Compact Objects and Binaries in Dense Star Clusters
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Simulations of Globular Cluster Evolution with Multiple Stellar Populations

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Abstract. The formation of stars with light-element abundance variations in globular clusters and the subsequent dynamical evolution of these multiple populations remains an open question. One of the most widely discussed is the AGB scenario, in which chemically processed material from the envelopes of AGB stars mixes with re-accreted primordial gas flowing into the center of the cluster. Based on this scenario, more than two hundred MOCCA simulations of cluster evolution have been carried out, incorporating additional physical processes related to the external environment of globular clusters and the initial properties of multiple stellar populations. Analysis of the simulations shows that most observed properties of multiple stellar populations and the global parameters of Milky Way clusters are well reproduced, with the exception of the correlation between cluster mass and the fraction of second-population stars. We present a speculative scenario of globular cluster evolution that may account for the observed properties of Milky Way clusters, including the correlation between cluster mass and the fraction of enriched stars. The scenario further predicts that, under certain conditions, the pristine first population can be more centrally concentrated than the enriched second population, as observed in some clusters.

Keywords. stars: kinematics and dynamics, globular clusters: general, Galaxy: kinematics and dynamics

1. Introduction

Since their discovery, globular clusters (GCs) have been regarded as the simplest dynamic systems with a spherically symmetric structure and uniform chemical composition. The age of globular clusters is comparable to that of the Universe, and their formation history is inextricably linked to the formation of galaxies. Over the past decades, photometric and spectroscopic studies have revealed the presence of multiple stellar populations (MSP), primarily characterized by internal variations in light-element abundances (e.g., Bastian and Lardo 2018; Gratton et al. 2019, and references therein). Despite the great efforts of many theoretical and observational groups, the formation of MSPs in globular clusters is still a mystery. Observations, both spectroscopic and photometric, provide the following information:

- In massive clusters, some stars have different abundances of light elements: C, O, sometimes Mg are depleted, and Y, N, Na, sometimes Al are enhanced. Abundances are correlated or anti-correlated. This indicates a high-temperature CNO cycle;
- There is a very small Fe spread allowed (0.1 dex);

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• There is practically no time spread between populations. At most about a hundred Myr;
• Enriched population (2P) is centrally concentrated, but there are some exceptions;
• MSPs are clearly detected in massive, larger than a few $10^4 M_\odot$, and old (older than about 2 Gyr) clusters, and are observed not only in the Milky Way (MW);
• Fraction of 2P increases with cluster mass, may increase with cluster age.

From a theoretical point of view, the above observational facts indicate that:

• The light-element abundance variations in MSPs most likely originate from hot hydrogen burning (≈ 70 MK), but not from helium burning;
• Formation of MSP is connected with dense cluster environment - abundance trends essentially are not visible in the field population;
• Gas pollution occurs practically at the time of cluster formation - very small observed age spread;
• It seems that there are no special conditions needed in clusters, except cluster mass, to form MSP.

Several scenarios have been proposed to explain the emergence and continued evolution of MSPs. These models can be divided into two groups. The first group, in which the formation of an 2P is shifted in time relative to the pristine population (1P) and requires the re-accretion of the pristine gas by the GC and its mixing with matter ejected by Asymptotic Giant Branch (AGB) stars, belongs to the AGB scenario. The second group belongs to models in which 2P is formed at virtually the same time as 1P and does not require the re-accretion of gas by the GC. Matter ejected from massive stars and binary systems mixes with residual primordial gas. These scenarios include: interacting massive binaries, fast-rotating massive stars, early disk accretion, very massive stars, nucleosynthesis in accretion disks around stellar-mass black holes, and the recently renewed single-binary composite scenario. As pointed out in the review paper by Bastian and Lardo (2018), no scenario can explain a significant number of observational facts. In this work, we focus on the AGB scenario, as it is the framework for the simulations performed with the MOCCA code.

In the AGB scenario, once the residual gas from the formation of the 1P is expelled, the cluster remains near the original gas cloud. After some time, this gas is re-accreted onto the cluster, where it accumulates in the cluster center and mixes with material ejected from AGB star envelopes. This mixture is crucial for producing the observed light-element correlations and anti-correlations. Following a time delay, the 2P forms from the polluted gas accumulated in the cluster center.

In the next section, we present results from MOCCA simulations designed to test how environmental effects, gas re-accretion onto GCs, and the time delay of 2P formation influence the evolution of stellar populations. Detailed descriptions of the code and initial conditions are provided in Giersz et al. (2025a). A total of about 200 simulations were performed, with most models starting as tidally filling (TF).

2. Results

In this section, we analyze the impact of gas re-accretion, cluster migration, and some of the individual MSP and global cluster parameters on the evolution of the cluster mass, half-mass radius (R_h), and ratio between the number of 2P stars to the total number of stars (N_2/N_{tot}).

2.1. *Gas re-accretion*

In the AGB scenario, re-accretion of gas on the cluster is required. We know that the ejection of gas from the cluster leads to a decrease in the cluster mass, cluster expansion,

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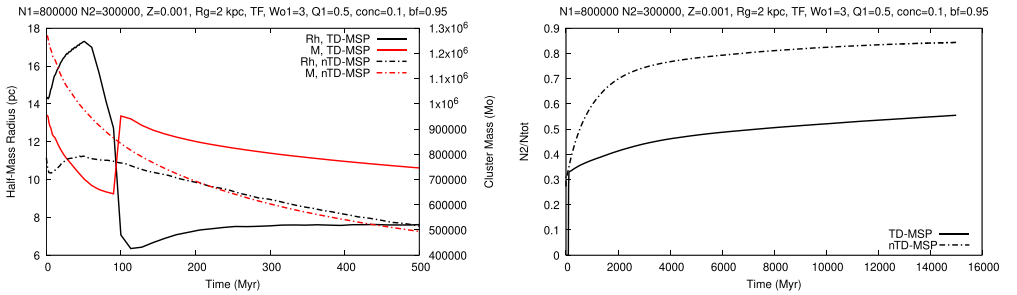


Figure 1. Left panel: Evolution of R_h for nTD-MSP model, and for TD-MSP model, and evolution of the total cluster mass for nTD-MSP model, and TD-MSP model. Right panel: Evolution of the ratio N_2/N_{tot} for the nTD-MSP model, and TD-MSP model. The global cluster parameters are listed at the top of each panel: N_1 - number of 1P objects, N_2 - number of 2P objects, Z - metallicity, R_g - galactocentric distance (size of the circular orbit), TF - tidally filling 1P, W_{o1} - King parameter for 1P, conc - concentration parameter ($conc_{pop} = R_{h2}/R_{h1}$), bf - binary fraction, Q_1 - virial ratio for 1P.

and half-mass radius growth. Thus, mass accretion should lead to an increase in the cluster's mass, its central concentration, and a decrease in the R_h. The left panel of Figure 1 shows this behavior for the model with time delay formation of 2P stars (TD-MSP). In contrast, in the model where 2P stars form simultaneously with 1P (nTD-MSP), the evolution is driven only by stellar-evolution mass loss and star escapes caused by the tidal field. After gas re-accretion, the cluster collapses, transitioning from TF to under-filling (nTF). This transition leads to a significant slowdown in the growth of the N_2/N_{tot} ratio, as shown in the right panel of Figure 1.

2.2. *Cluster migration*

It is known from many papers, e.g. Meng and Gnedin (2022) that as a result of strong changes in the tidal field of the forming galaxy, GCs can migrate further away from the center. Migration to greater distances means that clusters go from TF to nTF very quickly. This leads to a slower loss of cluster mass, an increase in half-mass radius, and virtually a halt in N_2/N_{tot} growth. Indeed, these predictions are confirmed in Figure 2. The left panel shows a significant increase in R_h and a slower decrease in cluster mass with increasing R_g. In the right panel, the ratio N_2/N_{tot} is practically constant after increasing the galactocentric distance. The migration of GCs introduces an additional parameter that influences cluster mass, R_h, and the N_2/N_{tot} ratio.

2.3. 1P virial ratio

To achieve a stronger increase in the N_2/N_{tot} ratio after GC migration and to reproduce the observed values, an additional physical process is required. It is known that the removal of the residual gas after the formation of the 1P is associated with a strong expansion of the cluster and its departure from virial equilibrium (e.g., Banerjee and Kroupa 2013, 2018). We can therefore assume that the initial model for 1P has $Q_1 > 0.5$. Increasing Q_1 will lead to a decrease in the mass of the cluster and R_h and an increase in N_2/N_{tot}, as is clearly seen in the Figure 3. The value of Q_1 will depend on 1P star formation efficiency (SFE). The smaller SFE, the larger Q_1. According to recent works, the amount of cluster expansion due to the residual gas removal is very uncertain and depends on many factors connected with the SFE, cluster structure, environment, and

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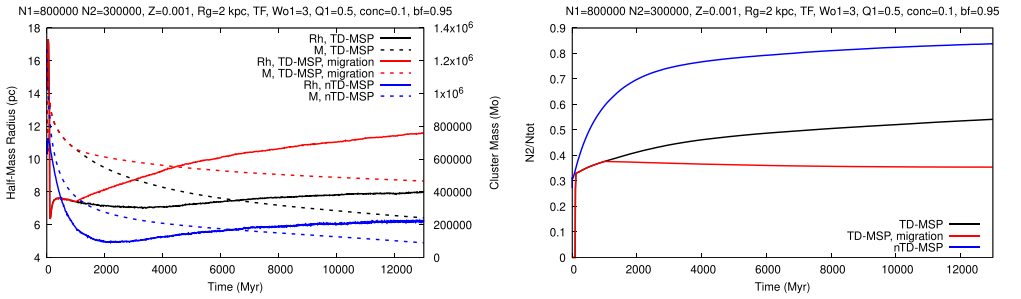


Figure 2. Left panel: Evolution of R_h for nTD-MSP model, TD-MSP model, and TD-MSP model with migration, and evolution of the total cluster mass for nTD-MSP model, TD-MSP model, and TD-MSP model with migration. Right panel: Evolution of the ratio N_2/N_{tot} for nTD-MSP model, TD-MSP model, and TD-MSP with migration model. The global cluster parameters are listed at the top of each panel and are the same as for Figure 1.

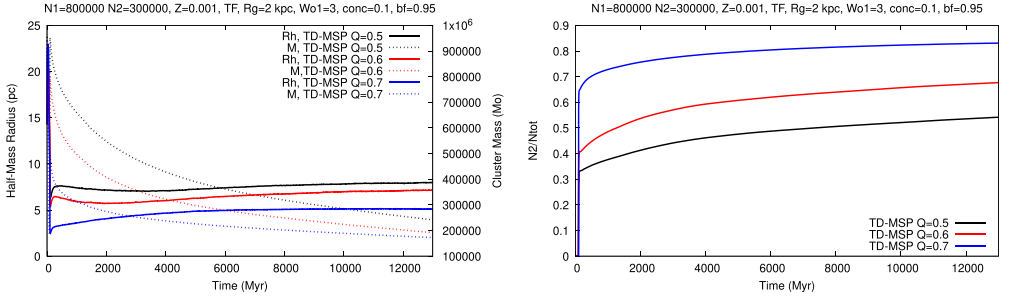


Figure 3. Left panel: Evolution of R_h and the cluster total mass for TD-MSP models with different Q_1. Right panel: Evolution of the ratio N_2/N_{tot} for TD-MSP models with different Q_1. The global cluster parameters are listed at the top of each panel and are the same as for Figure 1.

efficiency of the feedback processes (e.g., Farias et al. 2018; Geen et al. 2018; Zamora-Avilés et al. 2019; Krause et al. 2020; Polak et al. 2024). Therefore, the assumption that initially 1P is out of virial equilibrium and has $Q_1 > 0.5$ is plausible.

2.4. *King parameter,* W_{o1}

The King parameter for 1P is crucial for the long-term evolution of the cluster and the N_2/N_{tot} ratio. As can be seen from Figure 4 for W_{o1} larger than about 5, the N_2/N_{tot} ratio does not reach the observed values, and the models become similar to the single population models. The larger W_{o1}, the larger GC evolution time scale, and the slower increase of N_2/N_{tot}. This was already pointed out by Vesperini et al. (2021) and Hypki et al. (2022, 2025). A very interesting relationship can be observed in the right panel in Figure 4. For models with a small number of 2P stars relative to 1P stars, in the initial phase of cluster evolution, the N_2/N_{tot} ratio practically does not change, but after about 1-2 Gyr it increases rapidly and reaches the values observed for MW GCs. This feature of evolution may help to explain the correlation between the GC mass and the N_2/N_{tot} ratio.

2.5. *Galactocentric distance*

Another important parameter describing the evolution of MSP is R_g of the GC. As we can expect for the TF cluster, a larger distance of the GC from the galaxy center results in a larger tidal radius R_t and R_h and, consequently, a slower evolution of the cluster.

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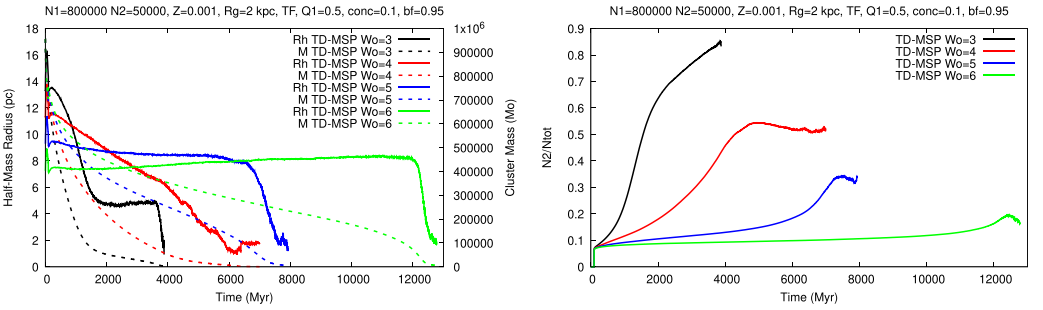


Figure 4. Left panel: Evolution of R_h and the cluster total mass for TD-MSP models with a different King parameter, W_{o1}. Right panel: Evolution of the ratio N_2/N_{tot} for TD-MSP models with a different King parameter, W_{o1}. The global cluster parameters are listed at the top of each panel and are the same as for Figure 1.

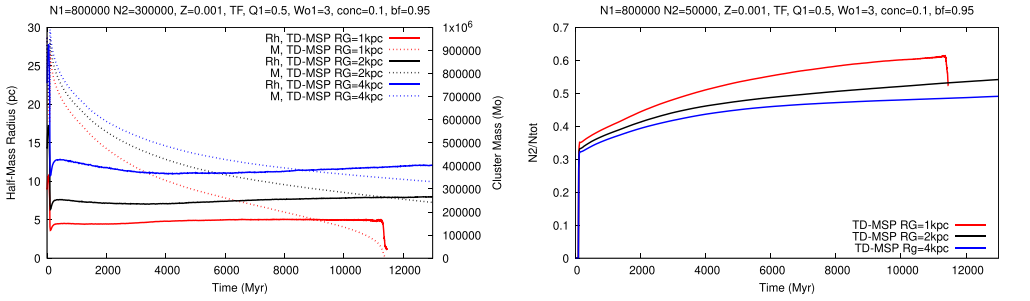


Figure 5. Left panel: Evolution of R_h and the cluster total mass for TD-MSP models with different galactocentric distance (R_g). Right panel: Evolution of the ratio N_2/N_{tot} for TD-MSP models different R_g. The global cluster parameters are listed at the top of each panel and are the same as for Figure 1.

This leads to the dependence, the larger R_g the larger R_h and the smaller N_2/N_{tot}. Indeed, we can observe this type of evolution of global cluster parameters in Figure 5. The cluster with the smallest R_g is characterized by the smallest R_h, mass and evolution time, and the largest N_2/N_{tot} ratio. It is important to draw attention to the fact that dependence on R_g is important from the point of view of MWGC observational parameters. The correlation between R_g and N_2/N_{tot} is not observed for MWGCs, and it arises from the specific initial conditions adopted in our models. This trend is expected to be strongly blurred - or even erased - during the subsequent evolution of clusters due to environmental effects associated with galaxy assembly.

2.6. *Summary of the MOCCA simulations*

After a brief presentation of the results obtained with the MOCCA code for models with MSP with delayed 2P formation, it is time to summarize the results and put them in a broader perspective.

The masses of MWGCs are contained in the range of roughly 10^4 to $10^6 M_\odot$, the R_h in the range of about 1 to 10 pc (larger radii on average have ex-situ GCs), and the N_2/N_{tot} ratio in the range of about 0.3 to 0.9. An exceptionally strong constraint on models of MSP formation in GCs is the correlation between the mass of the cluster and the N_2/N_{tot} ratio. The MOCCA simulations provide the following suggestions that may help understand the observational parameters of GCs with MSP in the framework of the AGB scenario:

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Table 1. Response of the observational global cluster parameters to changes in the models of the most important parameters describing the cluster environment and MSPs. The global cluster parameters are: cluster mass, R_h, and N_2/N_{tot}. The parameters describing the cluster model and MSPs are: R_g, W_{o1}, Q_1 and migration. ↑ means increase, ↓ means decrease, and = means unchanged.

Parameter	M	R_h	N_2/N_{tot}
R_g ↑	=	↑	↓
W_{o1} ↑	↑	↑	↓
Q_1 ↑	↓	↓	↑
migration ↑	↑	↑	=

• GCs just after the ejection of the residual gas should be TF or only slightly nTF. This means that they should preferentially form close to the galactic center. Too large R_g means much larger R_t, and it is difficult in this case to form a cluster that is TF;

• Only models in which the GC is TF or only slightly nTF reproduce N_2/N_{tot} ratios within the range observed for Milky Way GCs, provided that initially this ratio was not as large as observed;

• For newly formed GCs of the same mass, increasing R_g leads to larger R_h and a lower N_2/N_{tot};

• Models with smaller W_{o1} guarantee larger values of the N_2/N_{tot} ratio. The larger the W_{o1} the greater the mass and R_h, but too small W_{o1} will lead to too fast cluster dissolution;

• The greater the cluster's departure from virial equilibrium, the greater the N_2/N_{tot} ratio. The larger the Q_1 the smaller the mass and R_h;

• Migration of the cluster to larger R_g leads to an increase in present-day cluster mass and R_h. The N_2/N_{tot} ratio remains virtually constant after migration.

The reaction of the observational parameters to the changes in the global and environmental parameters discussed in the above points is summarized in Table 1.

When talking about modeling MWGC, the main focus should be on in-situ GCs, because ex-situ GCs were formed in other environments. GCs are formed in the very early stages of the galaxy's evolution, when the galaxy is a very hostile environment, with a highly changing tidal field and multiple close and strong interactions with nearby dwarf galaxies. The mass of the galaxy is rapidly being built up during this period. The work of Meng and Gnedin (2022) suggests that the period of rapid changes in the tidal field of a galaxy ends after about 1 Gyr. After this time, GCs virtually stop migrating outside. As many numerical simulations (e.g., Banerjee and Kroupa 2013; Leveque et al. 2022) have shown, gas ejection after the formation of 1P is associated with strong cluster expansion and excess of kinetic energy relative to potential energy ($Q_1 > 0.5$). Such a cluster will be characterized by a relatively low density contrast (rather small W_{o1}, significantly less than 5 or 6), and for small galactocentric distances, it should be TF. The cluster expansion due to gas expulsion is mainly related to SFE and not to the position of the cluster in the galaxy. Thus, clusters that form closer to the center have smaller R_t than those that arise further away, and can also more easily become TF or even TF overfilling, even if the SFE may be high as suggested by recent works by Calura et al. (2019); Polak et al. (2024).

The joint action of cluster migration and initial models with $Q_1 > 0.5$ seems to work in the desired direction - R_h of a few pc and significant values of N_2/N_{tot}, provided that the cluster is formed relatively close to the galactic center and it is initially relatively massive, at least about $10^6 M_\odot$.

The initial model parameters for the MOCCA simulations were chosen to explore the impact of specific assumptions related to MSP formation and evolution rather than to

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reproduce the full diversity of the MWGC population the agreement between the simulation results and observations is generally satisfactory, particularly in terms of the N_2/N_{tot} values. However, we acknowledge that the simulated clusters exhibit an anticorrelation between N_2/N_{tot} and present-day cluster mass, whereas observational data suggest a positive correlation. This discrepancy will be further discussed in the next Section, where a speculative scenario for MSP formation will be presented.

3. Speculative AGB scenario for MSP formation

Based on the results of the MOCCA simulations and the available literature on GC formation processes in zoom-in cosmological and purely hydrodynamical simulations, we introduce a speculative extension of the AGB scenario to provide a sketch of possible GC evolution in the strongly and rapidly changing environment of a Galaxy in the process of formation. To reproduce the mass- $mathrmN_2/N_{tot}$ correlation, let's assume that the availability of gas from which GCs can form decreases with distance from the galactic center. Thus, clusters forming farther from the center will have, on average, a lower mass of 1P and, more importantly, probably a significantly lower mass of gas that can again be re-accreted into the cluster and form 2P. The small value of N_2 relative to N_1 causes the increase in the N_2/N_{tot} ratio to be slow initially and only increase significantly after a period of 1 - 2 Gyr. Thus, if the cluster migrates during this time, its observed value of the N_2/N_{tot} ratio will be relatively low. For massive clusters formed from very massive gas clouds, the availability of gas is very high, which will lead to the formation of clusters that initially have a relatively large N_2/N_{tot} ratio. For such clusters, the increase in this ratio to large values occurs quickly and then stabilizes. This means that their migration can stop the N_2/N_{tot}ratio at relatively large values. Dynamical friction also seems to be an important player in this process. We know that its effectiveness depends on the mass of the cluster and the distance from the center of the galaxy. Therefore, very massive clusters formed too close to the center or located after migration in not very eccentric orbits will sink and merge in the galactic nucleus. Those that have larger eccentricities have a larger probability of surviving. Less massive clusters are likely to be born or to migrate to larger distances, and therefore, dynamical friction will not be effective for them. Therefore, the mutual interaction of dynamical friction, migration, and availability of gas from which GC can be formed may lead to the generation of the currently observed correlation between the mass of GCs and their N_2/N_{tot} ratio.

This is a rather speculative and perhaps a bit naive scenario requiring several physical processes to operate in the right time order and in the right environment of a young, assembling galaxy. Maybe this is the answer to the question of why, for young and massive star clusters that we are now observing, we do not see the observational signatures of MSPs. Simply, the current galactic environment is not suitable for the physical processes that enable the creation of MSP.

The scenario presented above should not be taken as the only explanation for the observed properties of MSPs in MWGCs. In our view, it is the leading scenario and accounts for the most important features of MSPs. However, other scenarios discussed in the literature may also contribute, operating alongside the AGB scenario and further blurring the photometric and spectroscopic distinctions between 1P and 2P stars. Indeed, it would be surprising if these additional mechanisms did not play some role in shaping what we observe in MWGCs.

Finally, we note that according to Ishchenko et al. (2024), the orbits of MWGCs can undergo significant evolution over a Hubble time due to variations in the Galactic tidal field, resulting in either inward or outward migration.

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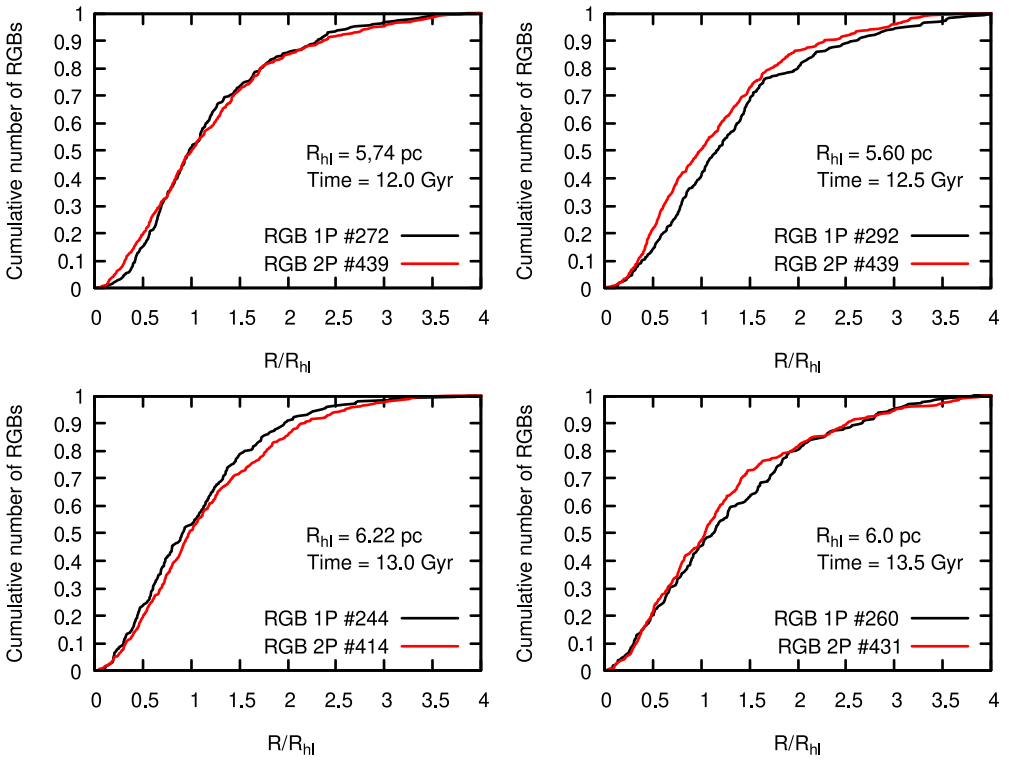


Figure 6. Cumulative number distributions of RGB stars for 1P and 2P as a function of distance scaled by half-light radius (R_{hl}) for selected projected (2D) snapshots from 12 Gyr to 13.5 Gyr. 1P is more centrally concentrated than 2P only in the snapshot at 13 Gyr. The number distributions of both populations change significantly over time, and the overconcentration of 1P is a transient feature. The R_{hl} values, snapshot times, and the number of RGB stars are provided in the insets of each panel.

4. Discussion

A good theory is always able to explain new observational facts. Let us then check whether the proposed speculative extension of the AGB scenario is able to explain the observations that have caused much trouble for all the MSP formation scenarios found in the literature.

Leitinger et al. (2023) and later Cadelano et al. (2024) published papers in which they showed that for some clusters (namely, NGC 3201 and NGC 6101) the A+ parameter indicates that 1P is more concentrated than 2P. Virtually none of the proposed scenarios can explain these observations. Inspired by Leitinger's results, we analyzed the MOCCA simulation results and found many examples where 1P is more concentrated than 2P. All these models are characterized by a not very large cluster mass at present and contain a BH subsystem. The clusters observed by Leitinger et al. (2023) are clusters captured by the MW during merger events with dwarf galaxies. This means that these clusters, despite their small mass, have large tidal radii, and they are dynamically old - they are located at a large distance from the galactic center. To make the MOCCA models similar to the observed NGC 3201 and NGC 6101 clusters, we assume that the GC forms in a dwarf galaxy close to its center, to be later captured by the MW to a distant orbit (Giersz et al. 2025b, for details see). In this way, the tidal radius and the radius containing half the luminosity are close to the observed values. One such MOCCA model is presented in Figure 6.

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In the Figure 6 we see that overconcentration, calculated as in observations for red giant branch (RGB) stars, is a transient feature. It appears and disappears. It is important to stress that the overconcentration is only visible for RGB stars, for other types of stars, in particular main-sequence (MS) stars, it is not visible. Both populations of MS stars are completely mixed with each other. To better understand why only for RGB stars overconcentration is observed and transient, we analyzed the interactions of RGB stars during the evolution of the cluster - the details and results of the analysis can be found in Giersz et al. (2025b). In short, the BH subsystem formed by 1P stars governs the cluster's evolution. Since 2P stars are more centrally concentrated, their RGB progenitor stars interact more strongly than those of 1P. As a result, they are more efficiently displaced from the cluster center or even escape, ultimately leading to an overconcentration of 1P RGB stars at the present day. A key requirement is that the number of RGB stars in the system is relatively small. Then, small-N statistics together with dynamical interactions can lead to 1P overconcentration. For larger N, the effect of stronger 2P RGB interaction is blurred. When observations are limited to RGB stars, small-number statistics and dynamical interactions can distort their spatial distribution, leading to biased conclusions about the overall distribution of MSPs.

5. Conclusions

Based on about 200 MOCCA simulations, we analyzed the influence of the most important parameters describing the MSP and GCs on the evolution of the cluster and its observational properties after 12 Gyr of evolution. The aim of the study was to determine such parameter ranges so that the cluster model after 12 Gyr of evolution best matches the ranges of observational parameters of the MWGCs; in particular, the cluster mass, R_h, and the N_2/N_{tot} ratio. Based on the simulation analysis and the results of cosmological zoom-in simulations, a speculative refinement of the AGB scenario for the formation and evolution of GCs with MSP was presented to obtain an observational correlation between cluster mass and the N_2/N_{tot} ratio. To achieve this, one must combine the influence of the strongly changing MW environment in which the cluster evolves with its internal evolution and the effects related to the ejection of the residual gas after 1P formation. All those physical processes have to operate in the right time order and in the right environment of the galaxy that is just forming and assembling. In order to confirm this speculative refinement, more sophisticated modeling of the evolving tidal field in which the GCs form and evolve is required.

It is very important to emphasize that models of GCs with MSPs based on the AGB scenario require completely different initial properties than models of clusters with a single population. Instead of GCs being highly concentrated and lying deep inside the Roche lobe, models that fill the Roche lobe are required. This carries strong constraints on where in the galaxy GCs are formed.

Our study suggests that the spatial distribution and, potentially, the kinematic properties of MSP may depend on the type of stars observed. This effect is particularly relevant for GCs with present-day masses of a few $10^5 M_\odot$, which have retained only 10-20% of their initial mass. Despite the significant mass loss, such clusters may appear dynamically young due to BHS heating and migration to larger Galactocentric distances. When observations are limited to RGB stars, small-number statistics and dynamical interactions can distort their spatial distribution, leading to biased conclusions about the overall distribution of MSPs. The overconcentration of 1P RGB stars relative to 2P RGB stars appears to be a transient effect. Confirming the findings of Leitinger et al. (2023) and Cadelano et al. (2024), that in some MW GCs, 1P RGB stars are more centrally concentrated than 2P RGB stars, requires observations of MS stars to see if the same trend is seen for them. Our MOCCA simulations show no 1P overconcentration

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relative to 2P among MS stars. Verifying this observationally would be a crucial step toward understanding MSP properties and supporting the AGB scenario.

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