Hierarchical systems in globular clusters

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The paper introduces preliminary results of the improved version of the MOCCA code which is now able to follow the formation and evolution of hierarchical systems (e.g. triple and quadruple stars) in star clusters. The masses of binaries which formed hierarchical systems due to strong dynamical interactions are on average larger than the average masses of all binaries, as expected. However, these higher masses do not seem to come from the fact that hierarchical systems consist of at least three stars – it is rather caused by the fact that the inner binary is massive itself. The third star, in the case of a triple system, is typically a low mass object.

1 Introduction

The MOCCA code stands for MOnte Carlo Cluster simulAtor and is currently one of the most advanced codes which is able to simulate star clusters of the real size and at the same time, it allows to have a full dynamical history of the evolution of all stars in the system. The code was described in details in Hypki & Giersz (2013)[1] and its flexibility was demonstrated while studying the formation and evolution of blue straggler stars. This paper introduces the first, preliminary results of a new version of the MOCCA code which is now able to follow the formation and dynamical evolution of hierarchical systems.

Hierarchical star systems are multiples of higher order than binary, i.e., triples, quadruples, etc. They are crucial for our understanding of a number of astrophysical phenomena, such as formation and destruction of compact binaries and other sophisticated stellar objects, like blue straggler stars, as well as the dynamical evolution of star clusters. Their presence and properties have crucial influence on their environment and can explain the origin of some peculiar objects, like for instance very wide binaries which are frequently members of triple systems (Reipurth & Mikkola, 2012; Simón-Díaz et al., 2015). Characterization of multiple stellar systems, in particular their dynamics, is thus an important ingredient for testing current star formation models. Detailed studies of stellar multiplicity have been performed over a wide range of stellar masses and ages, for reviews see e.g. Duchêne & Kraus (2013) or Reipurth et al. (2014).

Recently, many observational surveys revealed that high order multiple stellar systems are common in our Galaxy. This is true for a diversity of astronomical environments – in the solar neighborhood, among solar-type stars (Duquennoy & Mayor, 1991; Tokovinin, 1997), for nearby low-mass stars (Janson et al., 2014), young star-forming regions (Kraus et al., 2011), open clusters (Talamantes et al., 2010; González et al., 2014; Simón-Díaz et al., 2015), and globular clusters. Kraus et al. (2011) conducted a high-resolution imaging study of the Taurus-Auriga star-forming

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region in order to characterize the primordial outcome of multiple star formation. They found that $\sim 2/3 - 3/4$ of all Taurus stars are components of multiple systems of two or more stars. This was confirmed by another study for the same star-forming region, by Daemgen et al. (2015), who estimated that $62\% \pm 14\%$ of all Taurus stars between 0.7 and 1.4 $M_{\odot}$ appear to be multiple. Raghavan et al. (2010) presented an extensive survey of companions to nearby solar-type stars based on the Hipparcos catalog. They found that the overall observed fractions of single, double, triple, and higher-order systems are $56\% \pm 2\%$, $33\% \pm 2\%$, $8\% \pm 1\%$, and $3\% \pm 1\%$, respectively, counting all confirmed stellar and brown dwarf companions. In turn, nearby low-mass stars of M-type show $21\% - 27\%$ multiplicity fraction, depending on the mass ratio distribution (Janson et al., 2014).

In globular star clusters (GCs) hierarchical multiple systems are most often studied with the use of numerical simulations (Aarseth, 2001; Aarseth & Mardling, 2001). So far, our theoretical understanding of how dynamical interactions which involve hierarchical stellar systems influence the evolution of star clusters is very limited.

As reported by Moeckel & Bonnell (2013), based on N-body simulations, tens of percent of hierarchies in globular clusters experience collisions, typically between two stars of the inner binary, depending on the environment, the hierarchy, and the age of a cluster. Another characteristics of clusters hosting hierarchical massive systems is the enhanced production of high velocity runaways. It seems that the primordial multiplicity of massive stars play an important role in the generation of these rare events in GC simulations. This suggests that they may be used as diagnostics of cluster's history.

Still, vast majority of existing numerical simulations of GCs evolution include only single stars and binaries in the initial population. These models do not take into account the dynamical formation of hierarchical systems and thus neglect their whole dynamical input. This is a huge imperfection, since dynamical interactions which involve triples occur more or less as often as encounters involving single or binary stars only (Leigh & Geller, 2013).

Recently, the need to include the higher order multiple systems also in our simulations became significant, for instance to study the dynamical impact of triples on blue straggler formation (Hypki & Giersz, 2013), black holes (Antonini et al., 2016), or pulsars (Trenti et al., 2008). Thus, it was crucial to implement this feature into the MOCCA code. In this paper only the preliminary results are presented. Sec. 4 of this paper shows that the MOCCA code is capable of performing detailed simulations of star clusters in order to follow the formation and evolution of hierarchical systems.

2 The MOCCA code

The MOCCA code allows to perform detailed simulations of the evolution of star clusters. For advancing the evolution of the star cluster, i.e. positions and velocities of objects, it uses Monte Carlo method described in details by Giersz (2006, and referenes within). For strong dynamical interactions the MOCCA code uses Fewbody scattering code (Fregeau et al., 2004) and the stellar evolution of single and binary stars relies on the SSE and BSE codes Hurley et al. (2000, 2002). For detailed description of how the MOCCA code works see Hypki & Giersz (2013).

Over the last years the MOCCA code proved its value on a number of occasions.

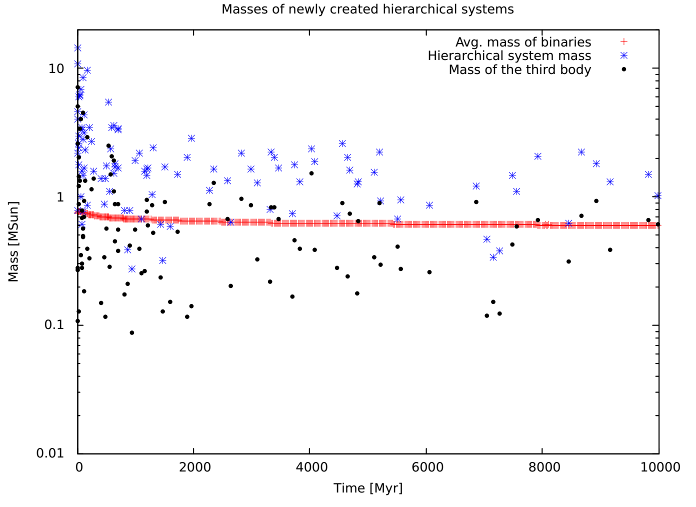

Fig. 1: The time evolution of masses (in $M_{\odot}$) of the newly created hierarchical systems (blue points) are plotted together with the average masses of the binaries in the star cluster (red points). The plot shows results for the simulation with $N = 200$k.

It was used to construct a dynamic evolutionary model of the real Galactic GC M22 (NGC 6656) which is known to hold stellar mass black holes (Heggie & Giersz, 2014). The MOCCA code is not only suitable to study the star clusters as a whole but also it is more than capable to follow in details the formation and evolution of exotic objects (e.g. Hypki & Giersz 2013 to study blue stragglers, Giersz et al. 2014 to follow the formation of IMBHs).

The previous version of the MOCCA code was able to deal only with single and binary stars. All higher hierarchies, which might form due to strong dynamical interactions using Fewbody code, had to be manually disrupted. None of the parts of the MOCCA code was able to deal with the hierarchical systems.

The MOCCA code was heavily changed and the new data structures that are able to handle any arbitrary hierarchical system were added to the code. MOCCA is now able to follow the dynamical formation and evolution of triple, quadruple and higher hierarchies in any simulations. Only for the sake of simplicity and testing the MOCCA code form only triple and quadruple stars at the moment. Once the code and the results of the simulations will be well understood, more complex hierarchies will be switched on. For the stellar evolution, the MOCCA code uses the same codes – SSE and BSE (Hurley et al., 2000, 2002) – there are no new procedures which deal with the stellar evolution of hierarchical systems (e.g. stellar winds, mass overflow).

3 Simulations

This paper presents only two initial models which show that the MOCCA code indeed is capable of dealing with hierarchical systems. More detailed analysis of a larger number of simulations is planned for the next papers in the series.

These chosen models essentially differ only in the initial number of stars and initial binary fractions (Model 1 has $N = 50$k, $fracb = 0.1$, and Model 2 has

$N = 200$k, $fracb = 0.2$). The rest of the initial parameters are the same: initial model – Plummer; IMF of stars – Kroupa et al. (1993) in the range $[0.1; 50]$ $M_\odot$; IMF of binaries –Kroupa et al. (1991, eq.1), binary masses from 0.2 to 100 $M_\odot$; binary mass ratios – uniform; binary semi-major axes – uniform in the logarithmic scale from $2(R_1 + R_2)$ to 50 AU; binary eccentricities – thermal (modified by Hurley et al. (2005, eq. 1)); metallicity – 0.001.

The main purpose of these two models is to perform sanity checks of the MOCCA code and get some first, simple results about the rate of formation of the hierarchical systems. The hierarchical systems begin a completely new area for the MOCCA code. One have to check carefully the results of such test simulations before planning to deal with more realistic problems. New simulations will cover various initial conditions and various sizes of star clusters.

The new version of the MOCCA is capable of following any arbitrary hierarchy of stars. However, for the sake of simplicity in the two test simulations only triple and quadruple stars are allowed. All other strong dynamical interactions which lead to the creation of more complex objects are skipped. Additionally, there are no primordial hierarchical systems in the models. All triple and quadruple systems were created as a result of strong dynamical interactions.

4 Results

In this section a few properties of binaries which created new hierarchical systems and properties of hierarchical systems themselves are discussed.

Here, the model with $N = 200$k is discussed only. The model with $N = 50$k has the same initial binary properties, like semi-major axes and eccentricitie's distributions. The only difference is that there are less hierarchical systems present in the 50k simulation. All conclusions from this subsection hold also to the 50k model.

Fig. 1 shows the time evolution of the masses of newly created hierarchical systems (blue points) together with the average masses of all binaries present in the star cluster (red points). Additionally, the masses of the third, outer star in triple systems are shown with black points. There are only a few examples of hierarchical systems which have outcome masses less than the average binary mass. The majority of them is well above this value. The more massive objects which are inside binaries have larger probabilities of having strong dynamical interactions. Thus, they have more chances to capture a companion star and create a stable triple during one of such events.

As it was expected, newly created hierarchical systems are more massive than the average mass of binaries. However, it is not caused by the fact that they contain three or more stars. The binary, which captures the third object, is already more massive than the average binary mass. Capturing the third body only increases this difference, as seen in Fig. 1.

5 Discussion and Summary

This paper presents only some preliminary results on the properties of hierarchical systems for two test simulations. It shows that the MOCCA code is capable of following the formation and evolution of complex hierarchies in details.

The masses of newly created hierarchical systems, as expected, are on average larger than the average mass of binaries. Interestingly, the larger mass is not caused by the fact that the hierarchical stars have more than two components. It is due to the fact that the internal binary is massive itself. The third star, in the case of triple systems, is typically a low mass object.

The next step is to incorporate into the MOCCA code procedures to perform internal dynamical evolution of the hierarchical systems in between two consequent time-steps to check whether the hierarchical systems remain bound.

Acknowledgements. The project was supported by Polish National Science Center grant 2016/20/S/ST9/00162.

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