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Review of the doctoral thesis of
Tathagata Saha
Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences (CAMK PAN)
entitled:
Morphology of Circumnuclear Accreting Gas in Active Galactic Nuclei
supervisor:
Dr. hab. Alex G. Markowitz

The thesis of Tathagata Saha tackles the topic of studies of the physics and morphology of the inner parts of Active Galactic Nuclei (AGN). The Author combines both theoretical and observational expertise to discuss the environment of supermassive black holes (SMBHs) in distant galaxies. The topic is highly relevant and significant, given the recent advancements in technology and the influx of new discoveries that have challenged the existing understanding of this field. This thesis is particularly valuable as it utilizes innovative modelling codes and novel X-ray time-domain data, thus making a significant contribution to the studies on AGN.

The work comprises 138 pages and contains five chapters, including the astrophysical introduction to the topic with the description of methods of studies, followed by two chapters based on articles led by the PhD candidate, published in or submitted to high-profile astrophysical journals, an additional chapter of not yet published work and the final chapter with a summary of all chapters. The presentation and layout of the thesis are very good, with numerous figures and tables.

The introduction Chapter 1 in extent outlines the scientific context of the thesis, introducing the field of AGN studies, including the historical background and the basic physics behind the current models of AGNs. Various types of AGNs are briefly described. This is followed by the introduction to the main topic of the first chapter of the work, namely the gaseous torus of an AGN, where the Author extends the intro contained already in Chapter 1 (which was shrunk to fit the format of the publication). Next, the Author provides an introduction to the topic of temporal variability in Seyfert AGNs, focusing primarily on changing-look AGNs (CLAGNs) as accretion-change events, presenting their observational properties. The final subsection of the introduction on extreme variability events (1.7) leaves the reader unsatisfied, as it would have been a perfect place to describe in a bit more detail the current status of large-scale multi-wavelength time-domain surveys, in particular the optical ones, which there are plenty and their data is being used here, as well as eROSITA, the survey whose data plays an important role in this very thesis.

Chapter 2 includes an article published in MNRAS in 2021, with the PhD candidate as the main Author and two more authors, including the supervisor. The article is a study of the reliability of various theoretical models used for modelling X-ray spectra of AGNs to understand the morphology and emission of the AGN torus. Realistic data of X-ray observatories XMM-Newton and NuSTAR were simulated with known input parameters for the torus. Then, the synthetic data were fit using Bayesian methods to investigate how the input parameters were retrieved and what degeneracies could be seen between the model parameters. The Authors find that most parameters are well recovered, with some exceptions to morphological parameters, which can be measured only with significant error bars.

The paper included in this chapter can serve as a guidebook for the X-ray community and users of various competing torus models with a one-stop-shop comparison of models and a study of their limitations. The Authors also discovered one particular energy band, which is crucial to be part of the input data in order to improve the parameters' recovery. Moreover, it was found that while a single epoch X-ray dataset often leads to incorrect conclusions on Compton-thick obscurers or reflectors, adding more epochs of data can help overcome this problem. These are invaluable findings, useful to the researchers using various models of AGN toruses.

In Figures 3 and 5 the contour for Ecut (high energy cutoff) parameter is truncated at value of 400. I wonder if this is due to the lack of samples in the posterior distribution, or the boundary (listed in Table 1 as 60-500keV) is too close to the input value (400keV) for BORUS and UXCLUMPY. Parameter Ecut is also one of the worst recovered parameters (red point denoting input value is almost at the edge), hence I wonder if the poor recovery is partially induced by the truncation of the parameter space and hence the shift of the median to the lower value. It would also be good to see the contour plot for UXCLUMPY with Ecut input set to 200keV and how was it recovered given the 60-500 keV boundaries.

Chapter 3 includes the second article, which has been submitted to Astronomy and Astrophysics and is already made publicly available via arXiv. This article, in contrast to the first one, is a detailed study of the observational data of a peculiar AGN, LEDA 1154204. The object has exhibited an optical, IR, UV and X-ray flaring event, during which it showed a change in Seyfert type from 1.9 to 1. Studies of such events provide an inside into the physics of accreting supermassive black holes, including the morphology and composition of dusty toruses. In my view, this work connects only weakly to the main topic of the thesis, however, I think it still very nicely complements the thesis with an exciting transient event analysis. It would have been interesting to somehow connect the discoveries of Chapter 2 and apply them to the work done in Chapter 3.

The work in this article is based on a wealth of observational data, including multi-band time-domain photometry (ZTF, NEOWISE, Switf, eROSITA) and spectroscopy, both archival and collected during the event, from a range of instruments. This, naturally, required extended cooperation with observers and experts on the data and the paper is co-authored by a fairly long list of people. It would have been useful if the parts of the analysis performed by the PhD candidate were emphasised and clearly stated, for example in this brief introduction to the chapter, apart from listing the contributions of other Authors in the Introduction Section 1.9. Nevertheless, I assume the role of the PhD candidate was the leading one since he is the lead author of the paper and in my view, this is perfectly fine to fit it in this thesis. Moreover, this paper/chapter contained a great wealth of observational data which required extensive effort to gather and analyze, and this alone is a good reason to include the paper in the thesis.

The wealth of data on the target allowed for extremely comprehensive analysis of its temporal evolution. The optical light curve was fit with a composition of mathematical functions, revealing a slow rise prior to the flare, a sharp 80-day-long flare in 2020 and a possible second flare in 2022. The multi-wavelength photometric data spanning many orders of energies were modelled as SEDs. Individual major lines were modelled with profiles including disklike and Gaussian shapes.

The nature of this flare and variability was discussed throughout the paper and it was found that a Tidal Disruption Event (TDE) can be ruled out due to a different decline slope of the lightcurve, lack of any HeII emission nor Bowen fluorescence in the optical spectra and Seyfert-like photon index of the X-ray spectra. Therefore, the Authors suggest the flare origin is connected with AGN-like accretion and found the Balmer lines can be modelled well with disk-like models, hence conclude the disk instability was the main reason of the changing-look behaviour of the AGN.

SED models were performed with synthetic spectra for two black hole masses, 10^7 and $4x10^8$ MSun, however, the latter value was derived from K-band magnitude of the AGN and BLR Radius-Luminosity-broad line FWHM relations. Both of the methods were noted in Sec.8.4 to have potential issues and the larger value of the mass was assumed to be an overestimation or due to wrong calibration. An order-of-magnitude difference in the mass determination should not be ignored and it would have been good to spend a bit more on investigating this issue. The higher mass could potentially be yet another reason to rule out the TDE scenario (typically not visible when SMBH mass exceeds 10^7 Msun). In SED models, however, in my view the use of two black hole masses was not necessary, moreover, these two models do not differ significantly anyway.

Chapter 4 includes work, which has not yet been published or submitted. A software suite was developed to become a pipeline applicable to eROSITA space mission data, containing X-ray time-series observations of dozens of AGNs. The main goal of the pipeline was to detect line-of-sight obscuration events in AGNs due to changes in column density, which in turn provide information on the morphology of the supermassive black hole environment. Because the spacecraft has remained in standby mode since early 2022, the pipeline could not be tested on real-time data, as envisaged by the Author. Nevertheless, this chapter describes the construction of the pipeline and a study of its expected performance using simulated data.

First, the spectra of eROSITA were simulated, using realistic characteristics of the instrument. The section on Methodology would benefit if more details were provided regarding the simulations of the instrument data, also a comparison with real data would be useful, if available. There were 400 spectra simulated, each for a different level of AGN flux and different obscuration. The hardness ratios of the source were estimated from each simulated spectrum together with error estimation and discussion on the detection limits in case of low flux levels. The detection probability maps were defined.

The results are discussed in section 4.4. Some of the results were moved to Appendix A, however, I think since Chapter 4 is fairly short, it was not necessary and would only require some simple reorganization of the chapter. The detectability of different obscuration levels was discussed as a function of the total flux level of the AGN and the limitations were identified, for example, at 1mCrab, due to the increase of the noise level, it is only possible to detect mildly-obscured states.

The chapter ends with a brief Summary. Generally, the work done in the paper is of high value, however, due to the lack of available real data, it seems incomplete. It is great, on the other hand, that the Author discusses future plans and how this tool can be applied to eROSITA archives and real-time data.

Chapter 5 contains conclusions for each of the main projects included in the thesis. The conclusions are structured in the form of questions and answers, which makes the reading very convenient and interesting.

SUMMARY

Summarising, I think the PhD candidate has done great research work and has performed it very carefully and laboriously. The thesis contains multiple studies on the topic and yields important novel discoveries. The Author demonstrated his proficiency in research through the completion of numerous complex tasks in data handling, astrophysical analysis, modelling, simulating and interpretation throughout the thesis.

In my view, Mr. Tathagata Saha's work meets all the necessary requirements imposed on PhD theses in Poland, and I, therefore, recommend it for further consideration.

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