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Globular cluster tidal interactions and mergers in the Galactic disc

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Abstract. The Galactic globular cluster system went and is still going through dynamical processes that require to be explored in detail. Here we illustrate how primordial massive globular clusters born in the Milky Way's disc evolved by stripping material from each other or even merging very early during their lives. These processes might explain the puzzling presence of star-by-star spreads in iron content observed in massive globular clusters and should be taken into account when studying globular cluster stellar populations. In this context, we show how the direct comparison between the predictions provided by our direct N-body simulations and observations can shed light on the origin and chemo-dynamical evolution of globular clusters.

Keywords. Galaxy: disk – Galaxy: evolution – Galaxy: formation – Galaxy: kinematics and dynamics – globular clusters: general

1. Introduction

Globular clusters (GCs) have long been considered as simple stellar systems, composed by stars born at the same time with the same chemical composition. Recent observations have, however, modified this picture, unveiling the presence of multiple stellar populations with anomalies in light elements, in almost every observed GC (see e.g. Gratton *et al.* 2012; Bastian & Lardo 2018). As a further complication, some of the most massive Galactic GCs present metallicity spreads larger than 0.1 dex (see e.g. Marino *et al.* 2015, 2018). The origin of multiple stellar populations in GCs is debated and has been explained through several possible formation scenarios including intra-cluster secondary star formation events from gas lost by first population stars (see Renzini *et al.* 2015 and Bastian & Lardo 2018 for a review of the proposed mechanisms and Mastrobuono-Battisti *et al.* 2013, 2016 for a study of their long-term implications). These processes are, however, unable to explain the observed metallicity spreads. Some of the clusters showing this feature have been proposed to be the stripped nuclei of former dwarf galaxies that merged with the Milky Way in the past (e.g. ω Centauri, see Johnson & Pilachowski 2010). Simulations indeed showed that GC mergers are possible both in the centre and in the field of dwarf galaxies and can produce clusters internal iron spreads (Antonini *et al.* 2012; Bekki & Tsujimoto 2016; Gavagnin *et al.* 2016). However, the age difference found between the metal-poor and metal-rich populations in Terzan 5 and its chemical

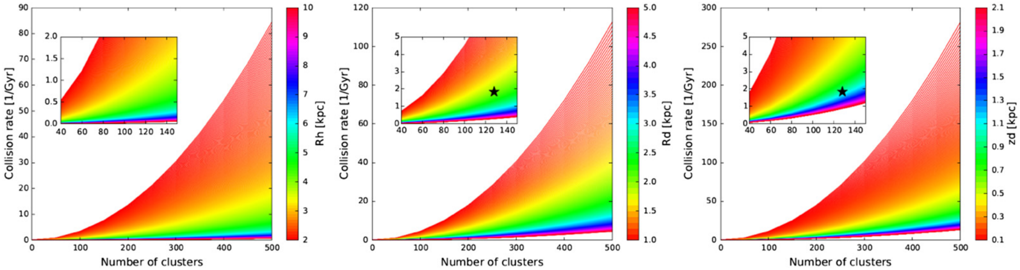

Figure 1. Cumulative collision rate as a function of the number of GCs, in the case of a spherical distribution (left panel), and of a disc distribution (middle and right panels). The colour code refers to the size of the spherical halo (left panel), the radial scale length of the disc for a scale height (0.8 kpc, middle panel) and scale height (2 kpc, right panel) typical for the Galactic thick disc. In the inset in the middle and right panels, the asterisk indicates the collision rate corresponding to a disc of scale length of 2 kpc and scale height of 0.8 kpc.

similarity with the Galactic bulge stars (Ferraro *et al.* 2016) suggest an in-situ origin for this cluster. In Khoperskov *et al.* (2018) we analytically estimated the encounter rate between clusters in the Galaxy, finding a close encounter rate of $\sim 1.8\,\mathrm{Gyr}^{-1}$ for GCs orbiting the thick disc of the Milky Way. We investigated these encounters using short-term tree-code N-body simulations. By simulating a population of 128 GCs of mass equal to $10^7\,M_\odot$, we found two major mergers and several stripping events that produced clusters with up to 50% contamination from a second progenitor. Those mergers and contaminations can generate the metallicity spreads observed in Terzan 5-like GCs. Here and in Mastrobuono-Battisti *et al.* (2019) we follow up these results with long-term (12 Gyr) direct N-body simulations of the interaction between pairs of GCs, initialising the simulation at the moment of the closest encounter and aiming at studying in detail the final structure of the resulting cluster as described in the following paragraphs.

2. Models and Simulations

The analytic calculation and the short-term simulations of a full population of disc GCs performed by Khoperskov *et al.* (2018) showed that while GCs cannot merge in the volume of the Galactic halo, the same systems can have up to 1.8 close encounters per Gyr if they orbit the Galaxy within the thick disc (see Fig. 1). In order to find the long-lasting signatures of the mergers, here we simulate pairs of clusters orbiting in a Milky Way-like potential consisting of a dark matter halo and co-spatial thin and thick stellar discs. The functional forms of these components are taken from Allen & Santillan (1991), while the relative parameters are given by (Pouliasis *et al.* 2017, Model II, see Mastrobuono-Battisti *et al.* 2019 for the details on the Galactic potential and orbits adopted for the clusters). We ran our simulations using either a King (1966) model representing a typical GC (Harris 1996), i.e. core radius $r_c = 1$ pc and tidal radius $r_t = 35$ pc, corresponding to an adimensional parameter $W_0 = 7$ (C1) or an ω Centauri-like cluster with $r_c = 4$ pc, $r_t = 80$ pc and $W_0 = 6$ (Meylan 1987, C2). The mass of the clusters is of $10^7\,M_\odot$ and each of them is represented by an N-body model with $N = 51151$. Once identified the potential mergers, we used the direct N-body code NBSymple (Capuzzo-Dolcetta *et al.* 2011) to follow the clusters for 12 Gyr of evolution. The energy variation at the end of the simulation, with respect to the initial value, is smaller than 10^{-4}.

3. Results

We simulated two C1 clusters, two C2 clusters and a composite pair composed by a C1 and a C2 cluster on selected orbits that lead to mergers (see Mastrobuono-Battisti

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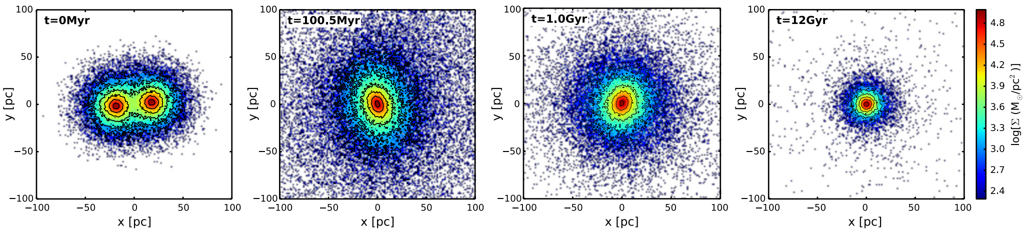

Figure 2. Isodensity contour maps of two C2 GCs that merge and form the CM2 cluster. The projection of the system on the xy plane is shown at different times. The merger is complete after less than 0.5 Gyr. The composite CM2 cluster becomes less massive and more compact with time. The system is plotted with respect to its density center.

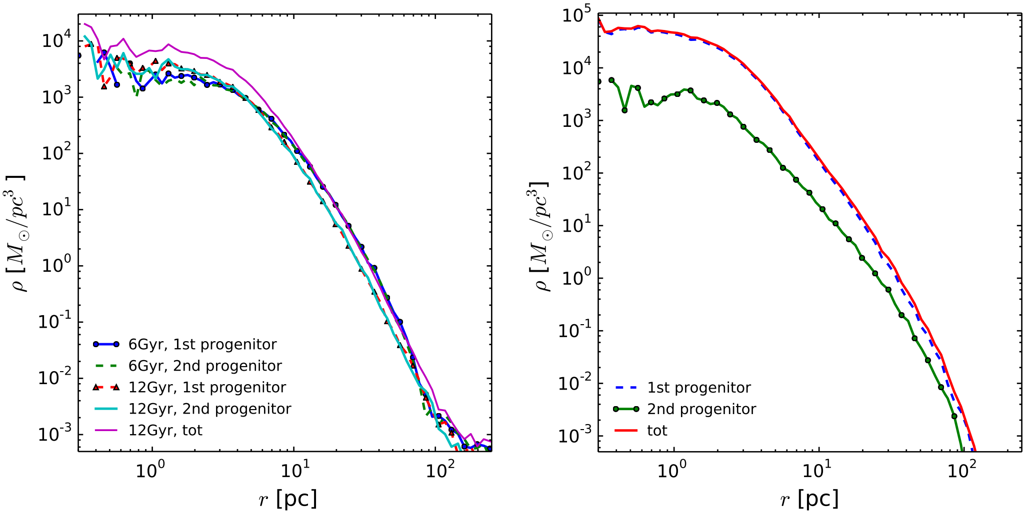

Figure 3. Left panel: Density of the two populations forming CM2 after 6 and 12 Gyr. The two populations are fully mixed and have the same density profile. Right panel: Radial density profiles of the two populations forming CM12 after 12 Gyr of evolution. The stars initially belonging to C1 (the first progenitor, blue dashed line) are more concentrated than the stars inherited from C2 (second progenitor, solid green line with dots). The final cluster is dense and massive (solid red line).

et al. (2019) for the structural parameters of the clusters resulting from the mergers). Fig. 2 shows the phases of the merger between two C2 clusters through the evolution of the density map of the composite system. The clusters are initially on their closest passage and the merger is almost complete after 100 Myr. The system becomes spherical after ~ 1 Gyr of evolution. In the case of equal clusters that merge (the final clusters are named CM1 and CM2), we observe a quick spatial mixing between the two populations that contribute for 50% each to the total cluster mass (see left panel of Fig. 3). If the denser and more compact cluster (C1) merges with the less dense and more extended cluster (C2) the cluster resulting from the process (CM12) shows signatures of the merger even after 12 Gyr of evolution. The population coming from C1 contributes for 90% of the total mass of CM12 and is more centrally concentrated compared to the population coming from C2 (see right panel of Fig. 3). Besides the spatial and mass differences, the two populations also show distinct kinematical behaviours, with an apparent and distinct rotation outside their respective half-mass radii (see Fig. 4). After 12 Gyr the C1 population dominates the mass and the rotation pattern of the final cluster. Rotating clusters are common (see e.g. Bianchini *et al.* 2018) and the mergers could contribute to

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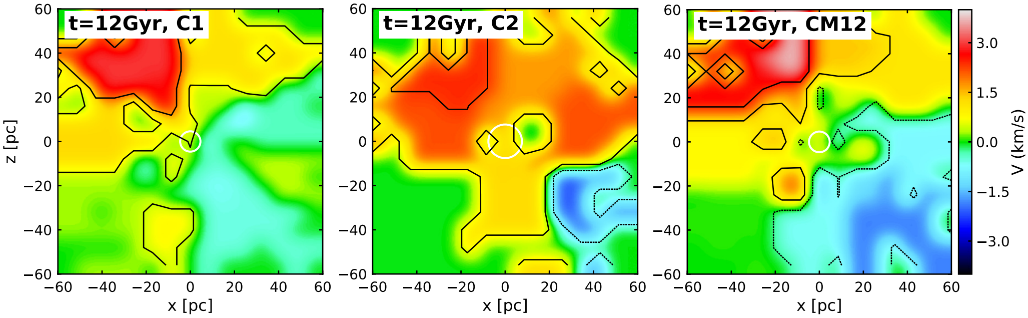

Figure 4. Velocity maps of the two populations forming CM12 (i.e. the stars initially belonging to C1 and C2, identified within the merger product CM12) after 12 Gyr (left and middle panels) and for CM12 (right panel). The cluster and each individual population are seen perpendicular to the maximum angular momentum of the system. The white circle represents the half-mass radius of each subsystem.

this feature with a component misaligned with respect to the total angular momentum of the cluster. As opposed to massive non-interacting clusters that loose 10-20% of their initial masses in 12 Gyr, CM1 and CM12 during and after the merger lose approximately 40% of their initial mass ($2 \times 10^7\ M_\odot$), while CM2 loses 75% of its initial mass. All the mass lost by merging GCs should be found in the current thick disc of the Galaxy.

4. Conclusions

We find that cluster mergers and more moderate mass exchanges could have happened between massive clusters in the primordial Galactic thick disc. The mergers generate new GCs with properties compatible with the massive GCs currently observed in the Milky Way. The mass loss rate observed following the merger is considerably larger than what observed for clusters that do not interact with any companion. We conclude that, assuming different metallicities for the progenitors, the observed mergers could explain the origin of iron spreads in massive GCs, and in particular Terzan 5 in the Galactic bulge.

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