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CONSTRAINING THE ORIGIN OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS WITH N-BODY SIMULATIONS

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Abstract. Globular Clusters (GCs) are composed by multiple stellar populations whose origin is still unknown. Second population (SP) stars are currently thought to arise from gas ejected by first population (FP) stars, which is then accreted into the primordial GC core. Such gas forms a stellar disk whose long-term evolution and effects on the embedding cluster can be followed by means of N-body simulations. Here, we find that as the SP disk relaxes, the old, first stellar population flattens and develops a significant radial anisotropy, making the GC structure become more elliptical. The second stellar population is characterized by a lower velocity dispersion, and a higher rotational velocity, compared with the primordial population. The strength of these signatures increases with the relaxation time of the cluster and with the mass ratio between the SP and FP mass stars. We conclude that GC ellipticities and rotation constitute fossil records that can be used as observational proxies to unveil the origin of multiple stellar populations.

Keywords: Milky Way, globular clusters, multiple populations, formation, dynamical evolution, observational signatures

1 Introduction

Recent observations revealed the complex nature of globular clusters (GCs). These dense stellar systems, historically considered the prototype of single stellar populations, are in fact composed by several stellar populations characterized by chemical inhomogeneities in light elements and by a strong anti-correlation between Na and O (Gratton et al. 2012). Second population (SP) stars are thought to account for ∼30%-70% of the total number of stars (D'Antona & Caloi 2008; Carretta et al. 2009; Pancino et al. 2010; Bastian & Lardo 2015). The origin of SP stars is still unknown and one of the possible formation channels is through FP gas accreted into the GC core. Possible sources for this gas is material ejected by FP asymptotic giant branch (AGB) stars (Ventura et al. 2001; D'Ercole et al. 2008), interacting massive FP binaries (de Mink et al. 2009; Bastian et al. 2013), very massive stars (Denissenkov & Hartwick 2014) or fast rotating massive stars (Decressin et al. 2007; Krause et al. 2013). Material ejected at sufficiently low velocities (lower than the escape velocity from the GC) can be retained in the cluster, concentrate at its center and mix with the leftover pristine gas and then fragment to form new stars (see Gratton et al. 2012, and references therein). In all the self-enrichment scenarios, the initial spatial and kinematical configuration of the younger stellar population strongly depends on the original gas configuration. (Bekki 2010, 2011) recently studied the case of dissipative accretion of material lost through AGB winds. In their simulations, they found that if the gas inherits even only a small amount of the orbital angular momentum of the progenitor stars, it will then produce a disk rather than a spherical distribution of gas. Such process leads to the formation of a SP stellar disk embedded in the FP spherical cluster. As we found in Mastrobuono-Battisti & Perets (2013) , the evolution of such embedded disks in an ω Cen-like cluster, significantly impact the evolution of the system leaving behind kinematical and morphological signatures on its structure. Here and in Mastrobuono-Battisti & Perets (2016) we generalize this analysis and study the evolution of embedded SP disks with a range of masses and we follow their long-term effects on the cluster structure, and the dependence of the properties of the cluster on the fractional mass of the SP stellar population. We also compare these results to the case of SP stars formed in an embedded spherical sub-structure rather than a disk configuration. In Section 2 we describe the methods and simulations used in our analysis. The results obtained are shown in Section 3. We draw our conclusions in Section 4.

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2 Methods and simulations

We follow the evolution of massive second population disks embedded in initially spherical clusters, by means of high-precision N-body simulations. To do so we use ϕGPU (Berczik et al. 2011), a direct N-body code running on graphic processing units (GPUs). We run our simulations both on the cluster Tamnun at the Technion and on the cluster Cytera in Cyprus. In order to smooth close encounters between particles we adopt a softening length of 10^{-3} pc. The relative energy variations at the end of the simulations are smaller than $\Delta E/E = 0.01$. The initial spherical, FP, component of the cluster is a single mass King (1966) model, similar to the best fit model of the density profile of ω Cen (Meylan 1987), with $W_0 = 6$, core radius $r_c = 4.4$ pc and tidal radius $r_t = 80$ pc. This system is sampled using $N = 50000$ particles, whose mass is 20 $M_\odot$, accounting for a total mass of $M = 10^6$ $M_\odot$. We begin our simulations after the cluster has already lost a large fraction of the FP stars. We embed the SP disk in the spherical FP component and we let the disk relax until it reaches a quasi-stable state, which is then considered to be the initial configuration of the system. During the pre-initial stage a fraction of the SP stars in the disk are expelled from the system, and are removed from the N-body simulation, leaving behind a disk whose mass corresponds to 19% (S19), 24% (S24), 29% (S29), 33% (S33) and 50% (S50) of the total stellar mass of the system, in the different models considered (see Table 1 in Mastrobuono-Battisti & Perets 2016, for more details). The choice of using particles masses larger than those of individual stars – justified by computational reasons – affects the dynamical time-scales, thus we rescale the simulation time to the relaxation time of the corresponding real system, using the procedure described in Mastrobuono-Battisti & Perets (2013). We assume an average stellar mass of $\langle m_* \rangle = 0.5$ $M_\odot$ and we evolve each system for 12Gyr of rescaled simulation time. The dynamics of stars born in a disk can give rise to different signatures observable in the cluster structure, compared with the effects of SP stars born in a spherical sub-cluster. In order to compare these two different initial configurations, we run an additional simulation where the SP stars are distributed inside the core radius of the FP population with a King profile with the same shape used for the FP stars. This comparison case is simulated only for a SP population comprising 50% of the total mass of the cluster (S50s, including both FP and SP stars). In this study we neglect tidal effects due to the Galaxy and stellar evolution. We use single mass particles, however we note that massive stars are short lived and low mass stars, whose mass range is limited, will dominate the evolution of the cluster.

3 Results

We analyzed the morphological and kinematical properties of the system after 12Gyr in order to find how the initial presence of a disk modifies the structure of the whole cluster, leaving behind long term observable signatures. The isodensity contours of each simulated stellar disk at the beginning of the simulation and after 3, 6, 9 and 12Gyr are shown in Figure 1. The second generation stars always remain confined within the central 10-20 pc without completely mixing with the FP population (see also Mastrobuono-Battisti & Perets 2013; Vesperini et al. 2013). The 19, 24 and 29% disks, at the end of the simulation, are almost spherical while the 33% and the 50% disks are still significantly flattened. We also note that the 50% disk is unstable and forms a central bulge that could lead to a faster angular momentum exchange with the FP population through collective effects rather than two-body relaxation (see also Mastrobuono-Battisti & Perets 2013). The left panel of Figure 2 shows the axial ratios of the whole system at the end of each simulation. The 19% disk is slightly prolate, with all axial ratios ~ 1, while the other systems are oblate. As shown in Mastrobuono-Battisti & Perets (2016), the projected axial ratios strongly depend on the viewing angle and increase with the mass of the SP disk. However, statistical analysis and future observations, e.g., potentially provided by the GAIA mission, could give more detailed information on the spatial structure of GCs, allowing a quantitative comparison between the theoretical expectations and the observations. The c/a axial ratio is smaller for larger disks, the 50% disk is almost perfectly oblate while the clusters with lower mass disks are more triaxial. The cluster is flattened at any radius, but the effect is larger in the central 10-20pc, where most of the disk stars reside. In contrast, the spherical SP system (model S50s) and its host cluster system do not show any significant flattening, as expected. Additionally, we found that the FP stars show a larger velocity dispersion compared with the SP stars. This anisotropy correlates with the mass of the disk. However, the same difference is also found when the SP has an initially spherical configuration. The anisotropy is thus a tracer of the mass of the second generation and not of its initial configuration. The right panel of Figure 2 shows the azimuthal velocity v_θ of the FP and SP stars as a function of the radius. In all the cases the FP stars show a mild central rotation with velocity between 0.5 and 1 km/s. The SP stars, regardless of the mass of the disk, rotate with v_θ between 0.5 and 2km/s (within the central $\sim$ 20pc). The rotation initially increases, up to ~ 3 pc, and then decreases at larger distances from

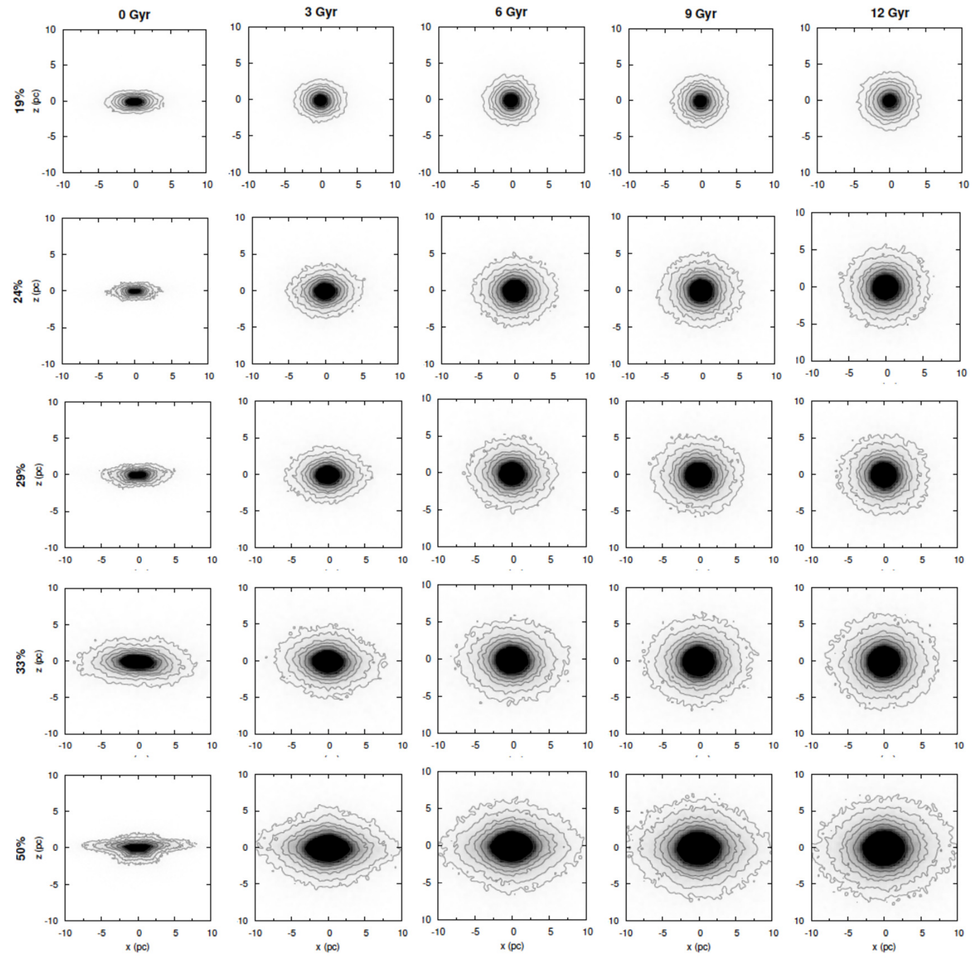

Fig. 1. The evolution of the SP simulated disks with time. The isodensity contours are given at 0, 3, 6, 9 and 12Gyr (going from the left to the right) and for the 19%, 24%, 29%, 33%, 50% mass fraction disks (going from top to bottom). The density contour levels are 50, 100, 200, 300, 500 and 1000 $M_{\odot}/\mathrm{pc}^3$. The z axis is parallel to the L_z component of the disk angular momentum. The disks clearly inflate with time, becoming almost spherical after 12Gyr. Different systems have different relaxation times so their final configuration slightly depends also on this factor. From Mastrobuono-Battisti & Perets (2016).

the center of the cluster. As expected (see also Hénault-Brunet et al. 2015), the spherical case does not show any significant rotation. Thus, in the AGB model or in any model where the SP stars form in a disk, the rotation, which is actually observed in many Galactic GCs (Kamann et al. 2017), can be potentially explained as the result of angular momentum exchange between an initially flattened and slowly rotating second stellar population and an initially spherical first stellar population.

4 Conclusions

We explored the long-term evolution of massive SP disks embedded in an initially spherical cluster composed of primordial, FP stars. We also compared these results with the case of SP stars in a spherical configuration. The presence of the disk imprints kinematic and structural signatures in the cluster properties whose strength is correlated with the SP population mass fraction and depend on the relaxation time of the system, but all the signatures are evident even after 12Gyr in any of the simulated cases. The presence and the strength of differential radial anisotropy between populations can be used as a tracer of the mass fraction of SP stars, while flattening and differential rotation are a clear consequence of an initial disk-like configuration of the younger

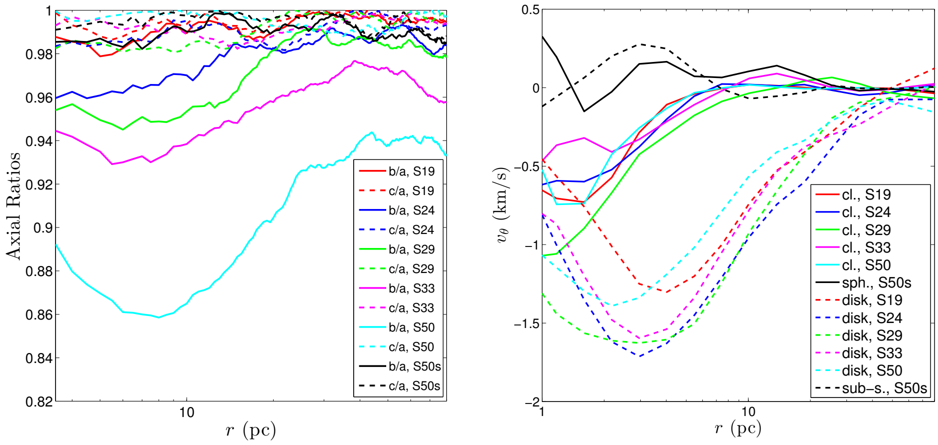

Fig. 2. The axial ratios of both first and second generation populations after 12Gyr of evolution (left panel) and the azimuthal velocity (right panel) for all the systems. The solid lines are for the initially spherical component, the dashed lines are instead for the flattened or spherical second generation population. From Mastrobuono-Battisti & Perets (2016).

population. The presence of the disk speeds-up the core collapse of the clusters because it reduces the relaxation time of the GC. We conclude that only the contemporary observation of flattening, lower velocity dispersion for the SP stars, radial anisotropy and SP rotation could point to an initially disk-like configuration of the younger, light-element enriched populations. The strength of these signatures could provide information on the dynamical age of the clusters and also on the fraction of SP stars present in the system.

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