ABSTRACT

of dissertation for the Philosophy Doctor (PhD) degree in the educational program «6D061100 – Physics and astronomy»

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DYNAMICS OF A SMALL BODY WITH VARIABLE MASS IN THE GRAVITATIONAL FIELD OF BINARY SYSTEMS WITH VARIABLE MASSES IN THE PRESENCE OF REACTIVE FORCES

General description of work. The restricted three-body problem, in general, describes the motion of a small body in the gravitational field of two main bodies, while the small body does not influence the motion of the two main bodies. This formulation of the problem, both in the case of constant mass and in the case of variable mass, covers many interesting physical phenomena. For example: the motion of a star in the gravitational field of two galaxies, the motion of a planet in the gravitational field of binary stars, the motion of an artificial celestial body in the gravitational field of sufficiently large natural celestial bodies, also includes the motion of small natural celestial bodies, which include cosmic dust, comets, asteroids in the gravitational field of natural large celestial bodies. It should be noted that the study of the asteroid hazard to planet Earth can also be investigated by a mathematical model of the restricted three-body problem.

The work considers a gravitating system consisting of three spherical celestial bodies. The masses of the bodies are variable. This system consists of a star, a planet, and an asteroid. It is assumed that the motion of the star and the planet is determined by their mutual gravitational attraction, as well as reactive forces that arise when their masses change anisotropically. An asteroid with a negligibly small mass does not affect the motion of the star and the planet and moves in their gravitational field. Although the mass of the asteroid is assumed to be small, its change also leads to the emergence of reactive forces and perturbation of its motion.

To study the general solution of the equations of motion of the planet and the asteroid, methods of perturbation theory based on aperiodic motion along a quasi-conical section are used.

An algorithm for analytical calculation of the perturbing force acting on a planet and an asteroid has been developed for expansion into a power series in small parameters of eccentricity and inclination with any accuracy. In the case of small eccentricities and orbital inclinations, equations have been obtained that describe the evolution of the planet and the asteroid. The obtained equations describe the general case when the masses of the star, planet and asteroid change non-isotropically at different rates, in the presence of reactive forces.

Then the obtained equations of secular perturbation were studied numerically using the Wolfram Mathematica mathematical package. For the numerical study, the system Sun+Jupiter+Asteroid Ryugu (for the internal problem) and Chiron (for the external problem) was selected.

Relevance of the dissertation theme. The dissertation is related to the pressing issues of modern astronomy about the origin and evolution of small bodies (asteroids, comets), planets, stars, planetary systems, which is one of the most important sources of information about dynamic processes in the Universe. The development of methods for their analysis and interpretation of the dynamics of celestial bodies is a priority task of modern astronomy. The work proposes an approach that allows taking into account the variability of the masses of gravitating bodies over time, which contributes to a better understanding of the dynamics of non-stationary gravitating systems.

The main goal of work. Qualitative and quantitative study of the influence of the variable masses of bodies on the dynamic evolution of a system consisting of two main bodies with variable masses attracted to each other according to Newton's law and a small body with variable mass moving in the Newtonian gravitational field of these two main bodies.

Research tasks:

1. Derivation of differential motion equations of the restricted three-body problem (star-planet-asteroid) with variable masses in absolute and in relative rectangular coordinate systems in the general case in the presence of reactive forces;

2. Derivation of new forms of the perturbed motion equation in the form of Newton's equations; Develop an algorithm for analytical calculation of the perturbing force, which act on the planet and on the asteroid, to decompose into a power series over small parameters e_j and i_j for any accuracy; Obtain the differential equations that determine the secular perturbations of the orbital elements of two bodies with variable mass moving around an unsteady central body in the framework of the constrained three-body problem;

3. Numerical study of the Sun-Jupiter-Asteroid Ryugu (for the internal problem) and Chiron (for the external problem) system, using the obtained evolution equations. Construct orbital element graphs. Analysis of the obtained results.

The object of the research. Binary galaxies and star, binary star and planet, star - planet - small body, planet - satellite - artificial small body within the framework of the mathematical model of the restricted three-body problem.

Research Methods. In the work, the motion of a planet and an asteroid is studied by methods of perturbation theory, based on aperiodic motion along a quasi-conical section. Modern methods of computer algebra and numerical calculations are used to analyze the dynamics of the evolution of non-stationary systems, and the mathematical package Wolfram Mathematica is used for their implementation.

Scientific novelty of the dissertation results.

The novelty and originality of the dissertation work lie in the fact that for the first time in it:

1. A new physical model of a system consisting of a star, a planet and an asteroid with arbitrary laws of mass change, changing isotropically and/or non-isotropically, at different rates, in different combinations, in the presence of reactive forces in the orbital coordinate system, within the framework of the restricted three-body problem, has been constructed.

2. Methods of perturbation theory based on aperiodic motion along a quasi-conical section have been developed. New forms of the equation of motion of a planet and an asteroid have been obtained in the form of Newton's equations in general. Equations have been obtained that determine the perturbations of the orbital elements of a planet and an asteroid with variable mass, moving around a non-stationary central body - a star, within the framework of the restricted three-body problem. A modified algorithm for analytical calculation of the perturbing forces that act on the planet and the asteroid has been developed for expansion in a power series in small parameters e_j and i_j, in principle, for any accuracy. New evolution equations of orbital elements of a planet and an asteroid with variable mass moving around a star are obtained. One first integral connecting the eccentricity and the semi-major axis is found from the evolution equations of the main bodies.

3. The obtained evolution equations of the planet and asteroid were studied numerically using the Wolfram Mathematica mathematical package, using the example of the problem Sun + Jupiter + Asteroid Ryugu (for the internal problem) and Chiron (for the external problem).

The main provisions for the defense:

1. Motion equations of a star, planet, and asteroid with arbitrary laws of mass variation and in the presence of reactive forces, obtained on the basis of a new physical model within the framework of the restricted problem of three bodies with variable masses, make it possible to study various effects of mass variability in the evolutionary tracks of gravitational systems.

2. The new general form of the equation of perturbed motion of celestial bodies with variable masses in the form of Newton's equations in an orbital coordinate system based on aperiodic motion along a quasi-conical section, as well as new basic evolutionary equations of planet and asteroid motion correctly describe the evolution of the orbital parameters of the star-planet-asteroid system with variable masses in the presence of reactive forces.

3. For the Sun+Jupiter+Asteroid Ryugu (for the internal problem) and Chiron (for the external problem) systems, it was established that the value of the semi-major axis due to the variability of the masses of the Sun Ryugu over 1 000 000 years (84 245 revolutions of Jupiter) increases from 1.1 AU up to 3.5 AU; the value of the eccentricities of the asteroids Ryugu and Chiron, due to the transverse component of the reactive force of the asteroid, starting from 200 000 years, decreases by 16% for Ryugu, and by 3% for Chiron; the value of the inclination of the asteroid's orbit, due to the variability of the masses of the Sun, fluctuates from 6 to 8 degrees, while the frequency of the period decreases and changes begin from 150 000 years.

The reliability and validity of the results. The results of the work were reported at a number of international conferences. Based on the reports and discussions, papers were written and, after review, sent for publication in journals indexed in the Web of Science and Scopus databases. The reliability of the work is also confirmed with theoretical models, conclusions about the nature of similar objects obtained by other authors.

Theoretical and practical importance of the dissertation. The obtained equations of secular perturbations of the restricted three-body problem are suitable for the general case, i.e. the mass change laws of three bodies can be arbitrary, both isotropic and non-isotropic, in any combinations. The obtained evolutionary equations can be applied to describe the dynamic evolution of the motion of a small body with variable mass in gravitating dual systems in the presence of reactive forces and under arbitrary laws of mass change.

Approbation of the dissertation:

1. Ibraimova A.T. Restricted three-body problem with variable masses in the presence of reactive forces // International Scientific Conference of Students and Young Scientists “Farabi alemi”. Almaty, Kazakhstan, April 8-11, 2019. - P.255.
2. Ibraimova A.T. New forms of the equation of perturbed motion on the basis of aperiodic motion along the quasi-cone section // International Scientific Conference of Students and Young Scientists “Farabi alemi”. Almaty, Kazakhstan, April 6-9, 2020. - P.283.
3. Ibraimova A.T. Evolution equations of the limited three-body problem with non-isotropically changing masses in the presence of reactive forces // International Scientific Conference of Students and Young Scientists “Farabi alemi”. Almaty, Kazakhstan, - April 6-8, 2021. - P.193.
4. Minglibayev M. Ibraimova A. Perturbation theory for non-stationary problems of celestial mechanics and its applications in dynamics of gravity systems with variable masses //International Astronomical Union Symposium 364. Iasi, Romania, October 18-22, 2021. – P.30. (online)
5. Ibraimova A.T., Minglibayev M.Zh. To the dynamics of the two-body problem with variable masses in the presence of reactive forces // Proceedings of the International Astronomical Union. - 2021. - Vol.17 (S370). - P.281-282. https://doi.org/10.1017/S1743921322003611
6. Ibraimova A., Minglibayev M. To the dynamics of the two-body problem with variable masses in the presence of reactive forces //XXXIst General Assembly International Astronomical Union. BEXCO, Busan, Rep. of Korea, August 2 – 11, 2022. – P.327. (online)
7. Prokopenya A.N., Minglibayev M.Zh., Ibraimova A.T. Perturbations in the restricted three-body problem of variable mass //Aplications of Computer Algebra – ACA 2022. Gebze Technical University, Gebze-Istanbul, Turkey, August 15-19, 2022. - P.60.
8. Minglibayev M., Ibraimova A. Two spherical bodies with non-isotropically varying masses in the presence of reactive forces //International Conference "Computational and Information Technologies in Science, Engineering and Education". Almaty, Kazakhstan, October 12-15, 2022. –P.93.
9. Prokopenya A., Minglibayev M., Ibraimova A. Derivation of the evolution equations in the restricted three-body problem with variable masses by using Computer Algebra //Applications of Computer Algebra – ACA 2023. Warsaw, Poland, July 17 – 21, 2023. - P.68. (online)
10. Ibraimova A., Minglibayev M., Prokopenya A.N. Study of the small body dynamics with variable mass in the presence of reactive forces in the framework of

the restricted three-body problem with variable masses //XXXII General Assembly International Astronomical Union. Cape Town, South Africa, 6-15 August 2024.

Publications. 15 scientific papers have been published on the basis of the dissertation work. Among them, 2 articles have been published in the Web of Science (Clarivate Analytics) database (Q2 and Q3). 3 articles have been published in journals included in the list of journals recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, and 10 papers were presented at international conferences.

The personal contribution of the author. The main results of the dissertation were obtained by the author. The task statement and discussion of the results were carried out jointly with scientific consultants.

Connection of the dissertation topic with the plans of scientific works

The dissertation work was completed in accordance with the plans of fundamental scientific research works of the Scientific Research Institute of the Ministry of Education and Science of the Republic of Kazakhstan, the Center for Fundamental Research on the topic: «BR10965141 - Development of the national Virtual Observatory based on robotic telescopes, Big-Data technologies, and high-performance computing» and «BR20280974 - Program of fundamental astrophysical research in Kazakhstan: observations and theory».

The scope and structure of the thesis. The dissertation consists of an introduction, 4 sections, a conclusion, a list of references, and an appendix.