The Influence of Gas Expulsion on the Evolution of Star Clusters

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Abstract. We present new results on the dynamical evolution and dissolution of star clusters due to residual gas expulsion and the effect this has on the mass function and other properties of star cluster systems. To this end, we have carried out a large set of N-body simulations, varying the star formation efficiency, gas expulsion time scale and strength of the external tidal field, obtaining a three-dimensional grid of models which can be used to predict the evolution of individual star clusters or whole star cluster systems by interpolating between our runs. When applied to the Milky Way globular cluster system, we find that gas expulsion is the main dissolution mechanism for star clusters, destroying about 80% of all clusters within a few 10s of Myers. Together with later dynamical evolution, it seems possible to turn an initial power-law mass function into a log-normal one with properties similar to what has been observed for the Milky Way globular clusters.

Keywords. stellar dynamics, methods: n-body simulations, galaxies: star clusters

1. Introduction

It is well known that most, if not all, stars form in star clusters. Star clusters form as so called embedded clusters within the dense cores of giant molecular clouds. The star formation efficiency (SFE), i.e. the fraction of gas that is converted into stars, can be defined as follows:

$$\epsilon = \frac{M_{ecl}}{M_{ecl} + M_{gas}} \tag{1.1}$$

where M_{ecl} is the total mass of stars formed in the embedded cluster and M_{gas} the mass of the gas not converted into stars. Inside molecular cloud cores, the star formation efficiency is usually smaller than $\epsilon < 30\%$ (Lada & Lada 2003), which implies that once the primordial gas is expelled by UV radiation and massive stellar winds from OB stars or supernova explosions, star clusters will become super-virial and their further dynamical evolution will be strongly affected by the gas loss.

If the star formation efficiency or gas expulsion time scale depends on the mass of the cluster, residual gas expulsion can also influence the mass function of star cluster systems. For example, observations of globular cluster systems show that globular clusters follow a bell shaped distribution in luminosity with an average magnitude of $M_V^0 \approx -7.3$ and dispersion $\sigma_V = 1.2$. For a mass-to-light ratio of $M/L_V = 1.5$, this corresponds to a characteristic cluster mass of $M_C = 1.1 \cdot 10^5 M_\odot$.

Their bell-shaped luminosity function sets globular clusters apart from young, massive star clusters in starburst and interacting galaxies and the open clusters of the Milky Way and other nearby spiral galaxies, which generally follow a power-law distribution over luminosities down to the smallest observable clusters, and the question arises whether the luminosity function of globular clusters is of primordial origin or whether globular

clusters also started with a power-law mass function and the present-day peak is due to the quicker dynamical evolution and preferential destruction of the low-mass clusters.

2. N-body simulations of gas expulsion

We have performed a large parameter study of residual gas expulsion from star clusters, varying the star formation efficiency, the ratio of the gas expulsion time scale to the crossing time of the star cluster and the ratio of the half-mass radius to the tidal radius of the star cluster. This grid of models will be useful in later studies of individual star clusters and also whole star cluster systems since the evolution of the clusters can be determined by interpolation between our grid points, without the need for further simulations. This makes it possible to determine the effect of gas expulsion on whole cluster systems where the large number of clusters prevents simulations for all individual clusters.

In our runs, we assumed that the SFE does not depend on the position inside the cluster, so gas and stars follow the same density distribution initially, which was given by a Plummer model. The gas was not simulated directly, instead its influence on the stars was modelled as a modification to the equation of motion of stars. We used the collisional N-body code NBODY4 (Aarseth 1999) on the GRAPE computers of Bonn University to perform the simulations. All simulated clusters contained 20.000 equal-mass stars initially and simulations were run for 1000 initial N-body times (equivalent to about 300 initial crossing times).

Gas expulsion was assumed to start at a certain time t_D, which was set equal to one N-body time unit. After the delay time t_D, the gas density was decreased exponentially on a characteristic time τ_M, so the total gas left at later times is given by:

$$M_{gas}(t) = M_{gas}(0)\, e^{-(t-t_D)/\tau_M} \,. \tag{2.1}$$

The influence of the external tidal field was modelled in the so-called 'Near Field Approximation', which assumes that the size of the star cluster is much smaller than its distance from the galactic centre.

Within the framework of our model, the fate of a star cluster can be deduced by specifying only three parameters: The star formation efficiency ϵ, the ratio of the gas expulsion time scale to the crossing time t_{Cross} of the star cluster, and the strength of the external tidal field, quantified by the ratio of the half-mass radius r_h to the tidal radius r_t. This reduction in the number of parameters makes it feasible to run a grid of models covering the complete parameter space. The following values were chosen as grid-points:

ϵ: 5%, 10%, 15%, 20%, 25%, 33%, 40%, 50%, 75%

r_h/r_t: 0.01, 0.033, 0.06, 0.1, 0.15, 0.2

τ_M/t_{Cross}: 0.0, 0.05, 0.10, 0.33, 1.00, 3.0, 10.0

Fig. 1 compares our results for the bound mass fraction as a function of the star formation efficiency with published results from the literature. Shown are cases where the gas is removed instantaneously (right group of points) and cases of slow gas removal. It can be seen that for instantaneous gas removal there is very good agreement between the results of this paper and published results. SFEs of 33% already lead to a final bound cluster, although only a very small mass fraction remains bound in this case. For a SFE of 50%, about 70% of the total cluster mass remains bound. In case of near adiabatic gas removal, we find that the critical SFE needed to produce a bound cluster is between 5% to 10%. This is about 5% smaller than what Geyer & Burkert (2001) found for their
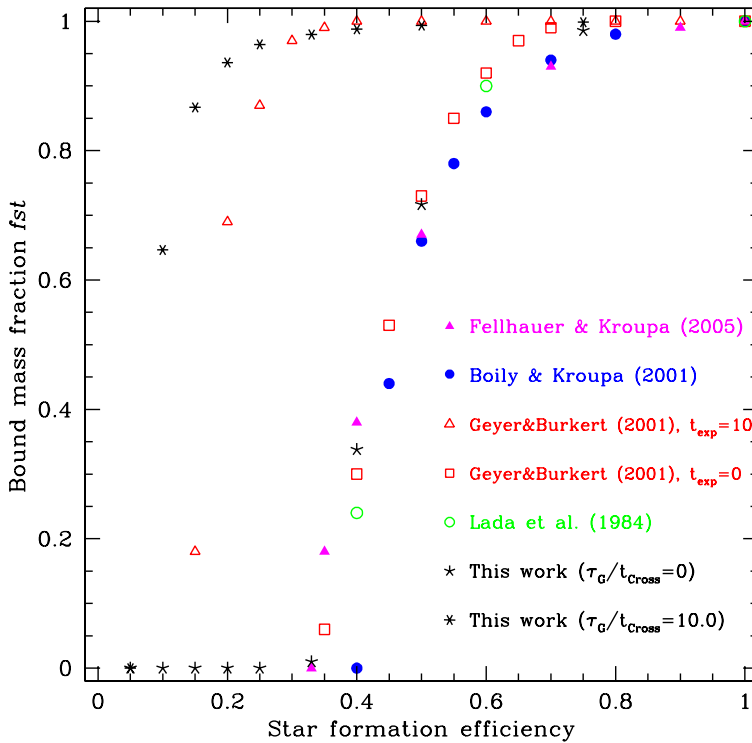
Figure 1. Comparison of the surviving mass fraction derived in this work with results from the literature. For instantaneous gas removal (right group of points) there is very good agreement between both. For slow gas removal (left points, stars and open triangles), the critical SFE needed to produce a bound cluster determined here is about 5% smaller than the one found by Geyer & Burkert (2001). This can be explained by the different initial density profiles and the fact that Geyer & Burkert (2001) assumed linear gas removal while we assume an exponential one.

model N2 with $t_{exp} = 10$. Performing additional N-body runs shows that the difference becomes significantly smaller if we let the gas fraction decrease linearly with time, as was done by Geyer & Burkert (2001). The remaining difference is probably due to the different density profiles. Geyer & Burkert (2001) used King $W_0 = 3$ and $W_0 = 5$ models in their runs, which are significantly less concentrated than the Plummer models we use. More results of our simulations can be found in Baumgardt & Kroupa (2007a).

3. Influence of gas expulsion on star cluster systems

In order to study the influence of gas expulsion on star cluster systems, we assume that pre-cluster molecular cloud cores are distributed with a power-law mass function $dN/dM_{Cl} \sim M_{Cl}^{-\beta_{Cl}}$ between lower and upper mass limits of $M_{Low} = 10^3 M_{\odot}$ and $M_{Up} = 10^7 M_{\odot}$. The star formation efficiencies ϵ are assumed to follow a Gaussian distribution with a mean of 25% and dispersion of 10%. The cluster radii are assumed to follow a Gaussian distribution with dispersion $\log \sigma_R/\mathrm{pc} = 0.2$ and various means given by $\log r_h/\mathrm{pc} = \log r_{hm} + k_r \log R_{GC}/\mathrm{kpc}$, i.e. our distributions are allowed to change with galactocentric distance. Most of our simulations had $\log r_{hm} = -0.3$ and $k_r = 0.2$.

We then study the influence of various destruction mechanisms on the mass function of star clusters. In particular, we study the influence of gas expulsion, stellar evolution,

two-body relaxation and an external tidal field, disc shocks and dynamical friction. The influence of gas expulsion was modelled by interpolating between the grid of runs made above. Interpolation was done by using the 8 grid points surrounding the position of each cluster and then by linearly interpolating in each coordinate. Stellar evolution reduces the masses of star clusters by about 30%. We applied stellar evolution mass loss after gas expulsion and before the other mechanisms, since most mass lost from star clusters due to stellar evolution is lost within the first 100 Myer. The effects of two-body relaxation and a spherical external tidal field were modelled according to the results of Baumgardt & Makino (2003). According to Baumgardt & Makino (2003), the lifetime of a star cluster moving through an external galaxy with circular velocity V_C on an orbit with pericentre distance R_P and eccentricity e is given by

$$\frac{t_{DisR}}{[\text{Myr}]} = k \left(\frac{N}{ln(0.02\,N)} \right)^x \frac{R_P}{[\text{kpc}]} \left(\frac{V_C}{220\text{km/sec}} \right)^{-1} (1+e). \qquad (3.1)$$

Here N is the number of cluster stars left after gas expulsion, which can be calculated from the cluster mass and the mean mass of the cluster stars as $N = M_C/<m>$. x and k are constants describing the dissolution process and are given by $x = 0.75$ and $k = 1.91$ (Baumgardt & Makino 2003). Disc shocks and dynamical friction were modelled according to the equations 7-72 and 7-26 of Binney & Tremaine (1987).

The gas expulsion timescales are derived by comparing the energy input from massive stars through stellar winds and supernova explosions with the total energy of a gas cloud. From this, we derive the following relation for the gas expulsion timescale τ_M (see Baumgardt & Kroupa (2007b) for a complete discussion):

$$\tau_M = E_{Gas}/\dot{E} = 7.1 \cdot 10^{-8} \frac{1-\epsilon}{\epsilon} \frac{M_C}{[M_\odot]} \left(\frac{r_h}{[pc]} \right)^{-1} \text{Myr}, \qquad (3.2)$$

where M_C is the mass of the cluster and r_h its half-mass radius. The gas expulsion time increases with cluster mass since more massive gas clouds have deeper potential wells, so it takes longer until the gas is expelled from them.

Fig. 2 depicts the resulting evolution of the mass function of clusters if we apply the above calculations to the globular cluster system of the Milky Way and evolve the system for a Hubble time. It can be seen that most low-mass clusters are destroyed as a result of residual gas expulsion. In total, only 21% of all clusters survive residual gas expulsion, mostly those starting with high masses. Due to the efficient destruction of low-mass clusters, the overall mass function develops a turnover and is in agreement with the observed mass function of globular clusters for both inner and outer star clusters.

4. Conclusions

We have performed a large grid of simulations studying the impact of initial gas expulsion on the survival rate and final properties of star clusters, varying the star formation efficiency, ratio of gas expulsion timescale to the crossing time of the cluster and the strength of the external tidal field.

Our simulations show that both the star formation efficiency and the speed with which the gas is removed have a strong influence on the evolution of star clusters. In case of instantaneous gas removal, clusters have to form with SFEs $\geqslant 33\%$ in order to survive gas expulsion. This limit is significantly lowered for gas removal on longer timescales and clusters with SFEs as low as 10% can survive gas expulsion in the adiabatic limit if the external tidal field is weak.
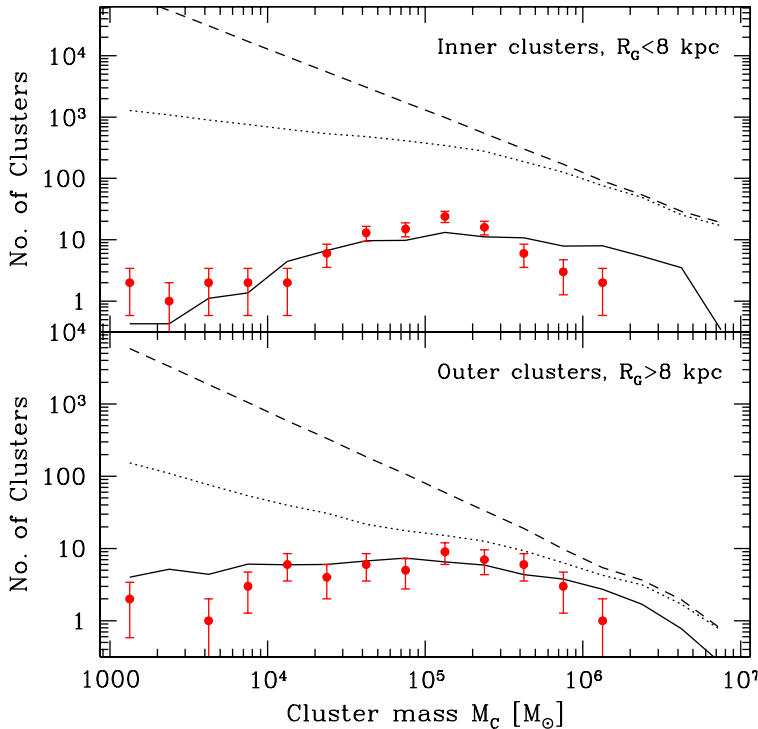
Figure 2. Mass distribution of star clusters before gas expulsion (dashed lines), after gas expulsion (dotted lines) and after a Hubble time (solid lines), compared to the observed distribution of Milky Way clusters (points). Most low-mass clusters are destroyed by residual gas expulsion. The distribution of surviving clusters is in good agreement with the observed one for both inner and outer clusters.

We have then applied these simulations to follow the evolution of the galactic globular cluster system. We assumed that globular clusters start with power-law mass functions, similar to what is observed for the galactic open clusters and young, massive star clusters in interacting galaxies. The dissolution of the clusters was then studied under the combined influence of residual gas expulsion, stellar mass-loss, two-body relaxation and an external tidal field.

We find that residual gas expulsion is the main dissolution mechanism for star clusters, destroying about 80% of them within a few 10s of Myr. It seems possible to turn an initial power-law mass function into a log-normal one, because clusters with masses between 10^4 to $10^5 \, M_\odot$ lose their residual gas on a timescale shorter than their crossing times as indicated by our feedback analysis. Stars released from these clusters become halo field stars. It seems possible that all halo stars originated from dissolved star clusters.

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