REVIEW

of a dissertation

for acquisition of the educational and scientific degree „doctor“

in a professional field 4.1. Physical sciences,

scientific specialty Theoretical and Mathematical Physics

by defense procedure at the Faculty of Physics

of Sofia University „St. Kliment Ohridski“ (SU)

Reviewer:

Prof. Boyko Milkov Mihov, PhD – Institute of Astronomy and NAO, BAS,

(academic position, first name, middle name, last name, scientific degree – place of work)

in his capacity as a member of the scientific jury according to Order No. RD 38-323 / 17.06.2024 of the Rector of Sofia University.

Dissertation title: „Optical effects in curved spacetime: gravitational lenses, shadows and the polarization of light“

Dissertation author: Valentin Olegov Deliyski

I. General description of the presented materials

1. Description of the submitted documents

The candidate Valentin Olegov Deliyski has submitted a dissertation, an Abstract in Bulgarian and English, as well as the mandatory tables for Faculty of Physics taken from the Regulations on the terms and conditions for acquiring scientific degrees and holding academic positions at SU „St. Kliment Ohridski“. He also submitted: a dissertation originality verification report, a dissertation plagiarism prevention procedure statement, a similarity report (generated by StrikePlagiarism.com), copies of publications, included in the dissertation, Curriculum Vitae, a declaration of the dissertation authorship, a diploma for the Master's degree, and a certificate of a full-time doctoral studies.

The documents submitted by the candidate for the dissertation defense correspond to the requirements of the ZRASRB, PPZRASRB, and the Regulations on the terms and conditions for acquiring scientific degrees and holding academic positions at SU „St. Kliment Ohridski“ (PURPNSZADSU).

2. Information about the candidate

The candidate Valentin Olegov Deliyski obtained Bachelor's degree in Astrophysics, Meteorology, and Geophysics at the Faculty of Physics of SU „St. Kliment Ohridski“ in 2019, and in 2021 he acquired Master's degree in Theoretical and Mathematical Physics at the same faculty. Scientific supervisor of the Bachelor's and Master's theses, entitled „Shadows of black holes“ and

„Gravitational lenses“, respectively, is corr.-member St. Yazadzhiev. In 2021, V. Deliyski was enrolled in regular doctoral studies at the Department of Theoretical Physics of the Faculty of Physics of the SU with scientific supervisors corr.-member St. Yazadzhiev and Assoc. Prof. G. Gyulchev, PhD. In 2024, after passing the exams from his individual plan with excellent grades, V. Deliyski finihed his doctoral studies with a right of defense. He has gave three talks during the doctoral studies – two at scientific forums and one during a scientific visit. The candidate also has experience as a GNC (guidance, navigation, and control) engineer of nano-satellites in the EnduroSat company. He is fluent in English and has considerable experience in the field of Information Technologies (programming languages, working environments; see also https://github.com/ValentinDeliyski, where author's software used in the dissertation is presented). V. Deliyski's scientific interests are in the field of relativistic astrophysics, more specifically the study of observational manifestations of exotic compact objects.

3. General description of the candidate's scientific achievements

The dissertation is dedicated to study the possibility of distinguishing exotic compact objects from black holes using current and future observations of the Event Horizon Telescope (EHT) collaboration. This possibility, in turn, can help us solve a fundamental problem for modern physics, namely the existence or not of exotic compact objects, such as wormholes and naked singularities, which, in turn, arise naturally in generalized theories of gravity. In this regard, the construction of theoretical images formed by different classes of relativistic objects is of great importance, because comparing the theoretical and observational characteristics (morphology, variability, polarization) of the images is the only way to confirm or reject a given relativistic object as forming them. In the dissertation, it is shown that both of the aforementioned classes of exotic compact objects possess a significantly different morphology of the formed images compared to that of Schwarzschild black holes. The polarization properties of the theoretical images are also examined, showing that the indirect images are strongly influenced by the gravitational theory describing the central object. It is concluded that increasing the number of telescopes and the operating frequency of the EHT makes the observations significantly more sensitive to the presence of images formed by exotic objects. All the results presented in the dissertation are of extreme importance not only for the theory of exotic compact objects, but also for astrophysics, because they can shed light on the nature of the compact object at the center of galaxies (active or not) – nowadays it is generally accepted that it is a supermassive black hole. The interpretation of the observed ENT images with the methods proposed in the dissertation can give us more information about the central object and its nature (black hole or exotic class compact object).

The dissertation is based on three published papers (two journal articles and one in the proceedings of the conference „Second National Forum on Contemporary Space Research“, held in Sofia) and one under review. The journal articles are published in Phys. Rev. D – a reputable international journal in the Q1 quartile. These two publications cover with an advance the minimum

national requirements (under Art. 2b, Par. 2 and 3 of the ZRASRB) and the additional requirements of the SU, when the conference article is considered as well.

The authorship and originality of the dissertation and the Abstract have been confirmed after checking in the plagiarism prevention system. The scientific publications included in the dissertation do not repeat those from previous procedures for acquiring a scientific degree and academic position.

4. Characteristic and evaluation of the candidate's teaching activity (if there is a requirement for this in PURPNSZADSU)

During his doctoral studies, V. Deliyski led seminars on „Statistical Physics“.

5. Content analysis of the applicant's scientific and scientific-applied achievements contained in the materials for participation in the competition

The dissertation, presented by V. Deliyski, contains 138 pages, 61 figures, 16 tables, and 86 references. It is divided into an introduction, general (three chapters) and specialized (three chapters) parts, a conclusion, and four appendices. Chapter 5 is based on publication I, Chapter 6 – on publications II and III, and Chapter 7 – on publication IV. The Abstract correctly represents the content of the dissertation.

The general part, Chapters 2 to 4, aims to provide the basic context and physical basis of the subject under consideration. Chapter 2 presents the basic laws of propagation of electromagnetic radiation in curved space-time (Maxwell's equations, WKB approximation). An approximation of geometrical optics is also derived, within which all optical effects in gravity are considered. Also presented are the general form of the dynamical equations of light rays (within geometrical optics), as well as the covariant equation for polarized radiative transfer. The dynamical equations of the light rays, under certain conditions, allow the existence of circular photon orbits, which separate the photons flying towards the central object into those that scatter in space and those that fall on it. Therefore, the properties of these orbits also determine the apparent shape of the object to a distant observer – a shadow surrounded by a photon sphere. Chapter 3 presents the main observational results of the EHT collaboration (the galaxy M87 and the source Sgr A*, located in the center of the Milky Way). The comparison of the observations with the GRMHD simulations, used by the ENT collaboration, is discussed – the biggest problem in the interpretation of the obtained images is their variability. Chapter 4 presents the exotic compact objects considered in the dissertation that do not have an event horizon (wormholes and naked singularities of Janis-Newman-Winicour and Gauss-Bonnet), as well as their main properties and optical manifestations. Emphasis is placed on the nature of circular photon orbits and the innermost stable orbits of massive particles.

The technical part, Chapters 5 to 7, presents the candidate's original results and considers in detail the observational manifestation of two classes of exotic compact objects – wormholes and naked singularities. Chapter 5 discusses the image morphology of the radiating medium around the

above classes of objects. The considerations are carried out for a thin Novikov-Thorne accretion disk in a static limit – these approximations allow to significantly reduce the number of free parameters of the model and to simplify the numerical calculations. At the beginning of the chapter, the general theory of the formation of images in static and spherically symmetric spaces is considered in detail. The system of parametric expressions, following from the theory and defining the image of the radiating medium, is solved numerically using the *Mjølnir* code, developed by V. Deliyski. The cases with and without a photon sphere are considered separately (only for naked singularities). As a result of the numerical calculations, it is shown that both classes of exotic compact objects have a significantly different morphology of their images compared to that of Schwarzschild black holes. A central ring-shaped structure is formed, located where the shadow of the object should be (for naked singularities, this is observed only at certain parameter values). These morphological deviations can serve as a test for the presence of an exotic compact object. The relative flux of the formed images is calculated and observations of M87 are simulated – it is shown that the morphological deviations (with respect to black holes) of the relativistic images of the rediating medium around exotic compact objects should, in general, be possible for observational detection. Chapter 6 considers how the nature of space-time around supermassive compact objects affects the polarization of the observed radiation. Polarization characterizes the structure of the magnetic field in the radiating region and, more importantly, its propagation to the observer is affected by the space-time geometry. This additional source of information can largely (but not entirely) remove the degeneracy of the image interpretation problem. A simplified analytical radiation model (presented in Section 6.1) and the *Mjølnir* numerical code were used to study the influence of space-time on the polarization of the acquired images. Direct and indirect polarized images of the radiating medium created by wormholes and naked singularities have been investigated for a large set of model parameters. It was found that direct images of the radiating medium are weakly influenced by the nature of space-time and strongly by the magnetic field, and that indirect images are strongly influenced by both the nature of space-time and the magnetic field. Chapter 7 seeks an answer to the question of whether it is possible with modern observational techniques to detect images, formed by the exotic compact objects considered so far. To do that, with the *Mjølnir* code, ideal images of M87 formed by exotic compact objects are generated at different values of the model parameters. The *ehtim* code then generates real images from the ideal ones (i.e. what an ideal image would look like to an observer on Earth, given the parameters of the available observing technique – resolution, sensitivity, etc.) using three configurations of telescopes and two operating frequencies. It is shown that as the number of telescopes increases, the images formed by exotic compact objects remain morphologically similar to those of black holes (i.e. a ring with a pronounced central depression and emission asymmetry), but the relationship between the minimum flux in the depression, and the mean one of the ring structure increases. However, if we increase the operating frequency, as planned for ngEHT, a central maximum in the depression is observed, which may serve as a sign that the image is formed by an exotic compact object.

The dissertation has four appendices, covering various aspects of solving the set scientific goal. I will note Appendix A, where the complete derivation of the emission functions from a superrelativistic charged plasma in thermodynamic equilibrium is presented, and Appendix Б, where the *Mjølnir* numerical code, developed by V. Deliyski, is presented (https://github.com/ValentinDeliyski/Mjolnir_GRRT).

The scientific achievements presented in the dissertation are of undoubted benefit in the interpretation of current and future observations with EHT-type instruments – in this line of reasoning, the scientific contributions of V. Deliyski can be characterized as an enrichment of existing knowledge. The fact that the publications on which it is based already have 20 independent citations, mainly in reputable international journals (PhysRevD, JCAP, EPJC), also points to the importance of the issues considered in the dissertation.

6. Critical notes and recommendations

My notes are of a technical nature and in no way diminish the scientific value of the dissertation:

- at the beginning of Chapter 5 it is written: „*Our goal is the following: To gain a qualitative picture of the morphological differences of exotic compact objects compared to Schwarzschild black holes.*“, while at the end of the same chapter it is concluded that „*The morphological deviations (compared to Kerr black holes) of the relativistic images of the radiating medium around exotic compact objects must, ...*“. Schwarzschild or Kerr?
- on page 80 it says „7.2“, but it should be „*6.2*“. On page 86 it says „*Chapter 7*“, but it should be „*Chapter 6*“;
- inaccurate translation of some terms from English to Bulgarian and the use of English terms directly in Bulgarian. For example, the more correct translation of „*For low inclinations the exotic images of wormholes are highly observationally relevant, ...*“ is „*За малки наклони спрямо лъча на зрение екзотичните изображения, формирани от пространствено-времеви тунели, са лесно достъпни за наблюдение, ...*“, not „*За ниски инклинации, екзотичните образи от пространствено-времеви тунели са силно релевантни за наблюденията, ...*“ (the quote is from the Abstract in English, p. 11).

7. Personal impressions of the candidate

I have no personal impressions of V. Deliyski.

8. Conclusion

After having familiarized myself with the presented dissertation, 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 meet the requirements of ZRASRB and the Regulations for its application and the relevant 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 professional field 4.1. Physical Sciences and no plagiarism was found in the dissertation, Abstract, and scientific works submitted for the competition.

I give my **positive** assessment of the dissertation.

II. GENERAL CONCLUSION

Based on the above, **I recommend** the scientific jury to **award the educational and scientific degree „doctor“** in professional field 4.1. Physical Sciences to **Valentin Olegov Deliyski**.

11 September 2024 Reviewer: .....

(Prof. Boyko Mihov, PhD)