STAND

of a dissertation

for the acquisition of the educational and scientific degree "doctor"

in professional direction 4.1 "Physical sciences", scientific specialty 01.03.01 "Theoretical and mathematical physics",

by defense procedure at the Faculty of Physics (F.Phys.)

of Sofia University "St. Kliment Ohridski" (SU)

The stand was prepared by: Assoc. Prof. Dr. Sava Dimitrov Donkov, Institute of Astronomy with NAO, Bulgarian Academy of Sciences, in his capacity of a member of the scientific jury according to Order No. RD 38-323 / 17.06.2024 of the Rector of Sofia University.

Dissertation topic: "Optical effects in curved space-time: gravitational lensing, shadows and polarization of light"

Author of the dissertation: Valentin Olegov Deliyski

I. General description of the presented materials

1. Data on the submitted documents

The candidate, Valentin Olegov Deliyski, has submitted a dissertation and an abstract, as well as the mandatory tables for the Faculty of Physics from the Regulations for the Terms and Conditions for Acquiring Scientific Degrees and Occupying Academic Positions at SU "St. Kliment Ohridski".

The documents submitted by the candidate for the defense correspond to the requirements of the ZRASRB, PPZRASRB and the Regulations for the Terms and Conditions for Acquiring Scientific Degrees and Occupying Academic Positions at SU "St. Kliment Ohridski" (PURPNSZADSU).

2. Applicant personal data

The candidate is a physicist, with professional experience, both in industry and teaching, aspiring to an academic career. His scientific interests are in the field of relativistic astrophysics, where he has contributed to the study of the observational manifestations of exotic compact objects.

Valentin Deliyski's education is entirely related to Sofia University and was as follows:

“Bachelor” - Astrophysics, Meteorology and Geophysics - Sofia University “St. Kliment Ohridski”; Subject: Shadows of black holes. Scientific supervisor: Prof. Dsc. Stoytcho S. Yazadjiev. Oct. 2015 - March 2019

“Master” - Theoretical and Mathematical Physics - Sofia University “St. Kliment Ohridski”; Subject: Gravitational lenses. Scientific supervisor: Prof. Dsc. Stoytcho S. Yazadjiev. Oct. 2019 - March 2021

“Doctor” - Theoretical and Mathematical Physics - Sofia University “St. Kliment Ohridski”; Topic: Optical effects in curved space-time: gravitational lenses, shadows and polarization of light. Scientific supervisors: Prof. Dsc. Stoytcho S. Yazadjiev and Assoc.Prof. Dr. Galin N. Gyulchev. Scientific consultant: Assoc.Prof. Dr. Petya Nedkova. July 2021 - July 2024

Research interests: gravitational lensing, numerical methods in physics, dynamical evolution of the Einstein-Hilbert field equations, relativistic hydrodynamics in curved space-time, self-gravitating systems, arctic research, satellite control.

Projects:

Gravitational lensing simulator

• Develops C++-based code that solves the polarized

radiative transfer in the curved space-time of black holes

and objects of generalized theories of gravity.

• The source code can be found at Mjølnir GRRT code

Competencies:

Languages: Bulgarian (native), English (fluent), Norwegian (B1)

Programming languages: C++, C, Python, Matlab, Latex

Working environments: Visual Studio / VS code, STM32 CUBE IDE, Simulink, AutoCAD Fusion

3. Characterization and assessment of the applicant's scientific and scientific-applied achievements contained in the materials for participation in the competition

The dissertation can be divided into two parts - general and specialized. In the general part (Chapters 2, 3 and 4) the general context of the study is set, i.e. the physical background picture on which the study develops is built. Chapter 2 presents the basic laws of propagation of electromagnetic radiation in curved space-time. The so-called an approximation of geometrical optics, within which the propagation of light in a gravitational field is considered, is derived. The general form of the dynamical equations of light rays, as well as the covariant equation for polarized radiative transfer, are also presented. Chapter 3 presents the main observational results of the EHT collaboration, on which the study is based. Chapter 4 presents the exotic compact objects considered by the authors, as well as their main properties. The specialized part of the dissertation covers chapters 5, 6 and 7. The authors' original results are presented there. These are discussed in more detail in the exposition below.

The thesis aims to investigate the possibility of distinguishing observationally exotic compact objects, specifically wormholes and naked singularities, from black holes, building on the results (and future prospects) of the Event Horizon Telescope (EHT) collaboration. For the first time, EHT was able to reach an observational resolution sufficient to image the immediate vicinity of the ultra-compact objects in the cores of the M87 and Milky Way galaxies. These and future observations will play a key role in studying gravity in the strongest field regime. They can contribute to the experimental confirmation of the existence of new fundamental fields and exotic compact objects that arise naturally from generalized theories of gravity.

The study focuses on three observational characteristics of ultra-compact objects: the morphology of the resulting images, their variability, and the polarization of their radiation. They carry with them information about the nature of the compact object as well as about the gravitational theory that describes it. The latter is nonlinearly engaged with the magneto-hydrodynamics of the radiating medium, which further complicates the task.

The following working hypothesis was adopted in the study:

The 2017 EHT collaboration observations can be reproduced from synchrotron emitting plasma around supermassive compact objects that do not have an event horizon.

The authors reach the following results, reflected in the dissertation and in the four publications listed below. Paper 1 (and thesis chapter 5) extends existing studies of naked singularities to wormholes. A certain semi-analytical approach was used to generate the images of single orbits. This shows that both classes of exotic compact objects have significantly different image morphologies to that of Schwarzschild black holes. A central ring-like structure forms, located where the object's shadow would be. This structure corresponds, in the case of wormholes, to photons that have passed through the throat and, in the case of naked singularities, to photons that have scattered from the singularity. Observational detection of such structures can serve as a clear sign of the existence of such exotic objects. Next, the authors turn to investigate the space-time imprint on the polarization detected by a distant observer. For this purpose, in publications 2 and 3 (respectively, chapter 6 of the dissertation), a simplified analytical model of radiation, generalized for arbitrary static and spherically symmetric metrics, is applied. The model requires the calculation of the wave vector of the photons on the source, which was performed with the Mjølnir code developed by the author. Finally, the following two main conclusions are reached:

1) Direct images of the radiating medium are weakly influenced by space-time (i.e. by the gravitational theory). The main physical factor determining their properties is the magnetic field.

2) Indirect images (mostly at n=1) are strongly affected by both the magnetic field and the metric. Depending on the geometry of the magnetic field, relative intensity deviations can reach, relative to Schwarzschild black holes, up to one order of magnitude.

Building on these results, the authors investigate through simulations and "ideal" (infinite resolution) numerical calculations the possibility of observationally distinguishing black holes (in the Schwarzschild case) from exotic compact objects (wormholes and naked singularities). This is the subject of paper 4 (respectively chapter 7 of the dissertation). For this purpose, several software packages were used: the author's package **Mjølnir**, which implements a complete model of the radiating environment and serves to obtain "ideal" observations; the **ehtim** package developed by EHT, which has two main functionalities: it simulates a realistic observation of the images generated with the help of **Mjølnir**, and also performs their reconstruction using the methodology of the EHT collaboration (with its help, the images of naked singularities for three different sets of radio telescopes, and two observing frequencies, are obtained); the **VIDA** package, which fits geometric models to its input images (used to model the images received by **ehtim** as ellipses with Gaussian thickness) The conclusion reached by the authors after the research done is the following:

3) Even with the expansion of the set of telescopes, if the observations are made at 230 GHz, as was done during the EHT mission in 2017, the images of black holes and exotic compact objects remain morphologically similar. However, there is one caveat: the intensity of the central depression of naked singularities compared to that of black holes increases by two orders of magnitude when the number of telescopes increases. The major breakthrough is reached when the frequency of observations is increased to 350 GHz, as planned for the ngEHT mission. The reconstructions then become sensitive to the central ring structure, which provides a clear criterion for distinguishing between classical and exotic compact objects.

I believe that the results are well justified and clearly stated. They are also illustrated for us with wonderfully crafted figures. Summarizing, I can say that Valentin Deliyski works confidently and competently in a very modern field of modern theoretical and mathematical physics, namely research of classical and generalized theories of gravity, and their validity and manifestation are compared with the most contemporary observations. The nature of the presented scientific work has, in my opinion, the purpose of establishing whether the solutions of generalized theories of gravity are observed, the so-called exotic compact objects (wormholes and/or naked singularities), and also how to distinguish them from classical compact objects (black holes) from EHT observational data. For this purpose, a working hypothesis (mentioned above) was formulated and a magneto-hydrodynamic model of the emitting plasma (in the accretion disk) under conditions of distorted space-time was assumed. The obtained theoretical results for the morphology of the images of the emitting medium and for the polarization of the light reaching a distant observer are compared with the observations, and the program code created by the doctoral student, especially for this purpose, plays an important role here. I can conclude that the nature of the research is to compare the results (solutions) of already existing theories, both theoretically and on the basis of the experiment, with the statement of new hypotheses and the development of new specialized software. The topic of the dissertation is extremely modern and is actually on the edge of modern science about the fundamental fields describing gravity around ultra-compact objects. The essence of the work requires high competence, both in theoretical physics and in modern mathematics, as well as serious skills in creating specialized software.

The research is reported in the following four scientific publications:

1) Paper 1 - V Deliyski, G Gyulchev, P Nedkova, and S Yazadjiev. Observational features of thin accretion disks around traversable wormholes. Journal of Physics: Conference Series, 2255(1):012002, Apr 2022; IF: 0.48, Q4 (2022)

2) Paper 2 - Valentin Deliyski, Galin Gyulchev, Petya Nedkova, and Stoytcho Yazadjiev. Polarized image of equatorial emission in horizonless spacetimes: Traversable wormholes. Phys. Rev. D, 106:104024, Nov 2022. IF: 5.0, Q1 (2022). Also presented in Physics Synopsis - https://physics.aps.org/articles/v15/s154

3) Paper 3 - Valentin Deliyski, Galin Gyulchev, Petya Nedkova, and Stoytcho Yazadjiev. Polarized image of equatorial emission in horizonless spacetimes: Naked singularities. Phys. Rev. D, 108:104049, Nov 2023. IF: 4.6, Q1 (2023).

4) Paper 4 - Valentin Deliyski, Galin Gyulchev, Petya Nedkova, and Stoytcho Yazadjiev. Observing naked singularities by the present and next-generation event horizon telescope. http://arxiv.org/abs/2401.14092, 2024.

Conference reports:

- A report was presented at the “2021 National Forum for Advanced Space Research”, on the topic “Observational signatures of ultra-compact objects with accretion disks”, on 08.10.2021.

- A report was given during a scientific visit to the Emmy Noether Research Group: “Gravitational waves from compact objects”, at the Eberhard Karl University in Tübingen, Germany, on 03.07.2024.

- Delivered a report at the Seventeenth Marcel Grossman Meeting on the topic “Polarized image of equatorial emission in horizonless spacetimes”.

From the attached list of publications, their impact factor and quartile, from the presented dissertation reports, and also from the candidate's equal or leading contribution declared by the co-authors, I can clearly conclude that Valentin Deliyski fully satisfies the minimum national requirements for Art. 2b, para. 2 and 3 of ZRASRB and even significantly exceeds the additional requirements of Faculty of Physics of SU “St. Kliment Ohridski” for the acquisition of the educational and scientific degree “doctor”. In addition, the scientific publications included in the dissertation do not repeat those from previous procedures for acquiring a scientific title or academic position. Also, no plagiarism has been proven in the submitted dissertation and abstract.

4. Critical notes and recommendations

I have no critical notes. I wish Valentin success in his academic career.

5. Personal impressions of the candidate

I have no personal impressions.

6. Conclusion

After having familiarized myself with the presented dissertation work, abstract and other materials, and based on the analysis of their significance and the scientific and scientific-applied contributions contained in them, I confirm that the scientific achievements of Valentin Olegov Deliyski meet and even exceed the requirements of ZRASRB and the Regulations for its application and the corresponding Regulations of the SU “St. Kliment Ohridski” for acquiring the educational and scientific degree “doctor”. In particular, the candidate satisfies the minimum national requirements in the professional direction and no plagiarism has been found in the dissertation, abstract and scientific works submitted for the competition.

I give my positive assessment of the dissertation work.

II. General conclusion

Based on the above, I recommend the scientific jury to award the educational and scientific degree “doctor” in professional direction 4.1 “Physical sciences” to Valentin Olegov Deliyski.

Data: 04.09.2024 **Reviewer: ....**

(Assoc. Prof. Dr. Sava Donkov)