Compact Objects and Binaries in Dense Star Clusters
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Insights into spatial mixing of multiple populations in dynamically-young globular clusters

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Abstract. Many galactic globular clusters (GCs) contain at least two stellar populations. Recent observational studies found that the radial distributions of the first (P1) and second population (P2) differ in dynamically-young GCs. Since P2 is conventionally assumed to form more centrally concentrated, the rapid mixing (or even inversion) in some GCs but not others is puzzling. We investigate whether dynamical processes specific to certain GCs might cause this. Specifically, we evaluate the expansion of P2 by binary-single interactions in the cluster core and whether these can mix the P1/P2 radial distributions, using a set of toy-models with varying numbers and masses of primordial binaries. We find that even one massive binary star can push the central P2 outwards, but multiple binaries are required to fully mix P1 and P2 within a few relaxation times. We also compare our results to observed properties of mixed young GCs (NGC 4590, 5053, or 5904).

Keywords. Globular clusters: general, Methods: analytical, Methods: numerical, Stars: binaries: general, Stars: kinematics and dynamics

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1. Introduction

Massive and old globular clusters (GCs) are known to host multiple stellar populations with distinct chemical compositions and kinematics (e.g. Carretta et al. 2010; Gratton et al. 2012; Bastian & Lardo 2018; Vesperini et al. 2021; Leitinger et al. 2025). The first population, or P1 stars, shows primordial abundances, while the enriched second population, P2, exhibits light-element variations that imply complex formation scenarios–ranging from *in-situ* formation in enriched gas to accretion of processed material (e.g. Carretta et al. 2010; Bekki 2011). Many formation models suggest P2 stars form preferentially in the core (e.g. Lacchin et al. 2022), but observations of dynamically-young GCs show diverse spatial distributions: some retain a centrally concentrated P2 population, others have higher numbers of P1 in the core, some are fully radially mixed (Leitinger et al. 2023), see also a selection of Galactic GCs in Fig. 1.

This variety in radial distributions of P1 and P2 suggests that some internal dynamics shaped the present-day structure of GCs. Since binary–single star scattering is a prevalent cause of stellar population heating and ejections (see, e.g. Heggie & Hut 2003; Binney & Tremaine 2008), we test whether massive binaries in GC cores could drive early redistribution or inversion of P2 stars.

2. Methods

To gain insights into the mixing capabilities of massive binary stars inside star clusters, we study a set of toy-models — i.e. our initial conditions are intentionally simplified to isolate the effects of the binary–single star interactions in the cluster core. In our follow-up paper (Pavlík et al. 2025), we expand this study to more realistic star clusters of various masses, radial profiles, and primordial binary star properties. Specifically, here we initialise all stars on circular orbits, so that their radial motion early in the evolution would be mostly affected by the binary–single star interactions and not by the random orientation of their orbits. We also adopt a uniform density distribution of stars to filter out rapid relaxation processes in the core.

Each cluster has ten thousand equal mass stars with $1\,M_\odot$ and either zero, one, or ten binaries with $30\,M_\odot$ components, circular orbits, and semi-major axes of 5 au. The masses of binaries are derived from the typical gravitational-wave sources, assuming they would be represented by black holes in real GCs. We label the single low-mass stars by their initial positions as 'P2' (below the quarter-mass radius) and 'P1' (everything else). We do not count the binaries towards either population. We average our results over ten random realisations of each model.

3. Results

We study the redistribution of P1 and P2 using their projected cumulative radial distribution functions, $C(R)$. From these we calculate the A^+ parameter (Alessandrini et al. 2016).

$$A^+_{R\mathrm{lim}} = \frac{1}{R_\mathrm{h}} \int_0^{R_\mathrm{lim}} \left[\frac{C_\mathrm{P1}(R)}{C_\mathrm{P1}(R_\mathrm{lim})} - \frac{C_\mathrm{P2}(R)}{C_\mathrm{P2}(R_\mathrm{lim})} \right] \mathrm{d}R, \tag{1}$$

where R_lim is the chosen limiting radius for normalisation. In Fig. 2, we use $R_\mathrm{lim} = 1\,R_\mathrm{h}$ for the central region, $4\,R_\mathrm{h}$ to compare with observations, and $10\,R_\mathrm{h}$ to include most of the cluster. In the models (Fig. 2), we scale R_lim by the projected half-mass radius, while the radial ranges of the observations (Fig. 1) are scaled by the half-light radii, R_hl; however, $R_\mathrm{h} = R_\mathrm{hl}$ in equal-mass star clusters. The dynamical age of the modelled and observed clusters is expressed in terms of their present-day half-mass relaxation time.

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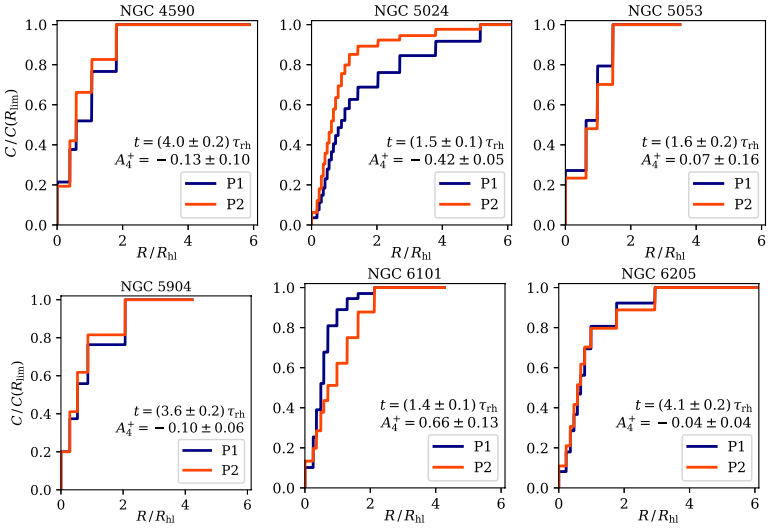


Figure 1. Cumulative distribution functions of P1 and P2 stars in a sample of dynamically-young Galactic GCs. We note that the displayed radial range goes up to six half-light radii, $R_{\rm hl}$, to show the whole clusters, but the parameter A_4^+ is calculated from stars only up to $4.27\,R_{\rm hl}$ (data taken from Leitinger et al. 2025).

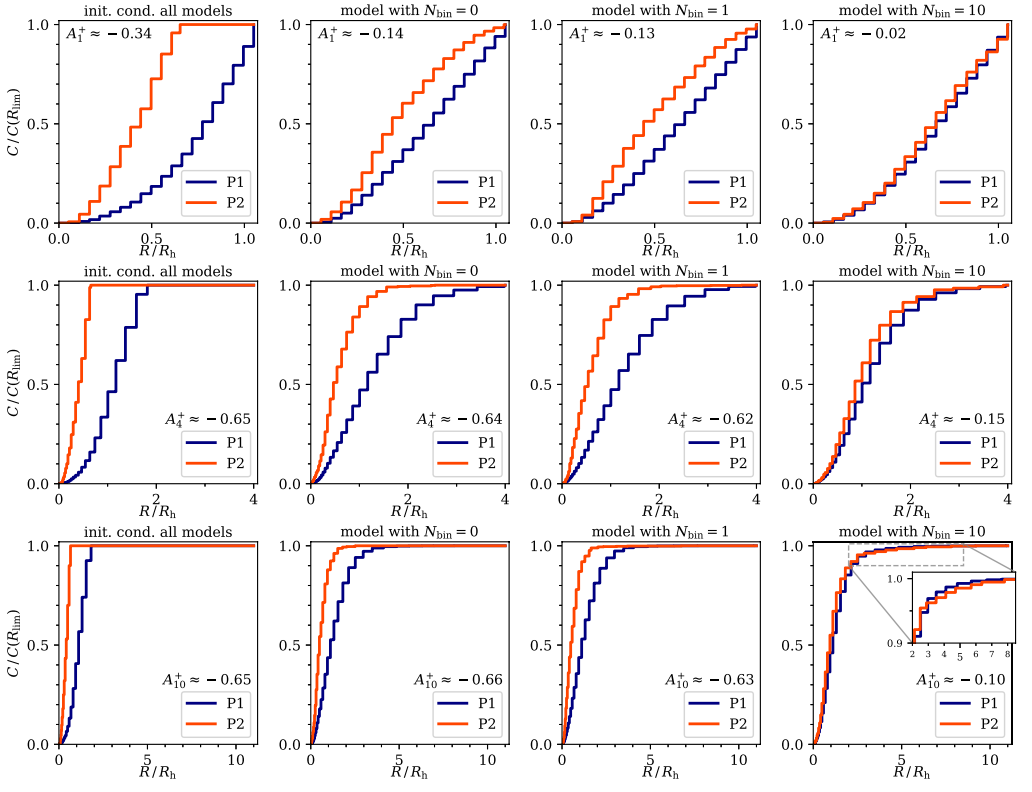


Figure 2. Cumulative distribution functions of P1 and P2 stars and their corresponding $A^+_{R\rm lim}$ values in our cluster models. Each row corresponds to a different projected radial range, $R_{\rm lim}$. The left-hand column shows the initial conditions, the columns on the right each show the evolved models (each containing a different number of binaries) at $2\,\tau_{\rm rh}$.

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Table 1. The mean values of A^+ at $2\,\tau_{\rm rh}$ and their uncertainties (see also Fig. 2).

$N_{\rm bin}$	A^+_1	A^+_4	A^+_{10}
0	−0.14	−0.64	−0.66
1	−0.13	−0.62	−0.63
10	−0.02	−0.15	−0.10
σ	±0.01	±0.03	±0.05

Table 2. The mean values of A^+ at $4\,\tau_{\rm rh}$ and their uncertainties.

$N_{\rm bin}$	A^+_1	A^+_4	A^+_{10}
0	−0.09	−0.57	−0.62
1	−0.08	−0.51	−0.57
10	−0.01	−0.10	−0.11
σ	±0.01	±0.03	±0.05

In the modelled clusters with N stars and the total mass M, this is in projection (e.g. Spitzer & Hart 1971; Binney & Tremaine 2008).

$$\tau_{\rm rh} \approx \frac{0.138\,N}{\ln\,(0.4N)}\sqrt{\frac{R_{\rm h}^3}{GM}}. \tag{2}$$

In Fig. 2, we plot the initial conditions of our models in the left-hand column and their evolved states at $2\,\tau_{\rm rh}$ in the right-hand panels (to be comparable with the observed dynamically-young GCs). In the top row of this figure, we see that the initially separated populations fully mix in the region up to $1\,R_{\rm h}$ in the model with ten binaries ($A^+_1 \approx -0.02$). The radial redistribution of P1 and P2 is lower in the models with one or no binary (and the difference between these two models is negligible). Even in the regions up to 4 or $10\,R_{\rm h}$ (middle and bottom row of the figure), the model with ten binaries appears mixed. We can even see a hint of inversion between 3 and $8\,R_{\rm h}$ (see the zoomed-out plot in the bottom-right panel). We do not see mixing or any signs of inversion at these radial scales in the models with one or zero binaries.

We list all values of A^+ at the evolutionary times $2\,\tau_{\rm rh}$ and $4\,\tau_{\rm rh}$ in Tables 1 and 2, respectively. From these and the figures above, we see that our simple models do not exhibit strong inversion ($A^+ > 0$) as in the case of the observed cluster NGC 6101. However, already at $2\,\tau_{\rm rh}$, the models with ten primordial binaries are comparable to the mixed GCs NGC 4590, 5053, 5904, or 6205. In turn, the models with a lower binary count are similar to the P2-centrally-concentrated NGC 5024. The level of P1/P2 mixing increases with the evolutionary time in our models (cf. Leitinger et al. 2023, 2025). We may also compare the two tables and see that A^+ usually decreases, except for the model with ten binaries, where its value stays almost the same (within the uncertainties).

4. Conclusions

Our preliminary numerical analysis shows that massive binary stars (presumably black holes) can cause mixing of stellar populations inside a star cluster. We investigate this mechanism further — both theoretically and numerically — in Pavlík et al. (2025).

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