БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ

ИНСТИТУТ ЗА ЯДРЕНИ ИЗСЛЕДВАНИЯ И ЯДРЕНА ЕНЕРГЕТИКА

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R E F E R E E   R E P O R T

of thesis for acquiring the educational and scientific degree "doctor" (PhD degree)

PhD candidate: Radostina Zhekova Zheleva,
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Title of the thesis: ***"Structure and astrophysics of self-gravitating objects in multiscalar theories"***

Referee: Prof. D.Sc. Lilia Kirilova Anguelova,
Institute for Nuclear Research and Nuclear Energy,
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1. Relevance and overall characteristics of the PhD thesis

Radostina Zheleva's thesis is dedicated to the study of self-gravitating astrophysical objects in multiscalar gravitational theories. At present, this topic attracts great interest due to the data obtained from a vast number of astrophysical and cosmological observations. Namely, assuming Einstein's gravity, the observational data imply that the energy density of the Universe is dominated by components called dark matter and dark energy, whose nature is not well understood. This motivates the development and investigation of alternative gravitational theories, which modify the General Theory of Relativity on cosmological scales. Studying the implications of such theories for astrophysical objects with strong gravitational fields (such as wormholes, black holes and neutron stars) is of great importance for developing observational strategies for their testing. Especially important in this respect is the recent impressive success in the detection of gravitational waves from mergers of binary compact objects. Analyzing the data from the observations of these gravitational waves opens up completely new possibilities for testing and differentiating between various theories of gravity. In this context, the multiscalar Gauss-Bonnet theories are of particular interest since (a multitude of) scalar fields typically arises in theoretical frameworks, which aim to achieve a unified description of gravity with the rest of the fundamental interactions. In view of all of the above, it is clear that Radostina Zheleva's PhD thesis is on a topic that is of significant interest for modern astrophysics.

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The thesis has, in essence, four chapters. The first three describe the new results, while the fourth summarizes the main scientific contributions. The thesis is based on three publications in prominent international scientific journals. Both the autoreferate and the thesis are well organized and written in a clear and competent manner.

2. Scientific contributions

The main scientific contributions in the thesis are the following:

(1) Chapter 1 is devoted to the study of traversable rotating wormholes with the aim of finding observational signatures, which can distinguish them from black holes. The wormholes in General Relativity (GR) are not traversable due to the null energy condition. In contrast, in the Gauss-Bonnet theory, as well as in other modified gravitational theories, this condition is violated and thus traversable wormholes can exist. The most general stationary and axisymmetric wormhole is described by the class of geometries constructed by Teo. The first chapter of the dissertation studies the quasiperiodic oscillations from the accretion disk around such a general wormhole. More specifically, it investigates the timelike circular geodesics in the equatorial plane of the wormhole and derives analytical expressions for their kinematic characteristics, as well as for the radial and vertical epicyclic frequencies. For a particular rotating wormhole solution, the dependence of the epicyclic frequencies on the angular momentum is also investigated. Further subjects of study in the chapter are the different kinds of orderings between the orbital and epicyclic frequencies in different parts of the parameter space. Finally, the quasi-periodic oscillations are compared to those in the case of a Kerr black hole. This comparison shows that wormholes can have specific distinguishing features and, in particular, richer resonance spectrum.

(2) In chapter 2, it is shown that static spherically symmetric black holes can exist in a certain type of multiscalar Einstein-Gauss-Bonnet theory, in which the scalar fields parameterize a three-dimensional maximally symmetric space. It should be noted that the multiscalar theories are qualitatively different from theories with a single scalar. In particular, in the multiscalar case it is possible to have new kinds of compact objects, when the geometry of the scalar manifold is nontrivial. Chapter two of the dissertation considers a number of coupling functions, which determine the interaction between the scalar fields and the Gauss-Bonnet term in the action. For each of these coupling functions, the corresponding equations of motion are solved numerically under certain conditions, needed to obtain black hole solutions. The numerical solutions found in this manner belong to two main categories: a) black holes with scalar hair and b) scalarized black holes. Further, a systematic investigation is performed of a number of important characteristics of these solutions, namely the area of the horizon, the entropy and the radius of their photosphere. In addition, it is also shown that the scalar charge of these solutions vanishes, as a result of which the scalar dipole radiation is negligible. Furthermore, for a particular coupling function, new branches of

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scalarized black holes are found, such that it is possible (in parts of the parameter space) to have simultaneously stable scalarized black holes and stable Schwarzschild black holes. Another important result is that, regarding observational properties, the deviation from GR is greater for black holes with smaller masses.

(3) In chapter 3, numerical solutions are constructed, which describe a type of static and spherically symmetric neutron stars in multiscalar Gauss-Bonnet theories with three-dimensional maximally symmetric scalar manifold. These solutions are non-topological and spontaneously scalarized. They are obtained for a specific equation of state, which is in agreement with the constraints arising from the observations of binary neutron star mergers. In addition, the existence of these solutions is contingent upon a particular choice of a coupling function, which allows spontaneous scalarization. The chapter also investigates the dependence of the binding energy of these solutions on the various parameters of the model and, furthermore, finds the parts of parameter space, in which there are bifurcations of the solutions. In particular, it is shown that the bifurcation point depends strongly on the Gauss-Bonnet coupling constant, the curvature of the scalar manifold and the number of zeros of the scalar field. It is also shown that the binding energy of the scalarized solutions is greater than of those in GR. This means that the corresponding neutron stars are energetically favored compared to those with trivial scalar fields.

3. Publications and their impact in the scientific literature

The thesis is based on three publications in prominent international scientific journals, all with quartile Q1. Namely, two of the publications are in Physical Review D and one – in the European Physical Journal C. This indicates a high level of the scientific work. It is worth pointing out that these publications have already received more than 30 citations, which is evidence that they are attracting interest in the scientific community.

4. Personal contribution of the candidate

According to the declaration submitted by the candidate, regarding the character of her contributions in the above publications, Radostina Zheleva has essential contribution in one of them (each of those publications is in a Q1 journal, as already mentioned). This ensures the fulfillment of the recommended criteria of the Faculty of Physics of Sofia University "St. Kliment Ohridski".

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CONCLUSION

Radostina Zheleva's thesis contains a number of original results, which are of considerable interest for contemporary astrophysics. The thesis is based on three publications in prominent international journals with high impact factor, which have already received tens of citations in the literature. In view of all of this, I strongly recommend that Radostina Zheleva be awarded the educational and scientific degree "doctor".

31.03.2023 г.

Prof. D.Sc. Lilia Kirilova Anguelova