The impact of metallicity and dynamics on the evolution of young star clusters

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Abstract The early evolution of a dense young star cluster (YSC) depends on the intricate connection between stellar evolution and dynamical processes. Thus, N-body simulations of YSCs must account for both aspects. We discuss N-body simulations of YSCs with three different metallicities ($Z = 0.01, 0.1$ and $1 Z_\odot$), including metallicity-dependent stellar evolution recipes and metallicity-dependent prescriptions for stellar winds and remnant formation. We show that mass-loss by stellar winds influences the reversal of core collapse. In particular, the post-collapse expansion of the core is faster in metal-rich YSCs than in metal-poor YSCs, because the former lose more mass (through stellar winds) than the latter. As a consequence, the half-mass radius expands more in metal-poor YSCs. We also discuss how these findings depend on the total mass and on the virial radius of the YSC. These results give us a clue to understand the early evolution of YSCs with different metallicity.

1 Introduction

The densest young star clusters (YSCs) are collisional environments: their central two-body relaxation timescale ($t_{\text{rlx}}$) is generally shorter than 100 Myr. For a realistic initial mass function (IMF), YSCs are expected to undergo core collapse (CC) in less than $t_{\text{rlx}}$. The reversal of CC is generally ascribed to hard binaries (i.e. binaries whose binding energy is higher than the average kinetic energy of a star in the cluster), because they transfer kinetic energy to stars through three-body encounters.

It has long been debated whether mass-loss by stellar winds and/or supernovae (SNe) is efficient in affecting CC (e.g. [Mapelli & Bressan 2013], and references therein). Stellar winds and SNe eject mass from a star cluster, making the central potential well shallower and quenching the onset of gravothermal instability. Furthermore, stellar winds are expected to depend on metallicity ($Z$): metal-poor stars lose less mass than metal-rich ones (e.g. [Vink et al. 2001]). Thus, the effect of stellar winds on CC is expected to be stronger at high $Z$. In this paper, we investigate the impact of $Z$-dependent stellar winds and SNe on the CC of YSCs, by means of direct-summation N-body simulations.

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2 Method and simulations

We adopt the STARLAB public software environment \cite{PortegiesZwart2001}, in the version modified by \cite{Mapelli2013}. This version includes recipes for Z-dependent stellar evolution \cite{Hurley2000}, stellar winds \cite{Vink2001} and direct collapse of massive metal-poor stars \cite{Mapelli2009}. The initial conditions of the simulated YSCs have been generated following a King profile. The mass of each simulated particle (which corresponds to a single star) has been randomly drawn from a Kroupa IMF with minimum and maximum mass 0.1 and 150 M\(_\odot\), respectively. The runs discussed in this paper are the following.

**Set A:** 300 N-body realizations of YSCs with virial radius \(r_{\text{vir}} = 1\) pc, dimensionless central potential \(W_0 = 5\), particle number \(N_* = 5 \times 10^3\). These runs have already been discussed in \cite{Mapelli2013}.

**Set B:** 30 N-body realizations of YSCs with \(r_{\text{vir}} = 1\) pc, \(W_0 = 5\), \(N_* = 5 \times 10^4\).

**Set C:** 30 N-body realizations of YSCs with \(r_{\text{vir}} = 5\) pc, \(W_0 = 5\), \(N_* = 5 \times 10^4\).

In each set of simulations, 1/3 of the runs have \(Z = Z_{\odot}\), 1/3 have \(Z = 0.1 Z_{\odot}\) and 1/3 have \(Z = 0.01 Z_{\odot}\). The structural parameters (core radius \(r_c\), half-mass radius \(r_{\text{hm}}\), half-light radius \(r_{\text{hl}}\) and total binary binding energy \(E_b\)) discussed in the following are the median value of different N-body realizations (with the same \(Z\)) in each set of runs, to filter out statistical fluctuations.

3 Results

![Fig. 1](image.png)

**Fig. 1** Core radius \(r_c\) (left-hand panel), half-mass radius \(r_{\text{hm}}\) (central panel) and half-light radius \(r_{\text{hl}}\) (right-hand panel) as a function of time for \(Z = 0.01 Z_{\odot}\) (red solid line), \(0.1 Z_{\odot}\) (black dashed line) and \(1 Z_{\odot}\) (blue dotted line). Runs of set A are shown (\(W_0 = 5\), \(r_{\text{vir}} = 1\) pc, \(N_* = 5 \times 10^3\)). Each line is the median value of 100 N-body realizations.

**Fig. 1** shows the behaviour of \(r_c\), \(r_{\text{hm}}\) and \(r_{\text{hl}}\) in the runs of set A, for different \(Z\). The YSCs in set A undergo CC at \(t \sim 2 - 3\) Myr (regardless of \(Z\)). The impact of \(Z\)-dependent stellar winds and SNe is apparent in the reversal of CC: \(r_c\) increases faster...
in metal-rich YSCs, because stellar winds are stronger than in metal-poor YSCs. At the same time, \( r_{\text{hm}} \) expands more in metal-poor YSCs than in metal-rich YSCs. The reason is that three-body encounters are more efficient in metal-poor YSCs (where higher core densities are reached during the CC) and inject more kinetic energy in the halo. The same trend is apparent in the half-light radius \( r_{\text{hl}} \): it expands more in metal-poor YSCs than in metal-rich ones. Furthermore, the difference between the half-light radii of metal-rich and metal-poor YSCs is a factor of two larger than the difference between the half-mass radii, due to mass segregation and to the Z-dependence of the stellar luminosity (Mapelli & Bressan 2013).

How much do these results depend on the mass and on the size of YSCs? The left-hand column of Fig. 2 shows the behaviour of \( r_c \) and \( r_{\text{hm}} \) in runs of set B, which are 10 times more massive than runs of set A, even if they have the same size (\( r_{\text{vir}} = 1 \) pc). The CC occurs again at \( t \sim 2 - 3 \) Myr. \( r_c \) and \( r_{\text{hm}} \) show the same trend in set B and in set A. The right-hand column of Fig. 2 shows the behaviour of \( r_c \) and \( r_{\text{hm}} \) in runs of set C, which are as massive as runs of set B but have larger size (\( r_{\text{vir}} = 5 \) pc). Thus, the YSCs of set C have lower central density, and the CC is expected to occur at later times (\( t_{\text{rlx}} \propto r_{\text{hm}}^{3/2} \)). In fact, the CC begins at \( \sim 60 \) Myr for \( Z = 0.01 Z_\odot \) and at later times for higher Z. In the metal-rich (\( Z = 0.1, 1 Z_\odot \)) YSCs of set C the CC is delayed, because the mass-loss by stellar winds is sufficient to keep the core stable against collapse. This implies that \( r_{\text{hm}} \) is marginally larger in metal-rich YSCs than in metal-poor ones, until the CC begins. During the CC, the half-mass radius of metal-poor YSCs starts expanding faster than that of metal-rich YSCs, producing the same trend as observed in set A and B.

This interpretation is confirmed by the top row of Fig. 2 which shows the total binding energy of binaries \( E_b \) (considering all binaries in a YSC at a given time). Since we do not include primordial binaries in our simulations, \( E_b \) represents the total energy that is stored in binaries as a consequence of three-body encounters. The YSCs of set C have \( E_b \sim 0 \) up to \( t \sim 60 \) Myr. In contrast, \( E_b \) in runs of set B grows dramatically during the first CC, decreases during the rapid expansion phase and grows steadily at later times. Thus, three-body encounters are almost negligible in the loose YSCs of set C, while they are the main engine of CC reversal in sets A and B.

4 Conclusions

We have shown that stellar winds are very important in the early evolution of YSCs and that their effects strongly depend on Z. In particular, the post-collapse re-expansion of the core is faster for metal-rich YSCs than for metal-poor YSCs, because the former lose more mass (through stellar winds) than the latter. As a consequence, the half-mass radius and the half-light radius expand faster in metal-poor YSCs. The initial size of the YSC plays a critical role, because the relaxation timescale and thus the onset of CC strongly depend on it (\( t_{\text{rel}} \propto r_{\text{hm}}^{3/2} \)). The total mass of the YSC has only marginal effects. Other YSC properties (e.g. \( W_0 \)) deserve further
The $Z$-dependence of stellar winds is still barely understood, especially in the post-main sequence evolution. Thus, forthcoming studies will also investigate the effects of different recipes of mass-loss by stellar winds.

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