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Report on the Doctoral Thesis of Mr Abbas Askar,
entitled
"Investigation of Black Hole Populations in Dense Stellar Systems using MOCCA code for Star Cluster Simulations"

prepared in the Nicolaus Copernicus Astronomical Center,
Polish Academy of Sciences

The topic of this doctoral thesis deals with numerical modeling of interactions between stars in dense globular clusters. The main focus is given to the formation of black holes in such systems, which frequently form binaries with other stars, including binary black holes. The black holes may be dynamically ejected from the cluster or sink into the center and build up a single massive black hole that dominates the kinematics of the surrounding stars. The latter formation, in contrast to dwarf galaxies, does not contain an exotic 'dark matter' component, however may reveal the presence of the Intermediate-Mass black hole in the core of a globular cluster.

The methodology used by Mr. Askar in his thesis is based on the numerical simulations of the star cluster evolution, and exploring the large grid (over two thousands) of models, which are spanning the whole parameter space of initial conditions. His computations are performed using the code MOCCA, which was originally developed by the Thesis Advisor, prof. Giersz, while using the formalism developed in the works of prof. Stodółkiewicz in 1980's. This Monte Carlo code is not publicly available, however it has been extensively tested before and its results were compared with the stellar cluster evolution results based on different methods (the N-body simulations). It provides solver for equations of the time evolution of specific energies and angular momenta of N stars within the shells with a given (changing) gravitational potential. The binary and triple encounters between the stars are also taken into account. The code employs in addition the external packages responsible for modeling of the stellar evolution, starting with all stars being initially at the Zero-Age Main Sequence and evolving them until some compact remnants are formed.

In addition, the Author of the thesis presents his new contribution to the field, with a visualization-like tool that mimics the observational properties of the globular clusters simulated with MOCCA. This tool, called COCOA, implemented the scripts that are standard for observers and produce for instance the optical images using various filters, or the color-magnitude diagrams. The aim was to visualize the simulated clusters in a way that is familiar to observers and enables to compare the models with real data.

The Thesis of Mr. Askar is written in a quite non-standard way. There is no 'classical dissertation', but a collection of articles published in refereed journals (4 works), printed in a journal-style format, each of them with separate bibliographies and introductions. In three of these articles Mr. Askar is the first author. The last but one Chapter, on the other hand, presents the unpublished and on-going projects, which are still under preparation and will possibly evolve into three new articles. All of this work is connected with the globular cluster evolution models, and exploits the large database of models produced by the Author with the MOCCA code. The Author prepared also the first and last chapter, with a general introduction, and then conclusions, to the whole topic (with a bibliography that is separately given, but to large extent overlapping with the articles'). The articles were written mostly within large groups of co-authors. In most cases the substantial contribution of Mr. Askar is confirmed by the statements separately provided by the collaborators.

The Thesis consists of 7 Chapters.

Chapter 1 contains a brief introduction to the topic of globular clusters and description of the MOCCA code. The last subsection describes the content of the thesis and main results presented in the published (and unpublished) work. This part is in general nicely written and could be sufficient for understanding of the thesis content. What is unfortunately missing, is a more physical description of the problem of globular cluster structure and dynamics. The author did not present the main equations which are solved by the code MOCCA. They are derived in classical literature, and it would be much better to provide these equations here, instead of the elaborate part about the 'importance of globular clusters', or in addition to the rather technical list of 'features' of the code. Also, the modules which compute stellar evolution, are here only very briefly mentioned with their acronyms and reference to the literature. But it is not explained what in fact these SSE and BSE models mean, what are the equations and the procedure of integration or assumptions used in these models.

In Chapter 2 the Author presents his simulations of coalescing black holes originating from the globular clusters. The main result is the limit for the merger rate density per year per unit volume, and prediction for its gravitational wave signal detection by LIGO. The discussion of this important finding was contributed by the expert in the field, prof. Bulik. However, despite the fact that apparently most simulations were performed here by Mr Askar, this paper was already used as the basis of the PhD dissertation of its second author, Ms. Magdalena Szkudlarek, in the University of Zielona Góra (Thesis entitled *"Numeryczne modelowanie astrofizycznych źródeł fal grawitacyjnych"*, defended in September 2017; see website: http://wfa.uz.zgora.pl/).

Chapter 3 presents the study of one specific globular cluster modeled within the Author's large survey, which has formed an intermediate mass black hole (IMBH) in its core. The resulting cluster is then interestingly compared with its observational properties with the known object, cluster NGC 6535. The photometric properties, revealed by the surface brightness profile of the simulated cluster, are qualitatively similar to the observations of NGC 6535. Also, the kinematics, described by the velocity dispersion profile, is compared with the observed data. Despite some systematic differences, which the Author explains as due to different ages and average metallicities of stars in the simulated and real objects, the results may suggest that in fact the cluster NGC 6535 is a prototype to the modeled one, and hence a massive black hole (ten thousand Solar masses) is possibly harbored there. More detailed future measurements of stellar velocity dispersion in the innermost part of the cluster are suggested to confirm this hypothesis. The discussion regarding observability of the kinematic properties of dense clusters of stars was benefited from the contribution of three collaborators from Canada, Australia, and UK. In my opinion, the discovery of IMBH presented here is an important contribution to the research on the origin of this hypothetical class of the black holes, occupying the intermediate range of masses between black holes found in stellar binaries and cores of galactic nuclei. I appreciate the new methodology utilized in this work by the Author, and convincing result.

Chapter 4 contains the most technical part, with description of features of the COCOA code, which is used to create the 'mock' observations of the simulated globular clusters, which mimic the real data. The article presents a suite of examples of the code performance, and even a short manual for the future users. Code written by the Author in *python* utilizes the routines written in C by dr Wojciech Pych. This work, albeit missing the original new scientific application, might be regarded as the Author's contribution to the astronomical community development. The scientific achievement based on this code was however given already in the previous Chapter.

Chapter 5 presents the research on the eccentric binary black hole mergers which originate in the clusters via the triple interactions. It is found that some of these merging binaries may have substantial eccentricity, however the fraction of eccentric binaries which obtain the large kick velocities and escape from the cluster, is rather small. The rates of these types of binaries as a function of time are then compared with analytical estimates. The analytical part implemented the General Relativistic framework, and was presented elsewhere by the first author of this paper, dr Johan Samsing. Unfortunately, neither the derivation of the pericenter distance, which is related with the gravitational wave frequency (Eq. 1), nor the post-Newtonian corrections used in the code for re-simulating the Globular Cluster models, are included in the thesis. This could easily be done in the Introduction chapter, especially because the Chapter 5 hints an urgent need for further development of relativistic models of dense stellar system evolution.

Chapter 6 is a collection of three unfinished works. In my view, only first of these studies is advanced enough to be included in the Thesis. It shows the analysis of the black hole subsystems, found in the simulated clusters database. The properties of such subsystem (its radius, total mass, average black hole mass, number of black holes) are fitted with the analytical power-law dependencies. Strangely, despite the Author claims that there is an analogy with the ‘black hole sphere of influence’, as defined previously by Merritt (2003) for the supermassive black hole in galactic centers, the radial profiles for an individual globular cluster with BH subsystem are not discussed. Does it have an offset? Does the surface brightness profile of outer parts fit to the Sersic profile (see e.g. Ferrarese et al. 2006)? Also, the meaning of the parameters fitted to the statistical scaling relations is not well explained.

The next ‘project’ presents a sample of observed 29 globular clusters in our Galaxy, and aims to verify with their observational properties, whether these clusters might contain a large subsystem of black holes. The results of this part are still inconclusive though.
The third ‘project’ is in fact only a sketch of idea related to the future study of the black hole X-ray binaries, potentially originating and then ejected from the globular clusters. The simulated binaries have however all low mass-transfer rates, in particular they are not able to explain the appearance of bright X-ray sources like the microquasar GRS 1915+105.

Some further minor comments on the content of the thesis are below.

1) The Introduction chapter contains a reference that is not in a proper bibliographic format (the “King model”, King 1966?).

2) The Introduction states vaguely that “many theories have been proposed to account for multiple stellar populations but failed to reproduce several observational constraints”. What were these theories? What did they fail in? More examples of such “vague” statements in this text can be given.

3) What are the units in Eq. 1.2? The ln(\gamma) is not defined.

4) I do not agree that the existence of an IMBH has not been confirmed yet. For instance, see the work of Grzędzielski et al. (2017, A&A, 603, 110) which gives the estimate of an IMBH mass in the ultraluminous X-ray source HLX-1, based on its observed time-variability properties.

5) In some figures in Chapter 6.1, there is missing 'log' on the axes label; also some figure captions suffer from mis-match in the descriptions of panels.

6) In project 6.3, the table is possibly missing some important information that could be used to verify the hypothesis of ejection of BH X-ray binaries, such as their measured peculiar velocities (see e.g. Mirabel 2017, Ann. Rev. A&A).

7) In Chapter 6.3, there is a clear misunderstanding about the Disk Instability Model, and the transient state. Various types of thermal instabilities in accretion disks may lead to its transient behavior, in this sense all the sources listed by the Author in Table may be called transients (see Janiuk and Czerny 2011, MNRAS, 414, 218) for a detailed explanation. The instabilities result in the disk outbursts, whose period depends on the global parameters of the system (mass transfer rate, orbital period, black hole mass).

To sum up, the thesis is extensively long and contains several important results, while some of the ideas could be easily postponed to the future work and explored with more care, at the post-doctoral research level. Regardless of the above critical comments, I generally conclude that the research presented in this thesis is valuable in the context of stellar clusters dynamics and fate of the black holes originating therein. It also proves the Author's ability for pursuing scientific research in collaborative work, making an original new contribution to the field. I mainly base this conclusion on the results presented in Chapters 3 and 4.
The dissertation meets the formal requirements made to the PhD theses ("*Ustawa Dz.U. Nr 65 poz. 595*"). Hence, I am requesting the admission of Mr Abbas Askar to the subsequent stages of the procedure, including the public defense.

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