REVIEW

on the dissertation

for acquiring the educational and scientific degree "Doctor"

in the scientific field and professional direction 4.1. Physical Sciences,

as part of the defense process at the Faculty of Physics (FzF)

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

The review was prepared by Assoc. Prof. Dr. Tsvetan Ivanov Vetsov, Department of Theoretical Physics, Faculty of Physics, Sofia University "St. Kliment Ohridski", in his capacity as a member of the scientific jury, in accordance with 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."

Author of the dissertation: Valentin Olegov Deliyski

I. General description of the presented materials

1. Information on the Submitted Documents

a) Type of Submitted Documents

Candidate Valentin Deliyski has submitted a dissertation and an abstract summary, as well as the required tables for the Faculty of Physics in accordance with the Rules for Conditions and Procedures for Obtaining Scientific Degrees and Holding Academic Positions at Sofia University "St. Kliment Ohridski." Additionally, 9 other documents (in the form of official statements and certificates from employers, project leaders, funding organizations, or project commissioners, references, reviews, awards, and other relevant evidence) supporting the candidate's achievements have been provided:

1. Dissertation in Bulgarian
2. Summary in Bulgarian and English
3. Author's statement of the contribution of the works
4. Declaration of authorship
5. Master's diploma
6. Curriculum vitae
7. Certificate of regular doctoral student status and completed exams
8. Protocol for checking the originality of the dissertation
9. Statement from Assoc. Prof. Dr. Galin Gyulchev confirming the absence of plagiarism
10. Similarity report excerpt
11. Application for admission to pre-defense
12. List of publications

[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.

[2] V. Deliyski, G. Gyulchev, P. Nedkova, and S. Yazadjiev, Polarized image of equatorial emission in horizonless spacetimes. Traversable wormholes. Phys. Rev. D, 106:104024, Nov 2022.

[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.

[4] V. Deliyski, G. Gyulchev, P. Nedkova, and S. Yazadjiev. Observing naked singularities by the present and next-generation event horizon telescope. [arXiv:2401.14092 [gr-qc]].

b) Structure of the Dissertation

The dissertation abstract summary in Bulgarian consists of 6 chapters, presented over 42 pages. It includes 16 figures and 6 tables, and references 39 sources.

The abstract summary in English also consists of 6 chapters, presented over 39 pages. It includes 16 figures and 6 tables, and references 39 sources.

The dissertation itself, written in Bulgarian, comprises 9 chapters and 4 appendices, presented over 138 pages in A4 format. It includes 61 figures and 16 tables, and references 86 sources. The structure and content of the dissertation are as follows:

1. Introduction: Briefly presents the problems and achievements of the chosen topic. The motivations and objectives of the dissertation are clearly outlined, along with the formulated hypotheses and chosen approaches to achieve the stated goals.

2. Chapter 2: Covers the fundamental laws of electromagnetic radiation propagation in curved spacetime and the theory of polarized light transmission.

3. Chapter 3: Presents the main observational results from the EHT collaboration, which form the basis of the candidate's research.

4. Chapter 4: Provides a review of the main properties and characteristics of the exotic compact objects considered by the candidate. These include wormholes, Janis-Newman-Winicour naked singularities, and solutions in the Gauss-Bonnet theory.

5. Chapter 5: Expands upon the research from publication [1] and reviews equivalent studies on naked singularities by other authors. The morphology of the apparent images from the emitting environment generated by such objects is examined. It is shown that, under certain conditions, their optical appearance significantly differs from that of black holes, evidenced by a set of exotic concentric ring-like images within the shadow region of black holes. These rings could serve as a clear indicator of such objects if observed. The assessments are based on the model of an optically thick accretion disk.

6. Chapter 6: Presents results from publications [2, 3]. It investigates the extent to which the nature of spacetime influences the polarization of the electromagnetic radiation coming from the objects and their surrounding matter. The candidate shows that direct polarized images of the emitting environment are minimally affected by the nature of the central object and the gravitational theory describing it. However, relativistic indirect images are significantly influenced. The hypothesis is that, with higher observation resolution, the polarization of these images could provide additional constraints on the nature of the central compact object.

7. Chapter 7: Discusses results from publication [4]. It is demonstrated that the morphology of the exotic central images is lost under current EHT observational conditions due to the effective resolution limits, but still leaves a signature in the form of increased background emission in the central depression of the final observations compared to black holes. It is shown that increasing the observational frequency from 230 GHz (used for all current EHT results) to 345 GHz (planned for future observations) could reveal visible traces of the exotic images.

8. Chapter 8: Contains the candidate's conclusions and a brief overview of the main scientific contributions.

9. Chapter 9: Lists the scientific publications related to the competition and the presentations given at various conferences and scientific forums.

c) Compliance with the Legal and Regulatory Requirements for Obtaining the Doctoral Degree

The documents submitted by the candidate for defense are in accordance with the requirements of the Law on the Academic Staff Development in the Republic of Bulgaria (ZRASRB), the Regulations for the Implementation of ZRASRB (PPZRASRB), and the Rules for

Conditions and Procedures for Obtaining Scientific Degrees and Holding Academic Positions at Sofia University "St. Kliment Ohridski" (PURPNSZADS).

2. Candidate Information

Valentin Deliyski is a graduate of the Faculty of Physics at Sofia University, where he completed his bachelor's degree in 2019 and his master's degree in 2021, under the supervision of Assoc. Mem. Acad. Sc. Prof. D.Sc. Stoytcho Yazadjiev. In July 2021, he began his doctoral studies in the Department of Theoretical Physics, with Prof. DSc Stoycho Yazadzhiev and Assoc. Prof. Dr. Galin Gyulchev as his advisors, and Assoc Prof. Dr. Petya Nedkova as his Scientific consultant. His research topic is "Optical effects in curved spacetime: gravitational lenses, shadows and the polarization of light."

During his doctoral studies, Valentin has led seminar exercises in statistical physics. Outside of his academic work, he is involved in the deployment and management of a nanosatellite (6U CubeSat) and is developing his own C++ code named "Mjolnir", which solves the equations for polarized radiation transfer in the curved spacetime of black holes and objects from modified theories of gravity.

Valentin has 4 scientific publications: 2 in Physical Review D, 1 conference paper, and 1 article in the electronic archive Arxiv.org. He has 22 independent citations and an h-index of 3.

3. General Overview of the Candidate's Scientific Achievements

a) The scientific publications included in the dissertation are 4 in total and meet the minimum national requirements (according to Article 2b, paragraphs 2 and 3 of ZRASRB) and the additional requirements of Sofia University "St. Kliment Ohridski" for obtaining the educational and scientific degree of "Doctor" in the relevant scientific field and professional direction.

b) The scientific publications included in the dissertation do not duplicate those from previous procedures for obtaining a scientific title or academic position.

c) There is no evidence of plagiarism in the presented dissertation and summary, as verified by the legally established procedures.

d) The candidate's scientific interests and contributions, as detailed in the dissertation, focus on theoretical astrophysics, specifically on relativistic images of dark compact objects such as black holes, wormholes, and naked singularities.

e) The research is primarily motivated by the recent advancements of the Event Horizon Telescope (EHT) collaboration, which is engaged in the experimental observation of these objects in the centers of various galaxies, including the Milky Way.

f) The dissertation aims to explore the theoretical potential for observing these objects and differentiating between them by analyzing their unique observational characteristics in future high-resolution EHT experiments. The candidate has successfully demonstrated this for wormholes [1,3] and naked singularities [2,4] by investigating the properties of light emitted from the visible images of thin accretion disks around these objects. As stated by the candidate::

„The goal of this dissertation is to examine the possibility of distinguishing such exotic compact objects from black holes via the current and future observational campaigns of the EHT collaboration"

„We assume the following hypothesis: The observations of the EHT collaboration from 2017 can be reproduced by a synchotron emitting plasma around supermassive compact objects which do not posses an event horizon."

4. Characterization and Evaluation of the Candidate's Teaching Activity (if required by PURPNSZADS)

Teaching activity is not required by the rules for obtaining the doctoral degree. However, Valentin lead seminars in statistical physics.

5. Substantive Analysis of the Candidate's Scientific and Applied Research Achievements Contained in the Competition Materials

a) Number of Scientific Articles: **4**.

b) Number of Independent Citations: **22** (according to NASA data).

c) h-index**: 3**.

d) Scientific Contributions by Publications:

[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, 2022.

The potential emergence of qualitatively new observational characteristics of images of accretion disks around compact objects has been investigated. Specifically, a class of traversable wormholes with a photon sphere has been examined. Distinctive features have been found in the obtained images that are not present in Kerr black hole.

Contribution: This provides possible methods for distinguishing traversable wormholes from black holes based on observational data close to or within the central region of the object.

[2] V. Deliyski, G. Gyulchev, P. Nedkova, and S. Yazadjiev, Polarized image of equatorial emission in horizonless spacetimes. Traversable wormholes. Phys. Rev. D, 106: 104024, 2022.

In this paper, the linear polarization of electromagnetic radiation from an accretion disk around a class of static traversable wormholes has been investigated. The study was conducted within the framework of a simplified model of a magnetized disk positioned in the equatorial plane. The aim is to identify distinctive features that differentiate wormholes from black holes based on the polarization properties of the observed radiation.

To achieve this, direct polarized images of rays reaching the asymptotic observer through the wormhole's throat at various inclination angles were obtained and compared with those for a Schwarzschild black hole. It was found that, at small inclination angles, both types of compact objects produce similar polarization signatures in the direct apparent images. More significant differences are observed under strong gravitational lensing effects, where the polarization intensity of indirect images (forming an additional structure of ring-like images with varying polarization properties) around wormholes can increase significantly compared to those around black holes.

Contribution: Differentiating wormholes from black holes based on their polarized images. The study demonstrates that higher-order images and the polarization of radiation passing through the tunnel's throat can provide distinctive features that serve as indicators for the presence of objects without an event horizon.

[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, 2023.

This study investigates the linear polarization from the accretion disk around weak and strong Janis-Newman-Winicour naked singularities. A simplified model of a thin magnetized disk, rotating in the equatorial plane and emitting synchrotron radiation, is examined. Observed polarized images are compared with those of a Schwarzschild black hole under physical parameters compatible with the M87 radiation source. For small inclination angles, the direct images of weak naked singularities closely resemble those of a Schwarzschild black hole. It is demonstrated that deviations in polarization properties increase with greater inclination or higher-order images. Strong naked singularities create significant observational signatures even in direct images, producing secondary disk images with more than three times the polarization intensity and a characteristic polarization direction.

Contribution: These additional structures allow naked singularities to be distinguished from black holes in observations of polarized light.

[4] V. Deliyski, G. Gyulchev, P. Nedkova, and S. Yazadjiev. Observing naked singularities by the present and next-generation event horizon telescope. [arXiv:2401.14092 [gr-qc]].

This study explores the observational characteristics of reflecting naked singularities, which effectively act as reflective barriers for isotropic geodesic lines, causing the scattering of falling photon trajectories back to an observer at asymptotic infinity. The model images obtained are formatted for comparison with current and future EHT data. Reflecting naked singularities result in a characteristic morphology of the accretion disk images, creating a series of bright rings in the central part of the image. The study investigates EHT's ability to detect this structure, focusing on two specific types of reflecting naked singularities: the Janis-Newman-Winicour space and a static spherically symmetric solution within 4D Einstein-Gauss-Bonnet gravity. The results are modeled against the background of the galactic object M87*.

It was found that the EHT from 2017 is not capable of detecting the series of bright central rings. However, the candidate’s research reveals an increased overall intensity in the central bright depression, with values significantly higher than those for a Kerr black hole. This fact can serve as a quantitative measure for the absence of an event horizon. Future EHT observations at 230 GHz could reveal a two-order-of-magnitude difference in the intensity of the central bright depression between naked singularities and black holes. Introducing a second observational frequency at 345 GHz would resolve qualitative effects in the disk image morphology of naked singularities, with certain bright spots becoming visible in the center of the image.

Contribution: The obtained bright central rings from reflecting naked singularities can be used as a clear indicator to differentiate these horizonless objects from Kerr black holes. According to Valentin’s research, even if these characteristic rings of naked singularities cannot be directly distinguished, they would still result in increased brightness in the central depression compared to Kerr black holes—something that could be detected in future EHT observations.

It is worth noting that another significant contribution of Valentin Delijsky’s research is the presentation of theoretical results (the reconstructed apparent images of the compact objects) in a form practically ready for comparison with the experimental data. Additionally, it should not be overlooked that the numerical investigations were carried out from start to finish using the candidate’s proprietary code, named “Mjolnir,” which is publicly available on the GitHub platform at: github.com/ValentinDeliyski/Mjolnir_GRRT.

6. Critical Notes, Questions and Recommendations

I have no critical remarks. I believe Valentin has excelled both scientifically and in terms of language and style in writing his dissertation. Only a few minor language and punctuation errors were noticed. In addition, I have the following questions:

1) Why are naked singularities interesting from an astrophysical perspective?

2) Besides the morphology of the images and the polarization of the radiation emitted from the accretion disk, are there other ways to obtain information about the nature of the compact objects? And are there any plans for future experiments in this direction?

3) Can a comparative estimationn be made on how significant the difference might be between the observable images obtained from a thin disk model if we replace it with another, more complex disk model?

4) What is the influence of the spin parameter a of the object on the morphology and the polarization of the aparent images? What can we expect when the spin $a > 0.5$?

7. Personal Impressions of the Candidate

I have an excellent impression of Valentin Delijsky, primarily due to the bachelor's and master's courses he attended during his studies at the Faculty of Physics.

8. Conclusion

After reviewing the presented dissertation, abstract, and other materials, and based on the analysis of their significance and the scientific and applied contributions contained within them, I confirm that the scientific achievements meet the requirements of the Law on the Development of Academic Staff in the Republic of Bulgaria (ZRASRB) and its implementing regulations, as well as the corresponding regulations of Sofia University "St. Kliment Ohridski" for obtaining the educational and scientific degree of "Doctor." Specifically, the candidate meets the minimum national requirements in the professional field, and no plagiarism has been identified in the submitted dissertation, abstract, and scientific papers.

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

II. OVERALL CONCLUSION

Based on the above, I recommend that the academic jury award the educational and scientific degree of "Doctor" in the professional field of Physical Sciences to Valentin Olegov Deliyski.

Tsvetan Vetsov

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Date: 14.09.2024 Reviewer: .....

(Assoc. Prof. Dr. Tsvetan Vetsov)