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Referee's report of the PhD thesis of Mr Vikram Kumar Jaiswal entitled „LIGHT ECHO STUDIES IN ACTIVE GALACTIC NUCLEI AND THEIR APPLICATION FOR DISTANCE MEASUREMENT"

I. Legal basis:

I prepared this review in honor of my appointment by the Scientific Council of the Center for Theoretical Physics of the Polish Academy of Sciences (PAS) on October 3, 2025. I was appointed to review the PhD Thesis for awarding the Doctor of Science degree in Physical Sciences to Vikram Kumar Jaiswal.

II. General characteristics of the dissertation

The doctoral dissertation of M.Sc. Vikram Kumar Jaiswal is entitled “Light echo studies in active galactic nuclei and their apploication for distance measurements” and was carried out under the supervision of Prof. Bożena Czerny. The dissertation is written in English. It consists of six chapters, including three chapters which are preprints of Mr Jaiswal fisrt author articles published/sumbitted in Astronomy & Astrophysics journal. The extensive bibliography contains many papers published in recent years.

The project focuses on studying light echoes, also known as reverberation mapping, in active galactic nuclei in order to investigate the structure of the central engine. Reverberation mapping is a method used to measure the size of disks in the central engine. While this method is already well-known and documented in the literature, Mr. Jaiswal analyzed discrepancies in continuum lags in detail and described their complex nature. He also compared observational data with models. This work builds on theoretical models and comparisons with observational data. Moreover, Mr. Jaiswal developed his own models and published articles on each stage of development (from lamp-post geometry to a two-lamp setup) and comparisons with well-studied examples (Vikram Kumar Jaiswal et al., 2023, A&A, 18 citations; Vikram Kumar Jaiswal et al., 2025, A&A, 2 citations; Vikram Kumar Jaiswal et al., 2023, A&A, 18 citations; and Vikram Kumar Jaiswal and Bożena Czerny, submitted, A&A).

Overall, the manuscript is polished and coherent, and contributes meaningfully to the study of accretion and in general, cosmology studies. This work is also very timely, taking into account the start of Vera Rubin Observatory's Legacy Survey of Space and Time, a 10-year optical, time-domain survey of the southern sky. The dissertation reads smoothly from chapter to chapter. The dissertation is clearly written, with interesting interjections.

The **first chapter** introduces active galactic nucleus physics and provides readers with all the necessary information about the known physics and geometry of AGNs. It smoothly transitions from

AGN discoveries to all AGN components and unification theory. In this chapter, Mr. Jaiswal includes many schemes that help readers understand the main physical properties of AGNs.

Chapter 2 provides a detailed description of reverberation mapping and outlines a comprehensive methodological framework for interpreting observational data and comparing it with existing and newly developed models. It is well-written and emphasizes the importance of developing this technique. The chapter effectively outlines the objective of Mr. Jaiswal's research and provides essential information explaining why observations, even those performed with the newest and largest telescopes, are inefficient for measuring the geometry of AGN inner structures. Only interferometry can complement the results obtained with the reverberation mapping technique. In my opinion, chapters one and two provide an introduction to the subject and Mr. Jaiswal's work. The simple tests provided by Mr. Jaiswal, such as estimating the aperture size of the telescope or the necessary angular resolution, clearly demonstrate the importance of the topic of this dissertation. Furthermore, the discussion of reverberation mapping in AGNs and the discussion of long-term monitoring surveys are a perfect introduction to the main analysis covered in the dissertation.

Problems with homogenious measurements of the Hubble constant is presented in **Chapter 3**. Beginning with the Hubble tension problem, Mr. Jaiswal walks the reader through various direct and indirect measurement techniques. He briefly explains methods ranging from Cepheid variables and the tip of the red giant branch for low-mass stars to the transformation of supernova Ia luminosity into the Hubble constant, step by step. He then provides brief descriptions of methods based on strong lenses, gravitational wave detections, and CMB probes. This complex topic is briefly described at the beginning of the chapter and provides an introduction to estimating the Hubble constant using reverberation mapping. At the same time, it introduces the modeling continuum of reverberation mapping using different levels of complexity. First, the simple lamp-post model and the spectral energy distribution of the well-studied source, NGC 5548, were used to determine whether this simple model could reproduce the lag spectrum. It was shown that this simple configuration, which creates an accretion-disk response, cannot mimic the observational SED and the lag spectrum. The first approach was then extended in the second step to include the contribution of the broad-line region of AGN using the FRADO framework. The FRADO model considers the physcially motivated clumpy structure of the BLR, which can cause light delays and explain the lag spectrum. This approach more precisely mimics the observed lag spectrum of NGC 5548, though it does not accurately represent the SED spectrum across the entire wavelength range. The second improvement explored was the addition of radiative transfer modeling to include the spectral contribution of the BLR. To accomplish this, Mr. Jaiswal used the CLOUDY photoionization code as well as the hot galaxy starlight model. This physically motivated step allowed him to reproduce both the SED of the source and the lag spectrum.
This detailed description of modeling the SED and lag continuum results in Hubble constant measurements for NGC 5548. The distance luminosity was chosen based on the best fit and was estimated at 74 Mpc. The Hubble constant was estimated at 66.8 km/s Mpc.

In a sense, the introduction to Chapters 2 and 3 summarizes the findings from the articles by the first author presented in the next three chapters. This structure provides the necessary background information to help readers understand the analysis steps and techniques used to obtain the results. Furthermore, Chapter 2 provides a solid rationale for developing a reverberation mapping technique that can be used on a global scale in the era of new optical surveys and interferometric observations.

In the **fourth chapter,** Mr Jaiswal attached the first author paper in which he models time delays in UV/optical continuum, and analyse the wavalenght relation of the delay. In this article a simple lamp-post model was used, with scattering from BLR to simulate real conditions. As it was also presented in

Chapter 3, this approacah is not able to fully mimic the lag continuum and the SED of the physcial source, however this article give a list of potential improvement for future analysis. This artilce, published in 2023, has already 18 citations, and it shows, how important is the work performed by Mr Jaiswal.

The **fifth chapter** consists of the second article by the first author, Mr. Jaiswal. This paper uses models and compares them with the well-known Seyfert 1 galaxy NGC 5548. The selection of this source was based on long-term observations using broadband photometry and spectroscopy, as well as previously performed wavelength-resolved reverberation mapping. This source is an excellent object with which to test different assumptions while modeling time delays. In this article, Mr. Jaiswal tested the FRADO model to mimic the physical properties of the BLR and then estimated the Hubble constant. This work demonstrates the potential of the reverberation mapping technique as an independent method for measuring cosmological distances and sheds light on surveys such as LSST as a potential source for detecting continuum time delays in AGNs with massive black holes. It also shows possible limitations for future LSST survey.

The **sixth chapter** includes the article submitted by the first author, Mr. Jaiswal. The article focuses on the vertically extended corona. In this study, a two-point corona substituted the single corona. The analysis revealed that the one-lamp and two-lamp coronas are indistinguishable from the perspective of the reverberation mapping technique. Although the reverberation mapping technique is powerful, this extensive analysis revealed that it has limited sensitivity and that only highly precise time delay measurements can distinguish the corona’s extension. The results show that the two-lampost configuration corona is not distinguishable by current observations, opening a new field for further analysis.

Comments:

- In my opinion, a brief summary of the work should be included at the end of the thesis. Although a conclusion is included in the abstract, adding one at the end would improve the well-written dissertation.
- Could I ask for additional comments on using this method for new surveys, such as LSST? Could the LSST's time domain be used to constrain AGNs using the reverberation mapping technique to statistically analyze the properties of AGN central engines?
- In Paper 2, Mr. Jaiswal analyzed the source NGC 5548. Could the same analysis be performed on the source mentioned in Paper 1 (Mrk 110)? I am not asking for a full analysis, but rather, if another source could be used to verify the methodology.
- In Paper 3, it is assumed that the radiation is perfectly thermally absorbed by the disk and reprocessed. If some of the radiation is scattered, how much could it influence the results?

minor comment:
introduction: I found it problematic that in Chapter 1 the variables in the equations are often not explained. Since the notation is preserved throughout the dissertation, I think it should be handled more carefully and no variable should be left unexplained.
Paper 1, Fig. 13: what is the difference between red and black lines? It is not obvious from the caption.

IV. Summary

In my opinion, the submitted dissertation provides valuable new input to the fields of reverberation mapping techniques and distance measurements using active galactic nuclei. In conclusion, Mr. Vikram Kumar Jaiswal has achieved the stated aim of his thesis. Based on the theoretical model

and comparisons with well-monitored sources, he has answered the question of whether the reverberation mapping technique, with additional physically motivated models like FRADO and CLOUDY, can mimic the lag continuum and spectral energy distribution (SED) of the analyzed source (NGC 5548). The affirmative answer for a single source is a valuable scientific contribution. The thesis is carefully and interestingly written. Mr. Jaiswal's two first-author scientific articles have been published in international peer-reviewed journals, and despite their recent publication, they are highly cited. The third is already submitted. This fact confirms the high quality of the Ph.D. candidate's scientific work. In my opinion, the candidate has demonstrated the ability to conduct independent scientific research and the knowledge necessary to interpret the results properly.

Therefore I conclude that the presented dissertation meets the formal requirements for PhD theses and recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense.

This is in view of the high scientific value of the results published in excellent journals, the doctoral student's scientific maturity, and his substantial scientific output. Taking this into account, as well as his co-authorship of other works not included in this thesis and his presentation of results at many international conferences, I would like to nominate Mr. Vikram Kumar Jaiswal for distinction.

Prof. dr hab. Katarzyna Małek

I sign with Cencert

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Konkluzja recenzji rozprawy doktorskiej
(Conclusion of dissertation review)

„LIGHT ECHO STUDIES IN ACTIVE GALACTIC NUCLEI AND THEIR APPLICATION FOR DISTANCE MEASUREMENT"

Tytuł rozprawy *(Dissertation title)*: .....

Vikram Kumar Jaiswal

Autor rozprawy *(Author of the dissertation)*: .....

■ Pozytywna ocena *(Positive conclusion)*:

Stwierdzam, że przedstawiona mi do recenzji rozprawa spełnia wszystkie wymagania ustawowe i zwyczajowe stawiane rozprawom doktorskim i wnoszę o dopuszczenie jej do dalszych etapów postępowania doktorskiego, uwzględniając publiczną obronę.

*(I conclude that the presented dissertation meets the formal and customary requirements for doctoral dissertations and I recommend its admission to subsequent stages of the procedure, including the public defense.)**

☐ Ocena negatywna *(negative conclusion)*

Stwierdzam, że przedstawiona mi do recenzji rozprawa nie spełnia wszystkich wymagań ustawowych i zwyczajowych stawianych rozprawom doktorskim i dlatego nie rekomenduję dopuszczenia jej do dalszych etapów postępowania doktorskiego.

*(I conclude that the presented dissertation does not meet the formal and customary requirements for doctoral dissertations and therefore I do not recommend its admission to subsequent stages of the doctoral procedure.)**

Uzasadnienie powyższej oceny znajduje się w raporcie będącym załącznikiem 1.
(The justification of the above assessment can be found in the detailed report in the attachment 1.)

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Data i podpis
(Date and signature)

Załącznik 1: Recenzja rozprawy doktorskiej
(Attachment 1: Review of the dissertation)

I sign with Cencert

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Zaznacz ocenę (Please tick the box with your conclusion)