makino (2003) and Vesperini & Heggie (1997) that clusters start tidally limited, i.e. \( \lambda = 1/3 \), is also not realistic. From recent observations it follows that the relation between \( r_{\text{h}} \) and \( M \) is much shallower, i.e. \( \lambda \approx 0.1 \) (e.g. Zepf et al. 1999; Larsen 2004; Bastian et al. 2005). With such a mass-radius relation, the massive clusters are not filling their “Roche lobe”. This situation was considered in \( N \)-simulations by Tanikawa & Fukushige (2005). They modeled the disruption of clusters in weak tidal fields, where the tidal radius of the clusters is smaller than the Roche lobe radius. They find that in those cases \( x \approx 0.9 \), i.e. almost as if the cluster is evolving in isolation (then \( x \equiv 1 \), Spitzer 1987). Hence, \( x \) depends on \( \lambda \). Lets consider the case of a realistic mass-radius relation, i.e. \( \lambda = 0.1 \) (Larsen 2004). Assume a constant mean stellar mass, i.e. \( M \propto N \) and lets approximate \( N/\ln \Lambda \) by \( N/0.85 \), which is a good approximation for \( N \gg N/\Lambda \approx 10 \). This, combined with \( x \approx 1 \) and Eq. 1 results in \( \gamma \approx 0.5 \). When clusters are disrupted by external perturbations (e.g. disc/bulge shocks, encounters with giant molecular clouds or spiral arms), \( t_{\text{dis}} \) scales with the cluster density (\( \rho_{\text{c}} \)) (e.g. Spitzer 1987; Gieles et al. 2006c; Gieles et al. 2007), which combined with \( \lambda = 0.1 \) results in \( t_{\text{dis}} \propto M^{0.7} \), again a value for \( \gamma \) that is smaller than 1.

In neither of the cases described above we get \( \gamma = 1 \) needed for the low-mass end of the GCMF. Hence not only the universality of the turn-over mass, but also the shape of the GCMF can not be explained by the standard picture where clusters start with a power-law CIMF with index \( -2 \) and evolve dynamically. The three predicted values for \( \gamma \) are quite close to the observationally determined value of \( \gamma = 0.62 \pm 0.06 \) (BL03).

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