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Review of the doctorate thesis of
Mr Abbas Askar
entitled:
Investigation of Black Hole Populations in Dense Stellar Systems using MOCCA code for Star Cluster Simulations

The thesis of Mr Askar tackles a very important astrophysical topic, namely the formation, evolution and fate of black holes with connection with the globular clusters. In the light of recent gravitational wave discoveries of population of large merging black holes and search for dark matter in form of primordial black holes, the study undertaken by Mr Askar is very timely and interesting. More importantly, the thesis is crossing the boundaries of purely theoretical discussions and extends to expected observational properties of black holes originating from globular clusters, as well as compares the observational data with the predictions. This makes the thesis a very strong voice in currently on-going debates on Galactic and extra-galactic black hole population.

The thesis is based on four accepted papers, published in high-profile peer-review journals (MNRAS and Astrophysical Journal), therefore I have no doubt about their highest scientific standards. There is an extended and detailed introductory part in the the thesis, as well as an additional chapter, which summarises the couple of additional publications or research works just submitted for publication, or still in progress. The thesis is contained on 99 pages and both published works, the introduction and the additional chapter are written in clear language and they read very well.

Below I describe each chapter and provide my comments.

Introduction

In the first chapter the Author introduces the topic of the thesis, its scientific background, motivation and tools developed and used throughout the work.

First, the Author presents a detailed and thorough description of the current status of science of globular clusters (GC), their physics and modelling attempts. Modelling of GCs is a challenging task, as it requires an inclusion of a whole spectrum of astrophysical processes, from star formation, binary formation and evolution, to supernovae and natal kicks of formed remnants. On the other hand, modelling of globular clusters is one of the best ways to understand their observational properties, as detailed observations and studies are often impaired and limited due to extreme crowding. The Author presents various approaches to this challenging task of numerical GC modelling, with their strengths and weaknesses. Popular and well-established N-body codes are presented.

Next, the Monte Carlo approach to GC modelling is described as being significantly faster than canonical N-body codes. Increase in speed of the modelling codes enables reaching to much larger GCs in terms of number of stars, allowing to simulate a million-star GC within a mere few days. This, in turn, allows the researchers to explore, for the first time, the influence of various initial parameters of clusters on their evolution. This approach was the main motivation for Mr Askar and his supervisor, Prof. Mirek Giersz, to employ Monte Carlo-based GC simulation in studies of GCs. The code used in this work, dubbed MOCCA, was developed over many years and relied on input and experience of many people. The MOCCA code was used to simulate nearly 2000 models of clusters with varying initial parameters, such as initial structure, central density, relaxation time, etc.

In the subsequent part of the Introduction Mr Askar describes the status of black-hole research in the context of globular clusters. Black holes are natural products of stellar evolution of the most massive stars and GCs are obvious sources of such objects. There has been some observational claims about stellar-mass black holes in GCs so far, as well as theoretical predictions on their formation and observational properties. However, there are still serious uncertainties on many crucial parameters of BH formation, most importantly the natal kick during a supernova, as well as fraction of disrupted binary BH systems. These unknowns lead to ambiguous conclusions on whether BHs are retained in the globular clusters, or get ejected. This discrepancy was one of the motivations of study undertaken in this PhD thesis.

Another topic raised in the thesis and introduced in the first chapter are Intermediate Mass Black Holes (IMBH) in globular clusters. Their formation in the central parts of clusters has been proposed before and there were claims of detections of IMBHs in GCs. However, the detections are still under debate and there is still many unknowns on their presence. In the Introduction Mr Askar gives an overview of the studies carried so far on IMBHs in GCs, however, my impression is that this section could have been extended, to include more details on the IMBH science, in particular on their connection to the growth of supermassive black holes in the very early Universe (e.g., Bañados 2018, Nature 553, 473). There is a separate introduction on IMBHs in Chapter 3 (Paper II), which also, in my view, is not tackling all aspects of the importance of IMBHs in current understanding of the galaxy evolution. It would also be good to mention about the attempts to detect IMBH in GCs via X-rays or optical flashes from stellar disruption (e.g., Jonker 2013, ApJ 779, 14).

Despite being thorough, the Introduction would, in my view, benefit if there was a mention on the origin of globular clusters (galactic, extragalactic) and its any possible relation to the observed/simulated parameters. Also, what are the most striking and obvious weaknesses of MOCCA, compared to classic N-body codes? If the results are similar, but the speed is better, why there are still people who use the N-body codes?

Chapter 2 (Paper I)

This paper discusses the origin of merging black holes seen in gravitational wave (GW) events and proposes some of them were produced in and later ejected from globular clusters. This is a significant work towards understanding of the origin of GW events. The black holes seen merging there were unusually massive, therefore it has been suggested in the literature that they originate from low-metallicity stars, or could even be composed of the dark matter in form of primordial black holes.

In this work the Authors used models of GCs obtained with the MOCCA code to search for binary black holes that can merge and produce GW signal. Such binaries can merge either inside the cluster or away from it after their ejection from the cluster. As noted in Sec.3, binary BHs would merge faster if located still within the cluster due to the influence of other members. This results in an increased merging rate very early on in the evolution of a cluster (Fig. 2). The merging rate also depends on the total mass of the cluster and is also increased for low metallicity systems.

In the final section the Authors discuss the results in the light of the assumptions and limitations of their experiment, for example, they note that the merger rate would be 3-5 times larger if the more massive GC were included in the study. The obtained rates of mergers of BHs originating from GCs resulting in GW signal are within the range of total rates obtained for the LIGO experiment, what indicates that a significant fraction of mergers might take their BHs from globular clusters. GCs therefore play an important role in production of potential BH mergers observed in GW experiments.

The paper is brief and concise, as it was published as a letter. Abstract and the text of the paper state that 2000 MOCCA models were used, while only 985 were useful, as only they contained a relevant natal kick prescriptions. In Section 2.1 the Authors note the models were not well reproducing all parameters of Milky Way's GCs, in particular the absolute magnitudes. I wonder what is the impact on these inaccuracies on the estimated rates, as this is not present in the paper.

There are two types of BH mergers considered: inside and outside of a cluster. Is there any possible impact of the merging location on parameters of observed GW events. If there is any dependence on the location of the BH merger, it could have been commented in the paper as a potential way of distinguishing the origin of the merging BHs.

This work has been published as a Letter in MNRAS and at time of writing this review it has already received 34 citations, a significant number indicating the importance of the publication. Among the papers citing this work of Mr Askar, there is one of the Abbot et al. papers from 2017, with the discovery of one of the most massive black hole mergers seen in a gravitational wave event (GW170104). This only emphasises the importance and relevance to the current research topics of the work done by Mr Askar. The statements from other authors of this paper clearly indicate that Mr Askar has conducted and lead the research as well as the preparation of the manuscript.

Chapter 3 (Paper II)

This work concerns a different scale of black holes in globular clusters, the intermediate-mass BHs (IMBH). These elusive BHs are currently in the focus of research from a range of angles. They are thought to be important building blocks of the very early supermassive black holes, hence their detection in the present-day Universe is essential for understanding the formation of galaxies. In particular, the formation and existence of IMBHs in GCs has been recently strongly debated. This paper is an important voice on this topic.

In this paper the Authors again employed a range of models produced by the MOCCA-SURVEY database and selected these where IMBH could have formed after 12 Gyrs of cluster evolution. Selected clusters were evolved and the resulting models were converted to real-like visualisations, obtained with a dedicated code, COCOA, prepared for this work by Mr Askar. The code itself is described and discussed in Chapter 4 (Paper III) of the thesis. The outcome of the COCOA was then compared to real images of Milky Way's clusters. One of such clusters, NGC 6535, was found to share many of the properties of the simulated one, therefore it was suggested this dark cluster harbours an IMBH.

In Section 3 the Authors define applied selection criteria on the models. There were actually 344 models which formed IMBH with mass more than 150 MSun, however, only in 42 the mass of the IMBH made up more than 50% of the cluster mass. This directly lead to a selection of dark clusters only (with large M/L). Further in Section 3 there is another selection criterion on the model with an IMBH making more than 70% of the mass of the cluster and being the most massive cluster. Why choosing the most massive cluster with the highest M/L to represent all dark clusters was not fully obvious to me. I am wondering what was the final IMBH mass fraction in all remaining 344 clusters, which formed IMBH. Also, how much different were 42 dark clusters from NGC6535?

The simulations had a limit on maximum stellar initial mass of 100 MSun. As this is mostly correct, I wonder what would be the impact on IMBH formation if more massive stars were allowed at lower metallicities.

Simulations of observations of the selected dark cluster and the agreement with the real data are indeed very impressive. The main significant difference is in colour and is attributed by the Authors to different metallicities. It is not clear to me why additional model with lower Z was only generated in Section 4.1, as it could have been modelled at the very beginning of the work. Are there any other significant differences in the second (low-Z) model parameters and the resulting mock cluster compared to the one selected from the MOCCA database?

The parameters of the observing conditions for the simulations of the images in COCOA code are meant to reproduce the real ones. However, I think that a seeing of 0.3 arcsec is a bit of a wishful thinking, unless it was clearly stated that it required Adaptive Optics (AO) instruments. Still, even for such ideal conditions, the blending of cluster stars will still be an issue and the assumption that all stars get resolved might not be correct. I wonder what would be the impact of blending on the retrieved photometric and kinematic parameters of the cluster.

Presence of an IMBH might cause an increased ejection of stars, resulting in orphan hyper-velocity stars wandering in the Milky Way. Could this be commented, especially in the light of the recent Gaia Data Release 2? Can Gaia data be useful to trace stars removed from GCs by interactions with their IMBHs, and how does this population of stars differ from other stars ejected from GCs by star-star interactions? Can this be tested with MOCCA models?

In summary, this work is an impressive comprehensive study of a cluster model and a realistic reproduction of its image and observational and kinematic properties. This is a unique analysis in which a cluster model is turned into an observational data, allowing for recovery of the simulated parameters. Moreover, a similar cluster has been identified among Milky Way's clusters and the same analysis was conducted. The work presented in this paper has a large potential for further extensions and analysis of other clusters with large mass-to-light ratios in order to probe the population of IMBHs.

Chapter 4 (Paper III)

This chapter describes an advanced code, dubbed COCOA, for creating mock observations of star cluster models. The code was used in chapter 3 to generate realistic photometric and kinematic data based on a MOCCA-simulated model of a dark cluster likely to harbour an IMBH. The code is flexible as it was also used in another paper, where the input data came from N-body simulations. While the main COCOA paper received so far only 1 citation (it is a very recent publication, from 2018), the other paper relying on COCOA results (Wang et al. 2016) has been cited already 53 times (according to ADS). This shows a great importance of the code and its applications.

The COCOA code is a crucial extension to the studies of globular clusters via their synthetic models. COCOA generates synthetic observations which can then be used for verification of the accuracy of real data analysis methods and can exhibit any issues or biases in such analyses. In particular, the synthetic data compared to the real one can be used to discover and trace the presence and parameters of invisible components of clusters, especially black holes, both stellar mass and IMBHs.

The code does the sky projection of the synthetic model of a cluster, then generates mock images with provided parameters on the imaging setup and conditions. A standard FITS files are generated, but the code is also capable of deriving the photometry based on PSF fitting. The photometry of a crowded stellar field such as a globular cluster, even when obtained with a very high angular resolution, is still subject to severe blending. This, in my view, has not been addressed enough in the paper. Section 3.1.2 mentions the simulated data retrieved about 75% of stars from the model and the loss is attributed solely to the depth of mocked images. This is probably not fully correct, as many stars are probably not recovered due to their blending with each other. Nevertheless, the resulting images and CMDs resemble the realistic ones, which is seen with the example NGC2808 cluster, simulated with fairly large value of seeing (0.78 arcsec).

It would be good to explore different telescope parameters, ranging from HST space observations and Adaptive Optics (AO)-assisted ground-based imaging (e.g., from VLT) to standard seeing-limited ground-based observations. Simulations shown in the paper only include very optimistic simulations using seeing of 0.3 arcsec, normally very difficult to achieve. Yet another interesting extension of the application, possibly to consider for future development, is the simulation of Gaia observations of clusters.

I acknowledge that preparation of such a sophisticated code can very rarely be done by a single researcher, yet alone a PhD student. Therefore, I am not surprised the contributions of other co-authors to the preparation of the code were fairly significant, for example, with Dr. Wojtek Pych as the main responsible person for generation of synthetic images. Such task requires an in-depth knowledge of the photometry and image processing, and I do not think that Mr Askar had simply enough time to gain it during his PhD studies related to a very different topic. However, all the statements emphasise that Mr Askar was the unquestionable leader of the project, its development and testing, as well as the main author of the manuscript.

Chapter 5 (Paper IV)

This work follows a series of papers related to the results of the MOCCA-SURVEY Database I. Here the authors used models of MOCCA galactic clusters as a basis and re-simulated them with a more detailed and accurate post-Newtonian physics. This allowed the authors to follow the binary-single BHs interactions and to compute the rate of high-eccentricity black hole mergers. They found that lack of inclusion of the General Relativity approach would lead to a serious underestimation of the eccentric mergers. The main conclusion of the work is that about 10% of all mergers observable with current GW experiments are due to three-body mergers with large eccentricities.

This paper was lead by Johan Samsing, a collaborator of Mr Abbas Askar, with the PhD candidate as the second author. The statement by Mr Samsing attached to the thesis, indicates that Mr Askar played an important role in the preparation of this work. However, I have some doubts if this paper should have been included in the PhD thesis at all, despite its obvious connection to the topic of the thesis. On the other hand, this paper, as well as about 10 other publications where Mr Askar was a significant co-author, they all reveal that the PhD candidate is already a very active researcher in the field who makes important contributions to the research of other scientists and their publications.

Chapter 6

This part of the thesis contains a brief summary of three additional research projects of Mr Askar, related to black holes in globular clusters.

Section 6.1.

Globular clusters produce black holes in the course of their evolution. How many of these BHs are retained in the cluster depends on its parameters, structure and time of the evolution. In this work the authors used a subsample of GC models generated by MOCCA, which had a significant number of BHs after 12 Gyrs, to study the properties of the Black Hole System (BHS) and its relation to parameters of simulated clusters. A number of correlations has been found and discussed, in particular, that there is a tight relation between cluster's luminosity at half-light radius with the density of BHS. This discovery can help observationally identify clusters with a large Black Hole Systems and IMBHs, and it was applied to Galactic clusters in the following paper.

This paper has been submitted to MNRAS and its most recent version (different than the one in the thesis) is available on arXiv. Mr Askar is the second author here, therefore I assume he did not have a leading role in this work (there are no statements from the collaborators for this paper). However, similarly to paper IV, this publication shows Mr Askar is an active collaborator playing important role in research carried out by other scientists.

Section 6.2.

In the work described in this section the properties of Black Hole Systems found and presented in Section 6.1, are utilised in order to identify GCs from the Milky Way which are likely to host hundreds of black holes. Among 140 globular clusters with parameters available in the literature the Authors selected 29 with a significant collection of black holes. Based on observational properties of these cluster parameters of the BHS were derived, such as number of BHs, an average BH mass or a number of black hole binaries. What would be interesting to see in either Sec. 6.1 or here, is the observational distribution of masses of retained black holes in these clusters and a discussion how do they depend on cluster' parameters. The Authors list a number of limitations of their approach to identify BH-filled GCs, noticing primarily that their results strongly depend on the BH natal kick prescription. In the extreme case scenario, if BHs get very high natal kicks, none of the 29 clusters can be assumed to have a significant number of BHs. However, since the problem of the natal kick of BHs is still under strong debate, the Authors assumed lower kicks following publications of multiple authors. Another weak point, also noticed in the work, is that a higher binary fraction could also mimic the BH population. Moreover, the uncertainties of the observational parameters also have influence on the estimates on numbers and density of black holes and the Authors admit that only some of the errors were propagated to the final results.

Nevertheless, this is still a very interesting and novel idea to identify GCs with BHs based on simulated models of clusters and their observational properties. Some of the clusters recognised this way were actually already suggested to harbour BHs, based on both simulations and observations, while the results for others are still controversial. This shows the importance of the studies carried out in this work which employ state-of-the art cluster simulations in order to predict their observational properties.

6.3.

The final section of the thesis is a report from a preliminary work, not yet published. However, it also concerns black holes and their relation with globular clusters, hence it fits nicely with the overall scope of the thesis. Here, black hole binaries ejected from globular clusters from the entire database of MOCCA models are studied in order to investigate their properties in comparison to the observed population of mass transferring X-ray binaries in the Milky Way. There were 145 systems out of 4244 ejected binaries, which in the time-frame of 10 Gyrs were at the stage of mass transfer between the donor and the black hole.

The results of the preliminary study by Mr Askar have several interesting points. The most striking is the overall evolution of such a binary system throughout its period inside a GC, where both the donor and the BH are formed predominantly via stellar and black hole mergers and not via canonical stellar evolution. Figure 6.9 shows a very complex path of the binary evolution, significantly different from similar plots in publications by Belczynski or Wiktorowicz, dominated by the Common Envelope Phase and much more simple. The comparison of properties of binaries simulated here and some of the observed known X-ray binaries indicates some agreement. In particular, its mass distribution is better reproduced here than in simulations of stand-alone binaries (e.g., from work of Wiktorowicz). However, the number statistics are very small and also the probability distribution for mass of observed binaries are actually more complex and very often have long wings towards larger masses (e.g., Ozel et al., 2010). Also, there was only a small sample of X-ray binaries selected for the comparison and it would be interesting to see how the mass distributions compare for BH mass for more cases (where only the mass of the BH is known).

It would be interesting to see the properties of the remaining 97% of ejected binaries, what are the masses of BHs and what is the distribution of their separations. Possibility for discovery of thousands of such wide BH binary systems were recently claimed to be possible with the use of Gaia astrometric data (Mashian & Loeb 2017 MNRAS, 470, 2611; Breivik et al. 2017 ApJ, 850L, 13).

The fraction of mass-transfer systems which get ejected from clusters (only 3% of all ejected binaries) is actually very small. How this number matches the numbers of clusters in the Milky Way and can this be scaled to their numbers? Can any of known BHs in the MW be traced back to a GCs where they originated from, using for example recent Gaia DR2 proper motions and radial velocities? How does the retained mass-transferring BH systems statistics compare to the observed ones? (e.g., Liller 1 cluster has three such systems).

Nevertheless, this preliminary work presents a yet another very interesting application of MOCCA-based globular cluster models.

Most important highlights of the thesis:

- showed that a significant part of black holes binaries merging in GW events could have originated from globular clusters
- presented a convincing case for an intermediate-mass black hole in globular cluster NGC6535 by comparison of its parameters to a similar simulated globular cluster
- Mr Askar lead the development of an advanced astrophysical code, COCOA, for simulations of mock photometry and kinematics of globular clusters based on input models. Such mock data has been shown to be very useful in studying the observational properties of clusters.
- discovered various relations between properties of Black Hole System and their relation to parameters of GCs, useful for identification of clusters in the Milky Way with numerous BHs.
- studied observational properties of clusters in order to identify clusters in the Galaxy with a significant population of BHs.
- analysed properties of simulated BH binaries ejected from globular clusters and found a better agreement with the observations than other studies simulating binaries outside of clusters

- Mr Askar is an active collaborator, taking part in published research of other scientists, often as a second important author

More significant problems:

- Impact of blending in simulated images in COCOA is not discussed; It could be good to investigate the impact of different photometric/instrumental conditions on results and cluster parameters retrieval.
- Small number of selected known X-ray binaries used in the comparison with expected ejected systems and use of exact values for BH masses instead of their mass functions make the comparison not accurate

Miscellaneous/minor issues

- some rare typos, mostly in the introduction and chapter 6, e.g., "which are are published" on page 1, or "universe" on page 6.
- error in citation of work of King ("The structure of star clusters….") in multiple places in the Introduction
- in Chapter 2/Paper I, Section 2 has only one subsection (2.1) and 2.2 is missing.
- in multiple figures, e.g., Fig.4 and 5 in Paper II: notation for solar mass is Mo - if LaTeX M_\odot was not possible, then better use MSun.
- Chapter 4/Paper II, subsection 2.3 has only one subsubsection (2.3.1)
- ! Cen on page 81, should be Omega Cen

SUMMARY

The reviewed work of Mr Abbas Askar fulfils, in my opinion, all requirements posed on PhD theses, therefore I recommend it for the oral defence. I would also like to propose to award Mr Askar's doctoral thesis with distinction due to the following aspects: scientific novelty, extensive research on a highly timely topic, good quality of the prepared work and an impressive number of first-author publications as well as the collaborative spirit of the research carried out by this young scientist.

Łukasz Wyrzykowski

Warsaw, 5 May 2018.

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