ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (Ph.D.)
in "6D061100 - Physics and Astronomy"

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STELLAR DYNAMICS IN CLUSTERS WITH BLACK HOLES

General description of the work

This dissertation focuses on the study of the orbital trajectories of globular clusters in the Milky Way galaxy, their interaction with each other and with the central supermassive black hole, as well as on the study of the dynamic evolution of star clusters that formed from gas-dust clouds with centrally increased star formation efficiency. The work presents analyses of the frequency of interaction between globular clusters and the central black hole, as well as the moments of their collisions. Moreover, the dissertation includes the study of the influence of black holes on the internal evolution of clusters after violent relaxation.

Relevance of the topic

Stars have played a pivotal role in the evolution of our observable Universe. Stars don't form individually; they originate within giant molecular clouds, giving rise to star clusters comprising thousands of stars or more initially. Globular star clusters hold a special significance as they can be considered the oldest objects in our galaxy, with ages reaching up to 10-12 billion years. These clusters are gravitationally bound objects that formed in the early stages of the Universe. Inside our Galaxy, over 160 globular clusters have been discovered, and information about these clusters are accessible in the Gaia DR3 astrometric database.

Exploring these globular clusters contributes to a deeper comprehension of the processes involved in forming our Galaxy. Additionally, scrutinizing the trajectories of these clusters aids in unveiling historical events near the central regions of the Milky Way. Examining the connection between these clusters and the central black hole provides insights into the origin of the central compact star cluster.

In addition, if a star cluster maintains its structure after undergoing violent relaxation, black holes should exist within it according to the modern theory of stellar evolution. However, in young clusters of the Galaxy located in its disk, effects associated with black holes are often not detected, leading to the

assumption of their absence in these clusters. Nevertheless, this study indicates that in the early stages of cluster evolution, effects related to black holes may be unobservable, regardless of the presence of black holes in the clusters.

The relevance of this dissertation is manifested in the creation of a numerical model that encompasses all stages of cluster evolution, taking into account various conditions of their formation across a wide range of spatial parameters. The study also addresses practical issues and ways to solve them using this new model.

The purpose of the work

Studying the trajectories of star clusters orbits and analyzing the impact of black holes on the dynamic evolution of star clusters in the Milky Way galaxy.

Objectives of the study

1. Determination of star cluster orbits using astrometric information from the Gaia DR2 and DR3 databases, along with assessing the frequency of close interactions and collisions between clusters in the Galactic potential field through N-body simulations.

2. Investigation of the influence of the central supermassive black hole on the motion of globular clusters using numerical modeling.

3. Analysis of the impact of black holes on the overall dynamics of the parent cluster based on numerical simulations.

Objects of research: Star clusters in the Milky Way galaxy.

The subject of research is the dynamic evolution and motion of various star clusters, examining the influence of different cluster parameters and Galactic potentials on their dynamics.

Research method.

Numerical solution of differential equations, numerical integration of the N-body problem using a fourth order Hermite method, parallel computation using the phi-GRAPE/GPU code based on the laws of classical physics, with CUDA/C, MPI, OpenMP technologies, and big data processing in Python utilizing NumPy, SciPy, and Pandas packages.

Conclusions for the defense

1. In the case of a changing galactic potential, strong encounters of globular clusters in Milky Way-type galaxies at distances less than 50 pc occurs on average 10 times per billion years.

2. According to the results of numerical modeling, close encounters of globular clusters with the central supermassive black hole occur, on average, once

every million years, with most clusters undergoing such collisions having formed in the galactic bulge.

3. Black holes within a cluster that has experienced violent relaxation due to instantaneous gas expulsion do not affect the dynamics of this cluster at a young age, but after about 500 Myr, this influence increases and leads to a change in the lifespan of the cluster.

The theoretical and practical significance of the work

The results of this dissertation provide us with a profound understanding of the processes involved in the formation and evolution of star clusters, thereby offering a more comprehensive insight into the history of galaxy formation and the evolution of the Universe as a whole. Additionally, the massive parallel computing methods developed in this research hold potential for application in diverse fields of scientific and industrial studies. The big data processing technologies developed during the analysis of computer simulation results can be successfully adapted and applied in astronomy and other domains where working with extensive datasets is critical.

Personal contribution of the author

The author actively participated in the research throughout all stages of the dissertation. The candidate carried out the preparation of initial conditions and the processing of computer simulation results. Due to the extensive workload associated with computer modeling, the execution of this stage was distributed between the candidate and other laboratory members. The formulation of tasks and the discussion of obtained results were conducted in collaboration with supervisors and international collaborators.

Reliability and validity of results

The results and conclusions obtained during the research, reflecting the content of all dissertation sections, are supported by publications of key scientific findings in peer-reviewed scientific journals at both the international and domestic levels. These publications include articles published in high-ranking journals in the 1st quartile (Q1) of Web of Science and Scopus databases.

Approbation of work

The results of the dissertation were published in three articles and several international conference proceedings. In particular:

in high impact factor journals in the Clarivate (Web of Science) database and the Scopus international scientific database:

Ishchenco, M., Sobolenko, M., Berczik,P., Omarov, Ch., Sobodar, O., **Kalambay, M.,** Yurin, D. MW GC on cosmological timescale III. Interaction rates. Astronomy & Astrophysics. – 2023. – Vol. 678. – P. A69 [**Q1**]

in journals recommended by the Control Committee for Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan:

Ishchenco, M., Sobolenko, M., **Kalambay, M.,** Shukirgaliyev, B., Berczik,P. MW GC:close encounter rates with each other and with the Central Supermassive Black Hole. Reports of National academy of sciences of the Republic of Kazakhstan; Vol 6, N 340

Kalambay, M. T., Naurzbayeva, A. Z., Otebay, A. B., Abdinassilim, A. T., Kuvatova, D., Assilkhan, A. D., Panamarev, T., Shukirgaliyev, B. T., & Berczik, P. P. Mock observations of simulated star cluster on solar orbit. // Recent Contributions to Physics. – 2022.

in the conference proceedings:

1. **Kalambay M.T.,** Otebay A.B., Zhumakhmetova M.D., Saparali A.K. Звездная динамика в центре активных ядер галактик. // Collection of abstracts of the international scientific conference “Farabi Alemi” - Almaty, 2020. - 299 p.

2. **Kalambay M.T.,** Otebay A.B., Saparali A.K., Abdramanova A.E., Shukirgaliev B.T. Белсенді ядролы галактика орталығындағы жұлдызды дисктің пайда болуына аккрециялы диск пен шоғырдың өздік айналысының әсері. // Collection of abstracts of the international scientific conference “Farabi Alemi” - Almaty, 2021. - 201 p.

3. **Kalambay M.T.,** Alei U., Panamarev T.P. Жұлдызды дискісі бар белсенді ядролы галактикаларды сандық модельдеу. // Collection of abstracts of the international scientific conference “Farabi Alemi” - Almaty, 2022. - 198 p.

4. Tleubek A.N., Yesimzhanova D.A., Uzankul G.E., **Kalambay M.T.** Мнимое наблюдение рассеянных звездных скоплении в разных галактических долготах. // Collection of abstracts of the international scientific conference “Farabi Alemi” - Almaty, 2022. - 221 p.

Relation of the dissertation topic with the plans of scientific works

The results and methods obtained during the dissertation work by the research plan were utilized in the implementation of projects. The projects include AP14869395 “Triune model of Galactic center dynamical evolution on

cosmological time scale" from the MES RK in the framework of the "Grant funding for scientific and (or) scientific and technical projects for 36 months 2022-2024" and AP13067834 "Understanding the properties of star clusters with artificial intelligence" from the MES RK in the framework of the "Grant funding for young scientific and (or) scientific and technical projects for 2022-2024".

The scope and structure of the thesis.

The dissertation comprises an introduction, four sections, a conclusion, and a bibliography with 247 references. It spans 121 pages of main computer text, featuring 35 figures, 64 formulas, and 10 table.