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Review Report on the PhD thesis submitted to Nicolaus Copernicus Astronomical Center

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Title: **"Photoionization modelling as a density diagnostic of line emitting/absorbing regions in Active Galactic Nuclei"**

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Tek Adhikari submitted the dissertation presenting his studies of photoionized matter which is present in a large range of radii in active galactic nuclei (AGN). In my opinion it was an excellent subject for a PhD thesis, because it allowed the student to learn a broad range of topics covering radiative transfer, atomic and plasma physics as well as astronomical observations with particular emphasis on optical, UV and X-ray spectroscopy. Usually my scientific interest is focused on the "central engine" of AGNs and absorption imprints from the surrounding matter present themselves as an unpleasant obstacle for investigation of the immediate surrounding of the central black hole. Reviewing this thesis gave me a nice opportunity to acquaint myself with current advancements in studies of these important ingredients shaping our view of AGNs. My impression is that works of the Warsaw group, in particular these of Mr Adhikari, represent a crucial contribution to this research area.

The material included in the dissertation (Chapters 4 and 5) has been published in three articles in highly ranked astrophysical journals (Astronomy & Astrophysics and The Astrophysical Journal) and three conference publications. I have not received statements from the co-authors about their contributions, but in all works Mr Adhikari was the first author, so his contribution must have been significant. Also most of the thesis is written in the first-person singular form, so it is immediately clear that these results were actually obtained by the PhD student. Perhaps the only case where this issue is somewhat unclear concerns the solution of the disk atmosphere structure in Chapter 5. Even if this part was done by one of the collaborators, it would not affect the evaluation of this dissertation – the amount of work in the remaining aspects is sufficient.

This PhD thesis consists of 6 main chapters. Lists of abbreviations and symbols are included at the beginning and an extensive bibliography at the end of this dissertation.

Chapter 1, with a concise description of the basic AGN phenomenon and the main components observed through absorption and emission effects, shows that the author has a comprehensive understanding of the astrophysical context of his work.

The photoionization simulations were performed with the use of two numerical codes, CLOUDY and TITAN, which are presented in Chapter 2. In general, this chapter gives a good overview of the advantages of both codes, their usage and the simulated properties which can be compared with observations. As I understand, the PhD student has only used the codes developed by other groups and he did not modify them or implement new physical processes. Then, this part could be a good opportunity to demonstrate an understanding of the underlying physical processes. Although the key equations are presented here, perhaps a slightly more complete descriptions could be expected. For example, how the trends in heating and cooling terms in Figure 2.1 can be explained? What causes the rapid change of these terms at about 5.3×10^{22} cm^{-2} and 9×10^{22} cm^{-2}?

The Compton heating/cooling term given by equation (2.6) is for the non-relativistic approximation. This description (i.e. of thermal equilibrium) was mostly copied from Dumont et al. (2000) so it concerns the TITAN code. What about CLOUDY? Using this approximation with radiation including a significant contribution of hard X-rays or even soft gamma-rays, such as considered in the next chapters, strongly overestimates the Compton heating rate due to the neglect of the Klein-Nishina decline of the cross section. Then, this may be an important issue and I think that this point could be discussed at least qualitatively.

On page 27 there is a reference to "the exponential parts of the curves of growth" shown in Figures 2.2 and 2.3. I do not see any exponential parts (at least in the common sense of an exponential growth), perhaps the author meant the saturated/flattened parts.

Chapter 3 presents some unpublished studies of the dependence of photoionized emission on density. This important effect was pointed out in the previous work of Różańska et al. (2008). Here Mr. Adhikari shows how it affects some detailed properties, e.g. the location of ionization fronts or thermal instability zones. Computations are performed for a specific spectral energy distribution (SED) of Mrk 509 reported by Kaastra et al. (2011). However, the SED shown in Figure 3.1 extends up to 1 MeV, whereas the SED measurements reported in table 2 of Kaastra et al. (2011), and shown on their figure 3, extends only up to 160 keV. The author can explain during the oral defense if it is only a plotting error or if this extraneous radiation was included in computations. Even if it was the latter case, the SED is dominated the UV bump so the results should not be strongly affected (although results in Chapter 4 indicate some dependence on details of X-ray emission for cases with an even stronger domination by the UV component).

Chapter 4 contains analysis of the absorption measure distribution (AMD), which is used for observational estimations of the distribution of the column density in the plasma as a function of ionization parameter. First, the author considers the SED of Mrk 509, using the

TITAN code computes the theoretical AMDs and compares them with the AMD found from observations of this AGN. Interestingly, some theoretical models reproduce very well the shape of the observed AMD, however, they strongly overpredict the normalization.

Then, various model SEDs are used to investigate how their shape affects the thermal and ionization structures and the resulting AMD. The theoretical SEDs are parametrized by the X-ray spectral index (some cut-off energy must also have been assumed, which is not explained), the disk and X-ray luminosities and the black hole spin and accretion rate parameters. The last two parameters have not been defined (at least the latter has various definitions in literature, including or not the radiative efficiency). These parameters are used to find the spectrum of thermal disk emission and I assume that the Novikov & Thorne formula was used, but it is not explained in the thesis. Two groups of SEDs – type A dominated by the UV bump, and type B with similar X-ray and UV luminosities – are then compared to illustrate that only case A predicts the AMDs with the shapes (characterized by location of features related with thermal instabilities) and normalizations similar to those observed. The total luminosities of cases A and B differ by almost two orders of magnitude and it is not clear how strongly this effect contributes to the difference in AMDs. The author states that he performed a much larger number of simulations and presents only some cases, chosen for illustration purposes, so perhaps his choice was guided by his understanding that the spectral shape is more important than the total luminosity (but it should have been noted).

In Figures 4.9 and 4.10 we see that the temperature distribution and corresponding AMDs show significant dependence on the X-ray spectral slope even in case A, i.e. with a strong domination of the thermal disk component. It would be interesting to have some deeper discussion of the involved physical mechanism. E.g., changes in the number of "the sudden temperature drops" are noted on page 63. What causes these changes? And, in the first place, why do these drops occur? Are these questions too trivial for photoionization experts or too difficult to be answered? In either case, a related note would be valuable for a reader.

The theoretical AMD of case A is compared with the AMDs observed in six AGNs in Figure 4.22 and a good agreement is seen for ionization parameters within the range of applicability of TITAN. My critical comment here is that the SEDs of these AGNs are roughly known, so we can check if they are indeed consistent with case A. For example the SED of one of these six AGNs, i.e. NGC 5548, is shown in Figure 5.1 and we can clearly see that it is of type B rather than A.

Then, although the author obtained some interesting results in modeling the ionization structure and its comparison with observations, it seems that the cases of both Mrk 509 and NGC 5548 demonstrate that some important effect is still missing in our understanding of these properties.

Chapter 5 is focused on the study of conditions for the appearance of the intermediate line emission region (ILR), in addition to BLR and NLR, in some AGNs. First, the author uses SEDs measured in objects belonging to different classes of AGNs to investigate if the ILR can be related with the spectral shape. Some assumptions implicitly made here appear rather risky to me, e.g. the SED of a NLSy 1 galaxy with the high-energy part extrapolated to the LAT measurement in gamma-rays is likely produced in the jet and then it is unlikely to represent the nuclear photoionizing radiation. Also I am not convinced that scaling of the SED of a LINER to the total luminosity of 10^{45} erg/s is justified, as LINERs are observed at much lower luminosities. However, these estimates lead to the final conclusion that the broad band spectrum does not determine the presence or absence of the ILR, so these shortcomings are not particularly important.

Then, the author shows that he can explain the presence of the ILR by using the density two orders of magnitude larger than that in computations by Netzer & Laor (1993), were the absence of ILR was originally explained. The author shows that such high density profiles can be explained if the ionized clouds are formed in the disk atmosphere. For this, the atmosphere structure equations are solved, but they are not presented in the dissertation. The term "disk-like profile" appears somewhat misleading to me as it implies that the density profile is similar to that of the disk, whereas it is very different. Perhaps "coronal" or "disk-atmosphere profile" could be used. In this part the actual luminosities (i.e. not scaled to 10^{45} erg/s) were taken onto account. It allowed to show that some ILR emission can be expected at low luminosities of LINER objects, for which the dust sublimation radius is small.

Chapter 6 contains a short summary of the obtained results. I think that the author should emphasize more clearly that his estimation of the wind location in Mrk 509 is model-dependent and the model does not precisely reproduce the observed features. Furthermore, while demonstration that ILR can be seen in some circumstances is very interesting, we still do not understand why it occurs only in some AGNs, which could also be noted here.

My minor comments:

There are some vague statements at least for people not actively working in photoionization simulations, e.g. "The preliminary photoionization simulations of gas illuminated by radiation field have shown ... " without any reference at the beginning of Chapter 3.

$\dot{m}$ is not defined and it is incorrectly referred to as "mass accretion rate" on page 60 and "Eddington ratio" in the symbol list → "Eddington-scaled accretion rate" or "dimensionless accretion rate"

Q_H is not defined (specifically, page 20: integrating over which quantity?) and referred to as (i) dimensionless in the symbol list, (ii) "per second" on page 20.

Some typing errors (I found more):

Page 22: $\Delta r/r \geq 3$ → $\Delta r/r \geq 0.3$

Page 25: tempreature → temperature

Page 31: "region is AGNs" → "region in AGNs"

"RPC" is used since page 40, defined on page 59, and not included in the list of abbreviations

Page 80: "band function" → "Band function"

Page 115: parentheses incorrectly used in a citation in third paragraph

Page 123: aap → A&A

Summary

In my opinion, the reviewed doctoral thesis represents a significant amount of work at a high scientific level. The conclusions about the effects of the luminosity and density on the appearance of ILR and about the possible relation of the latter factor with properties of disk atmospheres as well as the assessed impact of the spectral shape and the density on AMD, certainly extend our knowledge of photoionized plasmas in AGNs. My critical comments mostly concern the presentation of the results and do not undermine their scientific value. I am convinced that the PhD candidate has a solid understanding of his research area.

I declare that the dissertation fulfills all requirements posed on theses aimed for obtaining PhD degree (art. 13 of the Polish Act on academic degrees and academic title) and I recommend it for the public defense.

Łódź, 10 czerwca 2018