Dynamical evolution of star clusters with top-heavy IMF

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Abstract. Several observational and theoretical studies suggest that the initial mass function (IMF) slope for massive stars in globular clusters (GCs) depends on the initial cloud density and metallicity, such that the IMF becomes increasingly top-heavy with decreasing metallicity and increasing the gas density of the forming object. Using N-body simulations of GCs starting with a top-heavy IMF and undergo early gas expulsion within a Milky Way-like potential, we show how such a cluster would evolve. By varying the degree of top-heaviness, we calculate the dissolution time and the minimum cluster mass needed for the cluster to survive after 12 Gyr of evolution.

Keywords. star clusters, N-body simulation, initial mass function.

1. Introduction

Globular clusters (GCs) lose stars as a result of stellar and dynamical evolution. While the external effects caused by the gravitational field of the host galaxy might ultimately destroy GCs, the internal effects such as stellar evolution, stellar mass segregation, stellar remnants, and binaries can remove stars from GCs in a more subtle way, ultimately altering their dynamical structure and providing escapee stars that contribute to the host galaxy. The initial condition of star clusters determines the fate of a star cluster and the stars it loses to their host galaxy.

The initial mass function (IMF) of stars within an embedded cluster is one of the most important initial conditions that plays a significant role in star cluster evolution. Most studies of resolved stellar populations in the disk of the Milky Way showed that stars form following an IMF that has a universal form (Kroupa (2001); Kroupa (2002); Kroupa *et al.* (2012)) which is referred to as the "canonical" IMF. This poses a problem for star formation theories which predict a dependence on the environment where star formation takes place. The shape of the stellar IMF of a star cluster near its upper mass limit is a focal topic of investigation as it determines the high mass stellar content and hence the dynamics of the cluster at its embedded phase. Observation indicates that the IMF may depends on the star formation environment (cloud density and metallicity) and becomes top-heavy (i.e., overabundant in high-mass stars) under extreme starburst conditions (Dabringhausen *et al.* (2009); Dabringhausen (2012)). The data suggest that the IMF-slope is flatter in denser and metal-poorer environments. The need for top-heavy IMF also has been put forward to explain the observed trend of metallicity and M/L ratio found in $M31$ GC system, which shows a discrepancy with the SPS prediction (Zonoozi *et al.* (2016) and Haghi *et al.* (2017)). If this was the case, the evolution of GCs can

significantly change due to the different mass loss rates and number of black holes (BHs) formed and consequently affects on our understanding of the GC survival. While many aspects of the residual-gas expulsion in the embedded cluster with the universal IMFs have already been studied in the literature (Baumgardt & Makino (2003); Baumgardt & Kroupa (2007)), nobody has so far tried to perform a systematic study of the survival rate of the star clusters evolving under residual-gas expulsion with a varying IMF. Here, we investigate the pure effect of the top-heaviness of the IMF on the dissolution rate of GCs. We calculate a grid of models with a wide range of stellar masses, that undergo primordial residual-gas expulsion, and have a varying the MF-slope in the high-mass range.

2. The models

We ran simulations with different initial cluster masses in the range $M_i = 10^4$ to $3 \times 10^5 M_\odot$. For the initial density profile of the clusters, we consider the Plummer profiles in virial equilibrium. The corresponding size scale was set by the initial $3D$ half-mass radius, r_{hi}, following Marks & Kroupa (2012) as $r_{hi} = 0.1 \times \left(\frac{M_{ecl}}{M_\odot}\right)^{0.13}$ pc. Therefore the initial $3D$ half-mass radii of all models vary from 0.33 to 0.52 pc. We use N-body code NBODY6 (Aarseth (2003) and Nitadori & Aarseth (2012)) to evolve model star clusters from zero age to 12 Gyr, over a range of initial half-mass radii, embedded cluster mass, and stellar IMF-slope at high-mass range (i.e., $M > 1 M_\odot$). The dissolution times, T_{diss}, is defined to be the time when 95% of the initial number of the stars are lost from a cluster. All clusters move on circular orbits with circular velocity $V_G = 220 km s^{-1}$ at galactocentric radius $R_G = 8.5\, kpc$ through an external galaxy that follows an NFW potential. The range of stellar masses was chosen to be from 0.08 to $100 M_\odot$ and the metallicity of the clusters is Z = 0.001 dex. Gas expulsion is assumed to start at a certain time $t_D = 0.6$ Myr. The star formation efficiency is assumed to be equal to $\epsilon = 0.33$ in all models. The gas is not simulated directly, instead, its influence on the stars is modeled as a modification to the equation of motion of stars. The stellar IMF is adopted in the form of a three-segment power-law function as follow

$$\xi(m) \propto m^{-\alpha} : \begin{cases} \alpha_1 = 1.35, & 0.08 < \frac{m}{M_\odot} < 0.50 \\ \alpha_2 = 2.35, & 0.50 < \frac{m}{M_\odot} < 1.00 \\ \alpha_3, & 1.0 < \frac{m}{M_\odot} < 100.0 \end{cases} \tag{2.1}$$

In order to cover the canonical and top-heavy IMF, α_3 is varied from 1.5 to 2.3.

3. Dissolution time of star clusters

At the beginning of the evolution, the mass-loss is dominated by gas expulsion and early mass-loss associated with stellar evolution of massive stars. All models expand violently and lose a fraction of their stars. Depending on the abundance of heavy stars in each model which is determined by α_3, clusters lose 30% to 80% of their mass within the first 100 Myr by early stellar evolution. In order to understand how the top-heaviness of the IMF (i.e., the value of α_3) influences the half-mass radius of bound stars and the amount of mass lost by a star cluster during the evolution, we first consider initially identical star clusters but with different degree of the top-heaviness. The time evolution of the total masses and half-mass radii of stars bound to the clusters are shown in Figure 1. The initial mass and initial half-mass radius are the same but five different values are assigned to α_3. All models evolve for 12 Gyr unless they are disrupted before. We plot the initial cluster mass of $10^5 M_\odot$ as representative of all models. We find that increasing the degree of top-heaviness of the IMF significantly affects the evolution of the cluster.
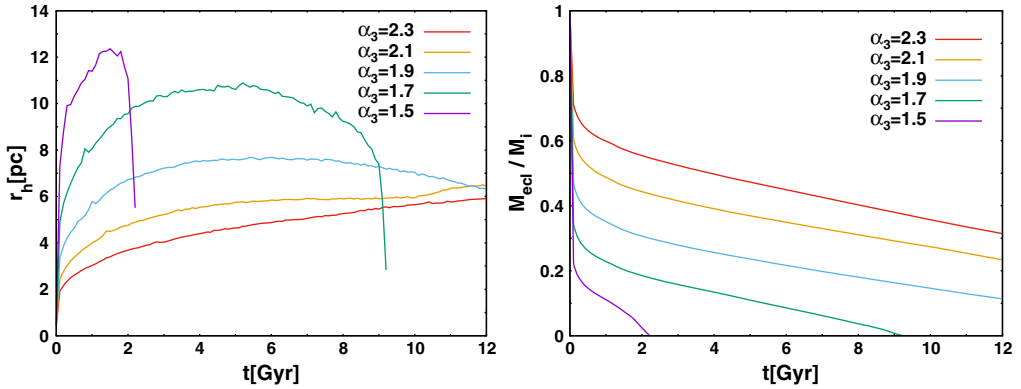
Figure 1. The evolution of the 3D half-mass radius and the total mass of a cluster with the initial mass and radius of $10^5 M_\odot$ and $r_h = 0.45$ pc for different initial values for α_3.
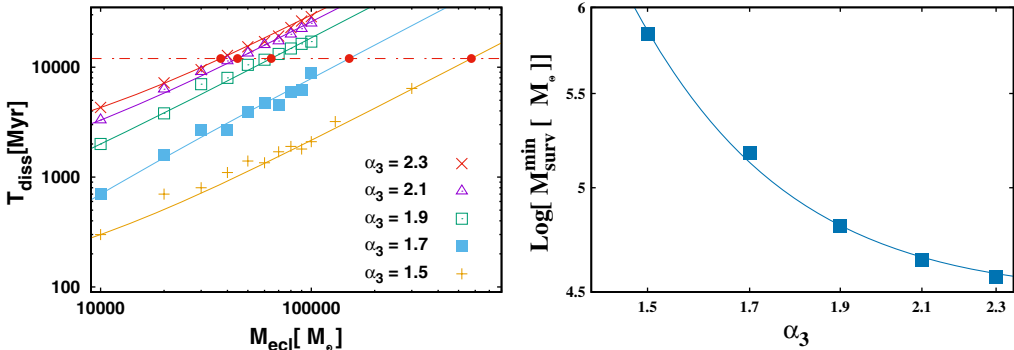

Figure 2. Left: The dissolution time versus the mass of star clusters for various α_3. The points show the results of N-body simulation for given initial mass and α_3 until dissolution time. The horizontal dashed red line indicates $t = 12$ Gyr. The rising solid lines show the results of our linear fit to the results of the simulations by Equation (3.1) for each α_3 from 1.5 to 2.3. The filled black circles show the minimum survived mass of the cluster for each α_3. Right: Plotted is the minimum survived mass of clusters (M_{surv}^{min}) for various α_3. The filled squares show the minimum mass of clusters for every α_3: clusters heavier than these points will survive after 12 Gyr. The solid line is our best fit.

The mass loss rate is higher for the cases with more top-heavy IMF. The cluster loses about 80% of its mass by early rapid gas expulsion and stellar evolution in the case of top-heavy IMF (with $\alpha_3 = 1.5$), but this value decreases 30% for clusters with canonical IMF (with $\alpha_3 = 2.3$). Consequently, the clusters with top-heavy IMF dissolve faster than the clusters with the canonical IMF.

Figure 2 depicts the cluster lifetimes T_{diss} as a function of the initial embedded cluster mass M_{ecl} for various IMF parameterizing with α_3. As can be seen, the dissolution time of clusters increases linearly with initial M_{ecl}. However, even though the strength of the tidal gravitational interaction due to the host galaxy is the same for both canonical and top-heavy IMF, dissolution is faster for clusters with the more top-heavy IMF (i.e. lower α_3). This is due to the larger amount of impulsive mass-loss from stellar evolution from clusters with the more top-heavy IMF and rapid gas expulsion which leads to a strong expansion. We find that the dissolution time scales as

$$log_{10} [T_{diss}(\alpha_3)] = a(\alpha_3) \, log_{10} [M_{ecl}] + b(\alpha_3), \tag{3.1}$$

where, the coefficients $a(\alpha_3)$ and $b(\alpha_3)$, in general, depend on the degree of top-heaviness. For all models, the slopes marginally are the same within the 2σ error bars and is nearly independent of the α_3 parameter. The best-fit values of a and b as a function of α_3 are $a(\alpha_3) = (-0.11 \pm 0.13) \ \alpha_3 + (1.10 \pm 0.25)$ and $b(\alpha_3) = (1.88 \pm 0.47) \ \alpha_3 - (3.98 \pm 0.91)$. Therefore, for any system with initial top-heavy IMF, it is possible to find out the dissolution time by these functions and Eq. (3.1).

We obtain a relation for the minimum surviving mass of the cluster (M_{surv}^{min}, i.e., the minimum initial mass of the star cluster that survives within a Hubble time) as a function of α_3. The horizontal dashed line in Fig. 2 shows the time $=12$ Gyr. The intersection of $T_{diss} - M_{ecl}$ relation for each value of α_3 with this horizontal line (red circles) specifies the corresponding M_{surv}^{min}. Determining the M_{surv}^{min} might help to understand the contribution of the dissolved star clusters in making and heating the Galactic thick disc.

Figure 2 (right panel) shows the minimum surviving mass for different values of α_3. By a polynomial least-square fit to the data we found that the minimum surviving mass scales with α_3 as $log_{10}(M_{surv}^{min}/M_\odot) = A \ (\alpha_3)^{-\eta} + B$, where, the coefficients $A = 15.7$, $\eta = 6$ and $B = 4.5$. Therefore, for a given value of α_3 one can calculate the mass of the embedded clusters that survive after a Hubble time. For example, when $\alpha_3 = 1.5$ the clusters heavier than $7 \times 10^5 M_\odot$ will survive after 12 Gyr of evolution, while for the canonical IMF, all clusters with the mass lower than $4 \times 10^4 M_\odot$ will be dissolved.

4. Conclusions

We have performed a large grid of simulations studying the impact of varying the degree of top-heaviness with the initial half-mass radius derived from Marks & Kroupa (2012) and initial gas expulsion on the survival rate and final properties of star clusters. Our simulations show that the degree of top-heaviness have a strong influence on the evolution of star clusters. All star clusters expand due to gas expulsion and for various α_3, star clusters expand by a factor of 3 or 4.

Open or globular clusters must, therefore, have formed more compact and with higher central densities than with what they have today. The simulations reported here should be useful for a number of follow-up projects. Our computations also allow us to study the impact of various α_3 on the evolution of dissolution time of whole embedded cluster systems in galaxies. The mass fraction remaining bound to each individual cluster, half-mass radius, the dissolution time and the expansion rate can be calculated by interpolating between the runs in our grid.

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