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A STUDY OF THE DYNAMICAL EVOLUTION OF NON-STATIONARY EXOPLANET SYSTEMS

ABSTRACT
of the PhD thesis for the degree of
doctor of Philosophy (PhD) in the specialty
«6D060300 - Mechanics»

The relevance of the research topic. The discovery of planets outside the solar system (exoplanets) was the beginning of a new era in the development of astronomy and the application of celestial mechanics. Prior to the discovery of the first exoplanet in 1995, the solar system was considered the only planetary system in the universe. All planets of the solar system have orbits close to circular $e \approx 0$, except for the orbit of Mercury, in which $e = 0.2$, the inclination of the orbit is 7^0.

The launches of various spacecraft - Corot (2006), Kepler (2009), Gaia (2013), TESS (2018), Cheops (2020) over the past 25 years have allowed the discovery of a large number (4174-29.01.2020) of extra-solar objects (exoplanets), some of which are comparable to Earth.

The actual problem of modern astrophysics, as well as theoretical and celestial mechanics, is the lack of explanation for the insignificant values of eccentricities and inclinations in exoplanetary systems. One of the possible reasons may be an anisotropic change in the masses of the central star and planets, which naturally affects the dynamic evolution of the system. Astrophysical studies make it possible to determine the change over time in the mass, size, shape of the central star and orbital elements of the planets based on observations. The topic is extremely relevant, because new spacecraft launches are planned, which should detect much more exoplanets, some of which may be comparable to Earth.

Until the end of the 19th century, problems in celestial mechanics were solved only for stationary celestial bodies. The differential equation of relative motion for problems of two bodies with variable masses was first applied by Guilden in 1884.

Further research V.G. Fesenkova, G.M. Idlis, T.B. Omarova, J.D. Hajidemetriou, L.G. Lukyanova, E.N. Polyakhova, A.A. Bekova, A. Deprit, L. Floria, and others showed the special importance of non-stationary celestial-mechanical model problems in the study of the nature of non-stationary space systems.

In the 80s of the last century, many theorists solved problems in the celestial mechanics of gravitating systems and actively studied the mass variability of gravitating bodies. Omarov T.B. investigated the dynamics of wide binary stars with intense corpuscular radiation. The problem of two bodies moving inside a gravitating pulverized substance was solved. In parallel with Omarov TB similar studies were conducted by a professor J. Hajidemetriou . As a result of parallel work in the history of dynamic astronomy, such concepts as “elements of Omarov-Hadjidemetriou” have entered.

The orbits of extrasolar planets vary greatly in magnitude of eccentricity and in magnitude of inclination. The formation of extrasolar planets directly depends on the mass of the central star. It turned out that the prevalence of giant planets is growing rapidly with increasing mass of stars. It also turned out that the planets of stars with intermediate masses (1.5-3 solar masses) are mostly massive and are in wide orbits with low eccentricity.

Over the past 10 years, the issues of anisotropic mass changes in dynamical systems have been actively studied by scientists around the world.

In this dissertation, in the sky-mechanical aspect, using well-known mathematical models, the effects of the influence of mass variability on the orbital elements of the planet are investigated in order to understand the nature of the dynamic evolution of planetary systems.

The aim of the PhD thesis to study a system of three mutually gravitating spherical celestial bodies, containing a central star and two planets, taking into account the anisotropic change in mass, which leads to the appearance of reactive forces acting on the bodies of the system in question, and identify the effects of the influence of mass variability on the orbital elements of the planet.

Objectives of the study:

1 Investigate the dynamics of a system consisting of three mutually gravitating spherical celestial bodies with masses changing anisotropically, obtain expressions for reactive forces in a relative coordinate system associated with a central star

2 In osculating elements based on aperiodic motion along a quasiconic section in Poincare variables and in analogs of Kepler elements, develop an algorithm for analytical expanding the perturbing function in a power series in the small parameter ej and ij with the required accuracy for the two-planet three-body problem with masses varying anisotropically at different rates.

3 Derive the evolution equations that determine the behavior of the orbit parameters in the analogues of the second system of Poincare variables, and the evolution equations in analogues of the Kepler elements in the Lagrange form.

4 Select exoplanetary systems for research. To obtain numerical solutions of evolution equations in analogues of the second system of Poincare elements and in analogues of Kepler elements using the equations of perturbed motion in the form of Lagrange and choosing the values of the system parameters from observational data from selected exoplanets.

5 To study the relationship between the presence of large eccentricities and inclination of the orbits of exoplanets with anisotropic changes in the masses of bodies in these systems.

Objectives of the study: is the dynamics of the evolution of unsteady exoplanetary systems.

The methods of scientific research. The initial equations for using the perturbation theory are the equations of motion in a relative coordinate system with the origin in the center of the "parent" star.

The equations of motion are studied by perturbation theory methods developed for non-stationary systems. The methods of perturbation theory based on aperiodic motion along a quasiconic section are used.

Modern dynamics of computer algebra and numerical methods are used to analyze the evolutionary dynamics of unsteady exoplanetary systems, and Mathematica is used to implement them.

Scientific novelty of the work:

An algorithm is developed for the analytical expansion of the perturbing function in a power series up to any order of relatively small parameters for the two-planet three-body problem using computer algebra methods and the modern Mathematica symbolic computing system.

2. A numerical solution is obtained for the evolution equations of the dynamic evolution of the exoplanetary system GJ 180: GJ 180b, GJ180c.

3. The effects of the influence of mass variability on the orbital movements of real exoplanetary systems are revealed. They are of fundamental importance in the evolution of stellar systems with variable masses. Temporary changes in masses significantly affect orbital movements, which naturally affects the dynamic evolution of the rotational movements of celestial bodies.

Theoretical and practical significance of the results.

The results obtained in the thesis can be used to study the dynamic evolution of non-stationary systems in the problems of three or more bodies in celestial mechanics. The results can be used to study the processes of formation and evolution of systems containing several planets. The results of the study will highlight the features of the evolution of planetary systems around the "old" stars - red giants, which have a high level of mass loss in the anisotropic configuration and at different rates.

Publications based on the dissertation published 10 published works. *Publication in the high-ranking scientific journals*

1. Prokopenya A., Minglibayev M., Shomshekova S. Computing Perturbations in the Two-Planetary Three-Body Problem with Masses Varying Non-Isotropically at Different Rates // Mathematics in Computer Science. – 2020. – Vol.14 – No. 2. – P.241–251. https://doi.org/10.1007/s11786-019-00437-0. [Impact Factor = 0.75.]. Q3. CiteScore-33-процентиль.

2. А) Прокопеня А.Н., М.Дж. МинглибаевМ.Дж., Шомшекова С.А. Применение компьютерной алгебры в исследованиях двухпланетной задачи трех тел с переменными массами // Программирование – 2019. - №2. – С.58-65. DOI:10.1134/SO132347419020092

3. Б) ProkopenyaA., MinglibayevM., Shomshekova S. Applications of Computer Algebra in the Study of the Two-Planet Problem of Three Bodies with Variable Masses // Programming and Computer Software. – 2019. – Vol. 45. – No. 2. – P.73–80. [DOI:10.1134/S0361768819020087] [ImpactFactor = 0.75.]. Q4. CiteScore-23-процентиль.

Publications in scientific journals included in the list recommended by the Committee on the Control of Education and Science (CCES) of the MES RK

1. Минглибаев М. Дж., Маемерова Г.М., Шомшекова С.А. Дифференциальные уравнения относительного движения нестационарных экзопланетных систем //Вестник КазНПУ, серия физико-математическая. – 2017. – Т.57. №1. – С.141 -147.

2. MinglibayevM., Shomshekova S. Analytical expressions of the perturbing functions in two planetary three - body problem with masses varyng non-isotropically when available for reactive forces // ИзвестияНАНРК, серияфизико-математическая. – 2018. –Vol. 319. №3. – С.134-163.

3. Минглибаев М., Шомшекова С. Статистический анализ экзопланетных систем по спектральным классам звезд // Вестник КазНУ им. аль-Фараби. Серия физическая. (Recent Contribution to Physics). – 2019. – Т. 68. № 1. – С.20-28.

1. Minglibayev M., Prokopenya A., Shomshekova S. Computing Perturbations in Two-Planetary Three-Body Problem with masses varying Non-isotropically at different rates // International ConferenceonApplicationsofComputerAlgebra (ACA-2018). – Universided de Santiago de Compostela. – 2018. – P.47.

2. Минглибаев М., Прокопеня А., Шомшекова С. Исследования вековых возмущений в двухпланетной задаче трех тел с переменными массами // Международная конференция «Астрономия 2018», приуроченная к XIII съезду Международной общественной организации «Астрономическое общество». – Москва. – 2018. – С. 232-235. 10.31361/eaas.2018-1.043.

3. Minglibayev M., Prokopenya A., Mayemerova G., Shomshekova S. On expansion of the perturbing functions in two-planetary three-body problem with masses varying non-isotropically at different rates // Computer Algebra Systems in Teaching and Research. – Siedlce. – 2018. Vol. VII. – P. 37-44.

4. Минглибаев М., Шомшекова С. К динамике планет в экзопланетных системах с родительской звездой переменной массы // Международная конференция «Современная звездная астрономия-2017». – Екатеринбург. – 2017.

5. Шомшекова С. Статистическое исследование нестационарных экзопланетных систем по спектральным классам центральной звезды // Материалы международной конференции студентов и молодых ученых «Фарабиәлемі». – Алматы. – 2017. – С.97.

The structure and scope of the thesis. The dissertation consists of a title page, contents, notation and abbreviations, 5 sections, which are divided into subsections, conclusions, list of references 81. There are 26 figures in the work. The total amount of work contains 119 pages, including one application on 14 pages.

The main content of the thesis. The introduction reflects the rationale for the relevance of the topic of the dissertation, purpose, object, subject, research objectives, substantiation of the scientific novelty of the work, its theoretical and practical significance, scientific principles to be protected, the number of publications available.

Chapter 1 analyzes the data of the European catalog in the NASA Exoplanet Archive database and selects exoplanetary systems to study their dynamic evolution. The main selection criteria:

a) Characteristic for unsteady exoplanetary systems, elongated and variable orbits, where there is a significant mass ejection of stellar matter, that is, the rate of mass loss of the order of $10^{-6} M_{\odot}$ / year

b) In accordance with the 3-body problem, we select systems in which 2 planets are already detected and all necessary orbital parameters are calculated.

c) The planets of the system move in orbits with a small eccentricity and inclination, and do not have massive planets in the zone of the effective Earth orbit

An analysis of the data showed that among the main sequence stars, the mass loss is greatest for M stars. The Wolf-Rayet stars were not considered, although they have more mass loss, since there are no conditions for the formation of planets near these stars. At the moment, all the necessary observable orbital parameters have the GJ 180 - GJ 180 b-GJ 180 c system.

In Chapter 2, based on the Meshchersky equations, equations of motion are obtained in the presence of reactive forces in an absolute (barycentric) rectangular Cartesian coordinate system. The equations of motion of the problem under consideration are obtained in a relative coordinate system with the origin at the center of the parent star, which are more convenient for using perturbation theory based on aperiodic motion over a quasiconic section. Equations of disturbed planetary motion in the form of Lagrange equations are obtained. Expressions are obtained for reactive forces with anisotropic change in mass in a relative coordinate system.

Chapter 3 presents the results of numerical calculations for evolution equations in analogues of the second system of Poincare variables. An analysis of the results showed that, with a change in the speed of departure of particles in the orbit plane over a time interval of 5000 Earth years, the orbital parameters practically do not change compared to the case of isotropic changes in mass, although the dependence of mass on time leads to noticeable changes in orbital parameters compared with the case of constant masses. With a change in the velocity of particles ejection perpendicular to the plane of the orbit, the reactive force affects some orbital parameters of the planets, for example, eccentricity and inclination analogues, which lead to more elongated orbits.

Poincare's elements describe this problem well for small eccentricities and inclinations, but calculations show that eccentricities and inclinations can increase. In analogues of the second system of Poincare elements, the equations of motion need to be converted several times, because of this there is a loss of accuracy.

Chapter 4 gives general equations for expanding into a series of perturbing functions in the two-planet three body problem with masses varying anisotropically at different rates, based on aperiodic motion along a quasiconic section.

The equation of motion is averaged over the average longitudes of bodies in the absence of resonances of average motion, differential equations are obtained that describe the evolution of orbital parameters over long periods of time. In this case, the effects of a decrease in the mass of the parent star and an increase in the mass of the planets due to the accretion of matter from the remnants of the protoplanetary disk are taken into account. Analytical expansions of the perturbing function in the form of power series in eccentricities and inclinations are obtained, in principle, with any necessary accuracy. The obtained relations make it possible to decompose disturbing functions with any accuracy with respect to eccentricities and inclinations and can be further used to study the dynamic evolution of exoplanetary systems with anisotropic changes in the mass of the parent star and planets.

In chapter 5, using the perturbation theory as the unperturbed (initial approximation), we consider the exact solution of the two-body problem with variable masses, which describes an aperiodic motion along a quasiconic section. Disturbing functions are obtained in the form of power series in eccentricities and inclinations up to the third order inclusive, and differential equations are derived that determine the behavior of orbital parameters in the form of planetary Lagrange equations. By averaging the equations of motion over the average longitudes of bodies in the absence of resonances of average motion, differential equations are obtained that describe the evolution of orbital parameters over a long time interval of 5000 Earth years. Using evolutionary equations in the Lagrange form, using the Wolfram Mathematica computer algebra system, numerical calculations of the evolution of the analogues of the orbital elements of the planets of the exisplanetary Gliese system GJ180: GJ 180 b, GJ 180 c.

It is shown that the presence of reactive force most strongly affects the inclination of the orbits and the longitude of the ascending node of the planets of the system.