Referee Report

On the PhD thesis for awarding the educational and scientific degree "**PhD"("Doctor")**

In professional field : 4.1 Physical Sciences

Scientific Specialty: 01.03.01 Theoretical and Mathematical Physics

Procedure of defense at the **Faculty of Physics**,

Sofia University "St. Kliment Ohridski (SU)

Reviewer: Svetlana Pacheva, Dr. Sci., Prof. at the Institute for Nuclear Research and Nuclear Energy (INRNE), Bulgarian Academy of Sciences (BAS), (pensioner) in her capacity of member of the Scientific Jury according to the Rector's of SU order No RD 38-94/21.02.2023

Title of the thesis: ***Constraining Strong Regime Gravity through Analysis of Compact Astrophysical Objects***

Author: Victor Ivaylov Danchev

I. General description of the submitted materials

1. Data on the submitted documents.

The candidate **Viktor Ivaylov Danchev** has submitted the following documents: (a) thesis and summary in English, summary in Bulgarian; also according to the Regulations for the terms and conditions for acquiring scientific degrees and holding academic positions at SU "St. Kliment Ohridski': (b) copies of his publications on the subject of the dissertation; (c) professional curriculum vitae; (d) Master's degree; (e) statement of authorship; (f) attestation for the third year of doctoral studies; (g) author reference table for contributions; (h) two appendices-declarations from Prof. Dr. Sci. Stoycho Yazadzhiev , Corresponding Member of BAS, certifying the originality of the results and absence of plagiarism in the candidate's dissertation. The documents submitted by the candidate for the defense correspond to the requirements of the Development of Academic Staff in the Republic of Bulgaria Act (DASRBA), the Regulations on the Implementation of the Development of Academic Staff in the Republic of Bulgaria (RIDASRB), as well as the Additional Requirements to the Regulations for the Terms and Conditions for Acquiring Scientific Degrees and Holding Academic Positions at SU "St. Kliment Ohridski" (RTCASDHAPSU).

2. Candidate’s data

The doctoral student Viktor Ivaylov Danchev graduated at the Faculty of Physics of SU "St. Kliment Ohridski" in 2019 in the program "Theoretical and Mathematical Physics" by defending his master thesis with excellent grade under the supervision of Prof. Stoycho Yazadzhiev. In the period 2020-2023, he became a full-time doctoral student in the doctoral program "Theoretical and Mathematical Physics" also under the scientific guidance of Prof.. Stoycho Yazadzhiev. Along with his doctoral research V. Danchev was succsessfully engaged with activity as a member of the scientific technical and engineering team of the high-tech company ENDUROSAT AD, a Bulgarian aerospace manufacturer which designs, builds, and operates CubeSats and Nanosatellites for commercial and scientific missions and develops intersatellite linking and data applications. Presently he holds the position of "technical director" from 2021 and is responsible for coordinating the company's technical team and its missions. I am very impressed that in addition to his scientific knowledge in the field of gravity, astrophysics and cosmology, related to his work on the dissertation, V. Danchev also possesses highly professional skills in the field of information technology. Along with this, he has actively participated in a lot of international scientific conferences and workshops in the USA, Austria, Russia, Portugal, Hungary and Bulgaria. Before starting his work on the thesis, V. Danchev was a co-author of 6 publications in the field of condensed matter physics (4 publications), high energy physics (1) and astrophysics (1).

Danchev’s dissertation is based on 3 articles co-authored with his scientific supervisor Prof. Stoycho Yazadzhiev and scientific consultant Dr. Daniela Doneva, published in some of the best international journals in physics with Q1-ranking. **General characteristics of the candidate's scientific achievements.**

The main motivation for the subject of the thesis was inspired by the modern rapid development of research on the new extended (modified) theories of gravitation generalizing General Relativity formulated by the Einstein-Hilbert action (GR). GR successfully describes the observational data in weak gravitational fields (e.g. in the Solar System). Generalizations of GR is mainly due to the great abundance of observational data in modern theory of gravitation, astrophysics and cosmology, some of which cannot be explained within GR, including the effects and manifestations of the so-called "dark energy" and "dark matter", the evolution of the

universe, the problems with "H_0-tension" - the discrepancies between, on the one hand, the value obtained from modern observations for the present moment Hubble parameter (the latter describing the expansion of the Universe) and its value extrapolated to the present epoch from the model's value for the early Universe), the gravity quantization problem, etc.

The problems solved in the dissertation are devoted specifically to numerical and analytical investigation of the structure and properties of compact objects in the Universe, which typically generate strong gravitational fields. The dissertation focusses on the following compact objects: neutron stars, black holes, pulsars consisting of a neutron star and a white dwarf pair, as well as a pair of black holes in the context of 3 modern gravitational theories: the standard GR; its extended theories: scalar-tensor and multiscalar-tensor theories and scalar Gauss-Bonnet theories of gravity. The topic of the dissertation is in the field of the modern fundamental scientific discipline - generalized (extended) alternative gravitational theories and applications in modern astrophysics and cosmology. Comparing the observable data for the properties of the compact objects with their theoretical values in different gravitational theories is crucial to the rejection or viability of a given generalized gravitational theory or for constraining the parameters in these theories.

This field is of great interest and is subject to intensive developments thanks to the known and expected to be known observational information from the large international scientific experiments conducted by e.g. the scientific collaboration LIGO-VIRGO-KAGRA and designed to obtain data from gravitational waves emitted by mergers of two or more compact objects formed from neutron stars, black holes, white dwarfs. Therefore, there is no doubt that the problems investigated in the dissertation are very challenging and interesting for a huge number of scientists. The dissertation, written in English, contains a total of 144 pages and consists of an Introduction, 6 chapters and a bibliography of 157 titles. The author's original results are contained in the last 3 chapters.

The main features of the candidate's scientific results can be formulated as follows:

(a) The scientific publications included in the dissertation meet both the minimum national requirements of (according to Article 2b, paragraphs 2 and 3 of DASRBA), RIDASRB as well as the additional requirements of SU "St. Kliment Ohridski" for the acquisition of the educational

and scientific degree “PhD”("Doctor") in Professional field 4.1 Physical Sciences, RTCASDHAPSU. More specifically, they significantly exceed these requirements. The dissertation is based on 3 articles (in all of which the candidate has substantial contributions), which have been published in some of the leading physics journals with Q1-ranking: ***European Physical Journal C (***1 publication***)*** and ***Physical Review D*** (2 publications);

(b) The scientific publications included in the dissertation do not repeat those from previous procedures for acquiring a scientific degree and/or holding academic position;

(c) There is no proven plagiarism in the submitted thesis and its summary. The summary, consisting of 56 pages and a bibliography of 82 titles, correctly reflects the content of the thesis.

4. Characterization and assessment of the candidate's teaching activity (if there is a requirement for this in RTCASDHAPSU**)**

The candidate has taught undergraduates on courses on ordinary differential equations (winter semester 2021/22) and on thermodynamics and statistical physics (summer semester 2021/22) at the Faculty of Physics of SU.

5. Content analysis of the candidate's scientific and applied scientific achievements contained in the dissertation.

The first four chapters 1-4 have an introductory and review character, preparing the theoretical and methodological, as well as the numerical basis for successful application to obtain the original results contained in chapters 5-7.

Chapter 1 is introductory and contains 4 pages, dedicated to the motivation and plan of the dissertation.

Chapter 2 contains a 10-page overview of gravitational theories, within which the considered class of compact astrophysical objects (black holes, neutron stars and pulsars consisting of a pair of neutron star - white dwarf or a pair of black holes) is studied. A more detailed consideration here is devoted to (1) GR; (2) scalar-tensor theories (STT) of gravity, in which gravity is described by 1 scalar field in addition to the metric tensor $\mathbf{g}_{\mu\nu}$,; multiscalar-tensor theories (MSTT), in which, in addition to $\mathbf{g}_{\mu\nu}$, there are N scalar fields, N > 1, taking values in an N-dimensional manifold, which, depending on the asymptotic conditions for the fields, can be topologically non-trivial; (3) scalar Gauss-Bonnet (sGB) gravitational theories, in which the additional scalar field is coupled to the topological Gauss-Bonnet term by means of a coupling function which depends on the scalar field.

Chapter 3, consisting of 22 pages, is an overview of the properties of the compact astrophysical objects. The matter inside the compact object in all gravitation theories (1)-(3) is described by the energy - momentum tensor $\mathbf{T}_{\mu\nu}$ of an ideal fluid, through which 2 additional unknown functions on the space-time are introduced: matter's pressure and density. The relationship between them is called the equation of state (EoS). There is great uncertainty in its form due to the fact that processes at densities higher than that of nuclear (baryonic) matter are not known (precisely such densities are expected in the central region of neutron stars). This uncertainty is also strengthened by the fact that nothing definite is known at present about the addition in the EoS of the hypothetical "dark matter" supposedly comprising 23% of the matter in the Universe. Therefore, the observational data should be compared against predictions from a large number of EoSs. In the dissertation, up to 53 EoSs have been used to obtain some of the physical characteristics of compact objects. To get the structural equations for the compact objects, their assumed symmetries should also be used, which significantly simplifies the equations of motion, following from the action of the corresponding gravitational theories (1)-(3). Physical boundary conditions should also be imposed. Thus, spherical symmetry is assumed for static objects and axial symmetry - for slowly rotating objects.

There is outer matter attracted by the compact object and located near its surface (called accretion disk). Important feature of the accretion disc is the innermost stable circular orbit - ISCO. Outer matter falls on the compact object if it rotates on an orbit smaller than ISCO. ISCO characterizes the X-ray emission of the accretion disk. In addition to ISCO, most models of accretion disc matter are also described by the characteristic frequencies of periodic oscillations of particles rotating on circular orbits under small radial and angular perturbations. These frequencies are called radial and vertical epicyclic frequencies. The dissertation qualitatively describes what differences can occur in the structure of the accretion disks of compact objects in the various generalized gravitational theories.

This chapter also reviews the so-called "universal relations" in gravitational theories. A type of new such relations are also subject to the author's original results. Here, by "universality" one means the independence on any of the different EoSs of a relation between the characteristics of a compact object. Previously, universal relations had been proven in GR by J. Lattimer, B. Schutz and C. Breu, L. Rezzolla, and in some generalized gravitation theories - by D. Doneva, S. Yazadzhiev et al.

In **Chapter 4**, consisting of 20 pages, the author reviews the main numerical methods used in the thesis. For most of his computer calculations, he uses C or Python programming languages, optimized for the numerical solutions to the specific nonlinear equations in the thesis. A ready-made Python library is used specifically for Markov chain Monte Carlo. It is well known that when applying the algorithms as a reference, clever amendments and additions are needed according to the specifics of the tasks, and V. Danchev has done this. *Let us emphasize that, due to the strong non-linearity of the problems in GR and its alternative extensions, numerical methods are an indispensable part of their solution.*

In **Chapters 5-7**, which contain the original results of the author, the main goal is to find new physically important and potentially observable effects that could not be obtained by the methods of Einstein's general theory of relativity (GR). Along with this, special attention is paid to possible inconsistencies between newly obtained effects in a given version of extended gravitational theory with well-established and observationally confirmed results of GR, which is a criterion for rejection or further modification of the corresponding gravitational theory that generalizes GR . The main results of the dissertation in chapters 5-7 can be formulated as follows:

Chapter 5, consisting of 24 pages, explores the basic properties of topological neutron stars(TNS), which represent a new class of compact astrophysical objects in the context of MSTT gravitational theories, introduced in previous works by D. Doneva and S. Yazadzhiev. Specifically, *slow-rotating topological neutron stars are studied here for the first time in the literature for the case of 2 different coupling functions* (the conformal factor that relates the metric tensor in the Einstein frame to the metric tensor in the Jordan frame is called a "coupling function"; in CTT, MSTT and sGB it is a function of the scalar field(s)). *For the first time in the literature, the inertial moment of TNS has been found and the corresponding standard universal ralation (independent of EoS) between the inertial moment, mass and radius of TNS are found*. In addition, *for the first time in the literature, the orbital and epicyclic frequencies for static and slow-rotating configurations in topological neutron stars, and the ISCO are numerically calculated*. Results are obtained and compared for two types of scalar field coupling functions. For a monotonic coupling function, no significant observational differences with GR are found, however the parameters are confined in a very small region. In the case of a non-monotonic coupling function, significant differences with GR are obtained. The latter result is important because it could be used as an observational identification of TNSs. *The results are obtained for 2 values of the topological charge of the scalar field* (the latter is nonzero only for massless scalar fields and controls the asymptotic of the field at spatial infinity in the static case). *This result makes it possible to search for topological neutron stars with non-trivial topological charges – also a new result in the literature*.

In **chapter 6**, consisting of 20 pages, for the *first time in the literature in the case of scalar-tensor (STT) theories, a new type of universal relations for quantities around the local maximum of the mass for a given branch of solutions is found.* Importantly, this new type of universal relations allows one to distinguish between theories with different parameters in a way that does not depend on EoS. The scalar field in a compact object in STT relative to the same object in GR leads to additional internal energy that resists gravitational collapse and this allows for the existence of objects with a larger maximum mass. Analogous reasoning can be conducted to justify increasing the parameter values of the coupling function. That this is indeed so, is confirmed by the numerical study of the point of maximum mass. *This new class of universal relations has also been traced after a contribution from non-baryonic ('dark') matter has been*

added to the EoSs. For this purpose, 53 UNS were used, and it was shown that the universality is also preserved in this case.

In **Chapter 7**, consisting of 24 pages, important new results on scalarization in neutron stars in the context of scalar-Gauss-Bonnet (sGB) gravitational theory are obtained. Namely, *for this theory, substantial constraints on the theory parameters (determining the particular form of the coupling function) have been found* from comparison with observational data for 3 binary pulsars (each representing a neutron star–white dwarf pair). The constraints are obtained by applying probabilistic Bayesian analysis using the Markov-Chain Monte-Carlo method. The probability function which limits the parameters is obtained from the difference between the predicted and observed change in the orbital period of the system which is due to the emission of gravitational waves. The constraints depend on the EoS, as well as on the presence/absence of mass of the scalar field. The obtained constraints on a massless scalar field are carried over to scalarized binary black holes. *In analogy with the newly obtained constraints on the parameters of the scalarized sGB theories, constraints on the maximum mass and topological charge of scalarized sGB black holes are accordingly derived.* These results are of significant interest for future observations of gravitational waves.

The candidate demonstrates high professional IT skills and ability to work with modern computer packages (based on the languages C and Python) for processing, analysis and comparison of numerical theoretical results with the available observational data.

The candidate's scientific contributions can be defined as:

(a) Development of new theories, hypotheses and research methods in the field of modern generalized gravitational theories, astrophysics and cosmology;

(b) Enrichment of existing theoretical knowledge and presenting it in a form convenient for comparison with the observational data and their further applications in the scientific fields mentioned above. All contributions in the candidate's dissertation have been published as noted at the beginning in 3 articles in scientific journals with high impact factors. For them, 19 independent citations have been noticed until the submission of the dissertation. In all of these three publications with co-authors, the candidate has made significant contributions, as certified by his supervisor.

6. Critical notes and recommendations

I have no substantial critical remarks about the content of the dissertation and the summary. Regarding the Bulgarian language terminology used in the Bulgarian version of the Summary , I would note, that the generally accepted terms are "space-time" and "ideal fluid", instead of the used "time-space" and "perfect fluid", but as you can guess, I include this remark rather to introduce of slight "gravity ripple" on the excellent exposition of Mr. Danchev' dissertation. I especially want to note that his thesis demonstrates that he perfectly understands the essence of

the research tasks solved in it and that he has thoroughly mastered both the knowledge on the analytical results in GR and its extensions, as well as the latest achievements in this field.

7. Personal impressions of the candidate

The quality of the scientific results in the dissertation and the candidate's professional CV convincingly present him as a young scientist with great creative potential and with obvious prospects for a successful future research career.

8**. Conclusion**

After having acquainted myself with the presented dissertation, summary and other materials, and based on the above analysis of their significance and the scientific contributions contained in them, **I confirm that the scientific achievements meet the requirements of DASRBA and RIDASRB for its application and the relevant RTCASDHAPSU. In particular, the candidate satisfies the minimum national requirements in the professional direction and no plagiarism has been found in the dissertation, summary and the scientific works submitted for defense. I give my positive assessment of the dissertation.**

II. General Conclusion

Based on the above analysis, **I recommend** with no hesitation to the Scientific Jury to award the educational and scientific degree “PhD” ("Doctor") in the Professional field 4.1 Physical Sciences to the candidate **Viktor Ivaylov Danchev**.

03.05.2023 Reviewer:

Prof. Svetlana Pacheva, Dr. Sci.