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Review of the doctorate thesis of
Mr Agostino Leveque
entitled:
Extra Galactic Globular Cluster machinery based on MOCCA code for Star Cluster simulations

The thesis of Agostino Leveque is tackling the topic of the connection between globular clusters (GC) and the evolution of galaxies, in particular their dark components. Globular clusters are a very important component of galaxies and their studies play a crucial role in understanding populations of black holes at different masses, from stellar mass, and intermediate-mass to super-massive black holes. The database of simulated globular clusters used in this work was MOCCA-Survey Database I, a well-tested dataset, which robustness has been confirmed by previous works of the group of Prof. Giersz. However, in this work, a significant effort has been invested into updating and extending the software and the simulation code to incorporate new developments in this area. In this work, a unique approach has been taken by merging a database of clusters with tools that account for their external effects within a galaxy. This method has been utilized to analyze the behaviour and evolution of clusters in galaxies and compare it to the observed characteristics of clusters in nearby galaxies and the Milky Way.

The thesis comprises seven chapters, a table of contents, bibliography, and is written in 110 pages. Chapter 1 is an introduction to the topic. Chapters 2, 3, 4 and 5 are reprints of four papers published in Monthly Notices of the Royal Astronomical Society in years 2021-2023. By the time of this review (May 2023), their citations had already reached a remarkable total of 20, independently indicating their significant contributions to the scientific community. Each of four papers are written by the PhD candidate (he is the first author) and his supervisor, together with a small number of collaborators. The choice of collaborators is clearly done very carefully, matching the topic of each paper, for example, in the black hole (BH) population study (paper III), one of the co-authors was A.Olejak from CAMK, known for her expertise on the topic of BH population synthesis in the Galaxy. Chapter 6 is a short overview of three additional submitted works to which the PhD candidate contributed significantly. Chapter 7 is a brief conclusion of the entire thesis.

Below I comment on the content of the major chapters 1 to 6.

Chapter 1 - Introduction
The Author describes the main motivation for the thesis work, in particular, how theoretical studies on globular clusters can help understand the formation and evolution of black holes at various scales and nuclear star clusters. The main aim of the thesis is therefore a preparation of a versatile and robust software suite and pipeline in which the evolution of clusters can be traced. This chapter is concise but contains all necessary introductions to all topics and tools used in the thesis, with the exception of AMUSE framework, used in Pap.IV.

Chapter 2 (Pap I)
The first paper from the series describes the method and the construction of the framework as well as the first results in the studies of extragalactic globular clusters using a combination of MOCCA cluster database and its extensions. The MOCCA-Survey Database (Askar et al. 2017) comprises almost 2000 genuine star cluster models with diverse initial conditions. The library of models of MOCCA-Survey was multiplied for different positions in a galaxy, densities, velocities and orbit eccentricities. The evolution of each GC was then traced and eventually only clusters which were not disrupted before 12 Gyrs were selected. The subsample of clusters was selected from the database to mimic the limits imposed by the observations of extragalactic clusters. The observational properties of clusters were derived and investigated. The Authors find that in order to differentiate different stages of the evolution of extragalactic clusters it is necessary to measure at least three parameters, namely core radius, central surface brightness and ratio between central and half-mass velocity dispersion.

Chapter 3 (Pap II)
In papers II and III included in the thesis, the Author used MASinGa (Modelling Astrophysical Systems In GAlaxies) semi-analytical code, designed for computing the evolution of clusters in galaxies and their gravitational potential. The Local Universe has been populated with clusters, in particular, the Authors reproduced the clusters within Milky Way and Andromeda galaxies. They found a good agreement with the observed properties of clusters in both galaxies, reproducing clusters' spatial distribution and half-light radii. As a main result of the simulation, the Authors studied the properties of the Nuclear Star Clusters (NSC) and the Super-Massive Black Holes (SMBH) and found the clusters provided only a small fraction of their current mass. This indicates the mass build-up of the nuclear cluster and the black hole must have been fed also from other sources, for example, mergers and gas accretion.

Figures 3 and 4 - the blue lines are not visible (MOCCA results), only in 1D histogram, not in the 2D.

Chapter 4 (Pap III)
In this paper, the Authors investigate the population of black holes in clusters in galaxies similar to the Milky Way and Andromeda. They again combined the results from the population synthesis code MASinGa with MOCCA-Survey database. Properties of BHs in these clusters were studied and clusters with Intermediate Mass Black Holes (IMBH), BH subsystems and clusters without any BHs were investigated. The study shows differences in BH abundances depending on the location of the cluster within a galaxy, in particular, clusters in the inner galactic region are found to be deprived of black holes. This paper also investigated the population of binary BHs, which were subject to mergers. It was found that 80% of merging binary BHs originate from dynamical interactions within the cluster. This also led to the determination of the merger rate in the local Universe at 1 to 23 events per year per Gpc^3. This number is somewhat smaller than from other works but remains similar and comparable.

Chapter 5 (Pap IV)
This work is not aligned in the series with the previous papers, but is still closely related to the topic of the evolution of globular clusters in galaxies, in this case, focusing on the survival of GC after the early removal of primordial gas. The MOCCA code was embedded in the AMUSE framework and here it was possible to simulate much larger globular clusters (up to 500,000 stars) compared to previous N-body versions of the code. Thanks to this expansion of the size of the studied cluster, more realistic models were possible to obtain (compared to 20,000 stars in previous studies). The Author compares his approach and results to similar studies from the literature and finds a good agreement of the resulting properties of clusters, however, he emphasises that his approach offers a more accurate outcome due to the presence of massive stars, which may play a crucial role in the first million years of the cluster evolution.

Apart from paper IV itself, the AMUSE framework was not introduced in the introduction to the thesis, leaving a feeling that the fourth paper has been added later and not completely matching the general scope of the thesis. It is worth noting that in this paper the Authors computed the amount of CO_2 generated during the operation of the supercomputer and they show that it was equivalent to driving a car for 170 km.

Typo: pap IV, p. 5745 starsthan -> stars than

Chapter 6
This chapter contains concise summaries of three additional works, some of which have already been published while others have recently been submitted to journals. The submitted works are not first-authored by the PhD candidate and it is not obvious which part of the team effort was done by the student. Nevertheless, these works nicely supplement the thesis, however, in my opinion, the thesis would have been complete even without this chapter.

The first one (6.1) is on the update of the MOCCA code for cluster evolution with the modern and up-to-date prescriptions for stellar and binary system evolution. New supernova recipes were included, taking into account recent developments in both the observational and theoretical sides of these studies (e.g. pair-instability supernovae or stellar winds). The modified code was run and the results were compared with the older versions. The main similarities and differences were discussed, for example, it was noted that the new version produced a larger fraction of WD-WD binaries and a smaller fraction of WD-MS binaries. Another difference was that the MOCCA models had larger central densities compared to the new code results, which suggests the new code produces fewer binary mergers.

The next work (6.2) tackled a new feature added to the MOCCA code on the evolution of more than a single stellar population. Multiple-population clusters are very often seen in the Galaxy hence it was only natural to include this effect in the simulations. The differences between the evolution of populations were studied. As an outcome, the Authors found that tidally underfilling clusters would contain more stars from the first population than the second one. Also, second-population binaries were found to be disrupted more frequently. In tidally filling clusters, on the other hand, the results were the opposite - the second population stars dominate and the number of binaries remains similar. These results are in agreement with the properties of clusters observed in the Milky Way, which is crucial if the models are to be used to understand the formation and evolution of observed clusters, in my view, the main purpose of such theoretical studies.

The third paper (6.3) is on the mass growth of Nuclear Star Clusters (NSC) and Super Massive Black Holes (SMBH) in the Milky Way and Andromeda galaxies. The idea and software presented in earlier chapters were applied here for the first time to explore the impact of cluster evolution on NSC and SMBH and their growth through infalls and mergers of IMBHs originating from globular clusters and then the accretion of gas onto the IMBH delivered from the cluster. Interestingly, the Authors managed to reproduce the masses of NCS and SMBHs in both Milky Way and Andromeda to agree with the observed values and they find the mass of the gas needed to be accreted in order to reproduce the mass of these systems. Such studies are essential in understanding the formation of nuclear systems in galaxies and their origin from globular clusters.

Figures 6.1 and 6.2 contain an error in the label of the Y-axis: IMBH -> SMBH.
Typo: p.97 wit -> with

I would like to make a note about the term *extra galactic* used in the thesis title and the titles of the series of papers. There is no consistency in the use of this term, sometimes it is written as *extra-galactic*, sometimes *extragalactic*. The capitalisation is also not consistent, interchanging between *extra galactic* and *extra Galactic*. When it comes to creating an acronym EGGCs, I would probably write all words with capitals and then use the acronym consistently, however, the acronym itself has only appeared in paper I.

SUMMARY
In summary, the PhD candidate explored different codes in combination with MOCCA code and the existing database. These software solutions were then applied to investigate very up-to-date and interesting topics in GC evolution, for example, the BH subsystem's behaviour or survival of GCs depending on the gas content. The Author in each scientific and computational case first presented proof that the proposed solution is robust and returns results which are consistent with previous analyses. Then the problems in GCs evolutions were studied in detail. The main outcome of the work was building a robust framework for simulating an entire MW-like galaxy with its globular cluster population.

I find no issues or problems in the work apart from a small number of minor typos. The work is prepared according to the standards expected of PhD theses, contains mature scientific results, and is of sufficient quality to qualify for a PhD degree. Therefore, I conclude that the reviewed work of Mr Agostino Leveque fulfils, in my opinion, all requirements posed on PhD theses, therefore I recommend it for the oral defence.

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Warszawa, 4 May 2023

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