ABSTRACT

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

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DARK MATTER PROFILES IN GALACTIC BULGES AND HALOS

The dissertation is devoted to the study of one of the most important problems of cosmology, astrophysics and particle physics - properties of dark matter

The relevance of the dissertation.

Dark matter is a mysterious type of matter that neither emits, nor absorbs electromagnetic radiation. Dark matter indirectly manifests itself only via gravitational interaction. Its presence can be registered by studying the rotation curves of galaxies and gravitational lenses. The rotation curve of galaxies shows the dependence of the linear velocity of objects (stars, gas etc) on the radial coordinate from the center to the halo of a galaxy. Zwicky (1933, 1937) measured the redshifts of galaxies in the Coma cluster. He found that the velocities of individual galaxies in the cluster are much greater than the velocity calculated by the total apparent mass of the cluster. He came to the assumption that the only way to explain the rapid rotation is the presence of hidden mass, which is not visible in the cluster. According to his estimates, the amount of hidden mass i.e. dark matter in this cluster can be 10 times greater than the total visible mass of the cluster. Roberts (1966), Rubin and Ford (1970) found that the rotation curves of spiral galaxies are flat to the periphery of galaxies. This fact contradicts the expected theoretical results, because the brightness of galaxies decreases rapidly as they approach the periphery, and in this region a Keplerian decrease is expected in the rotation curve. This difference in the theoretical and observational rotation curves is proof of the dark matter existence.

To date, the problem associated with the presence of dark matter in space, the existence of which can be argued from the conclusions emanating from the known laws of gravity, especially when observing the rotation curve of galaxies, is quite relevant. In modern astrophysics, the proposed mathematical models, as well as a number of indirect experimental data, indicate the presence of a hidden mass.

Astrophysical observations clearly indicate the presence of so-called dark matter and dark energy in our universe, and on a scale significantly exceeding ordinary baryonic matter. In general, the modern picture of the world looks like this: ordinary matter accounts for about 5% of the total mass-energy in the Universe, while the remaining 95% have a completely different, unusual, questionable nature. At the same time, the so–called dark matter accounts for about 27% of the matter filling the Universe, and the remaining 68% is responsible for a substance with a similar name - dark energy.

In any case, once it is recognized that most of the matter in the Universe is dark, it is expected that this component will determine the conditions for the formation of large-scale structures such as galaxies and their clusters. Therefore, it is extremely important to investigate and determine the amount of dark matter in various galaxies, including the Milky Way galaxy.

Usually the equation of state of dark matter is considered in the galactic halo in the literature, and in the dissertation the main attention is drawn to all the components of the galaxy: the core, the inner bulge, the main bulge, the disk and the halo. To model the rotation curve in the halo of the Milky Way galaxy, basically, the Navarro-Frank-White density distribution profile of dark matter is used. However, as it is well-known, it leads to the so-called cuspy problem, in which the density of the Navarro-Frank-White profile tends to infinity.

When studying the motion of stars in the central part of the Galaxy, it is believed that there is a supermassive black hole in the center and this statement does not contradict observations. At the same time, the central part of the galaxy is not active, that is, it does not emit X-rays or gamma rays, which are inherent in black holes. Therefore, it was assumed that there is a clump of dark matter with the same total mass as in the case of a supermassive black hole in the center of the galaxy, and the movement of stars is studied in the field of this object. There are similar works in the literature that assume different models of density distribution. For example, the Ruffini- Argüelles-Rueda model assumes that there is a compact object consisting of fermions and not a supermassive black hole in the center of the galaxy. In contrast to this work, we employ phenomenological density profiles of dark matter, which are well-known in the literature.

The purpose of the dissertation is the study of the dark matter distribution in various spiral galaxies, including the Milky Way, taking into account its core, bulge, disk and halo, the calculation of the dark matter mass using known phenomenological dark matter density profiles, as well as the derivation of the equation of state of dark matter, the speed of sound and the analysis of trajectories of stars in the central part of the Milky Way galaxy.

The object of the research.

The galaxies NGC 2403, NGC 3627, NGC 2976, DDO154, NGC 1560, NGC 5585 and the Milky Way galaxy, dark matter.

The subject of the research.

Galaxies rotation curves. Equations of state for dark matter. The speed of sound in the distribution of dark matter. Trajectories of test particles (stars) in the center of the Milky Way galaxy.

Research methods.

Analytical and numerical methods for solving nonlinear differential equations of second order, the least squares method, Bayesian information criterion.

Research tasks:

1. Analyze the rotation curves of galaxies NGC 2403, NGC 3627, NGC 2976, DDO 154, NGC 1560, NGC 5585, U11454, including the Milky Way galaxy

and calculate main parameters of dark matter models such as central density, scale radius and dark matter total mass;

2. Obtain pressure profile for dark matter from the hydrostatic equilibrium equation and calculate the dependence of the speed of sound on the radial coordinate;

3. Investigate the motion of stars near the center of the galaxy at distances less than 100 astronomical units from the center for two limiting cases: 1) in the gravitational field of a supermassive black hole in vacuum, 2) in the field of dark matter distribution without a black hole.

Novelty of the work.

The following results have been obtained for the **first time** within this dissertation:

1 The exponential sphere profile was used for dark matter distribution in all structural parts of the Milky Way galaxy, and it was found that the exponential sphere profile is the optimal model among the phenomenological dark matter density profiles in the literature and the corresponding masses, scale radii and central densities were calculated for all components of the galaxy;

2 The pressure profile was obtained from the optimal dark matter density profile in the Milky Way galaxy and the dependence of the speed of sound on the radial coordinate was calculated;

3 The trajectories of the movement of stars in the vicinity of the galactic center at distances of less than 100 astronomical units in the gravitational field of a supermassive black hole in vacuum and dark matter without a black hole were investigated.

The main provisions submitted for the defense:

1. To describe the rotation curve of the Galaxy, the optimal distribution of dark matter is the exponential density profile (sphere) $\rho_{Эксп}(r) = \rho_0 e^{-r/r_0}$ with parameters: for core $\rho_0 = 5{,}8 \cdot 10^{19}\, M_{\odot}/pc^3$, $r_0 = 1{,}4 \cdot 10^{-5}\, pc$, $M = 4.2 \cdot 10^6\, M_{\odot}$; inner bulge $\rho_0 = 3{,}6 \cdot 10^4\, M_{\odot}/pc^3$, $r_0 = 3{,}8\, pc$, $M = 5 \cdot 10^7\, M_{\odot}$; main bulge $\rho_0 = 190\, M_{\odot}/pc^3$, $r_0 = 120\, pc$, $M = 8{,}4 \cdot 10^9\, M_{\odot}$; disk $\rho_0 = 0{,}15\, M_{\odot}/pc^3$, $r_0 = 3000\, pc$, $M = 4.4 \cdot 10^{10}\, M_{\odot}$; halo $\rho_0 = 7{,}56 \cdot 10^{-3}\, M_{\odot}/pc^3$, $r_0 = 12 \cdot 10^3\, pc$, $M = 2{,}63 \cdot 10^{10}\, M_{\odot}$.

2. The equilibrium of dark matter in the Galaxy with an exponential distribution profile leads to a dependence of the speed of sound on the radial distance, which qualitatively corresponds to the behavior of the rotation curve.

3. Circular orbits in the gravitational field of a black hole in vacuum at distances less than 30 astronomical units become precessing elliptical orbits in the field of dark matter distribution with the profile of an exponential sphere without a black hole.

Scientific and practical value of the dissertation.

Results obtained in this dissertation will be quite helpful in explaining the rotation curves of different galaxies and in calculating dark matter mass. In addition, the knowledge of dark matter mass in the halo will allow one to observe and study distinct remote astrophysical objects. Research carried out in the dissertation presents theoretical and practical value for extending our knowledge in the field of relativistic astrophysics, cosmology and particle physics.

Reliability and validity of the research are confirmed by the presence of publications in journals of foreign countries with an impact factor and in publications recommended by the Committee for Quality Assurance in the Field of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, and in the proceedings of international scientific conferences of the near and far abroad

The personal contribution of the author lies in the fact that the entire volume of the dissertation work, the choice of the research method, problem solving and numerical calculations were performed by the author independently. The task statement and discussion of the results were conducted jointly with scientific supervisors.

Publications.

According to materials presented in the dissertation 11 publications have been published in total. 1 article published in the 1st (first) quartile in the Web of Science database with an impact factor of 5.287 and SJR 2.06, 2 articles in journals from the list of Committee for Quality Assurance in the Sphere of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan and 1 work in the English-language edition of Kazakhstan and 9 abstracts were published in the proceedings of local and foreign international scientific conferences.

Approbation of the dissertation.

The results of the work were presented and discussed at the following local and foreign international conferences:

– at the International Scientific Conference of Students and Young Scientists "Farabi Alemi" (2019, 2020, 2021, 2022 Almaty, Kazakhstan);

– at the International Scientific online Conference Sixth Marcel Grossmann Meeting, Rome, Italy, 07.07.2021;

– at the Kazakh-Uzbek seminar on the topic: "Effects of non-vanishing pressure of dark matter in the Milky Way galaxy" (28.02.2021);

- at the Kazakh-Uzbek seminar on the topic: "Investigation of dark matter profiles in galactic bulges and halos" (02/11/2022);

The volume and structure of the dissertation.

The dissertation work consists of an introduction, 5 chapters, a conclusion and 156 references, contains 106 pages of the main computer text, including 47 figures and 13 tables.