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Report on the Ph.D. thesis "Photoionization modelling as a density diagnostic of line emitting/absorbing regions in Active Galactic Nuclei", by Mr. T.P.Adhikari

I am pleased to provide my report on the aforementioned Ph.D. thesis. It represents an important and timely work, addressing important questions on the nature of the physical processes underpinning two of the basic characteristics of our structure model in the innermost region of Active Galactic Nuclei (AGN): ionized outflows and emission line regions. The goal of the thesis is not only important *per se*. Its results describe novel, physically-based methods to estimate the density of the astrophysical plasma surrounding the AGN. Should these methods be thoroughly calibrated by systematic comparison with future observations (of which the thesis provides already some promising examples), they may allow to provide observational constraints on the launch radius of ionized outflows, and therefore on the mass load and kinetic energy outflow rates. In turn, these quantities are crucial to estimate if these outflows have a significant feed-back impact on on the star formation and the metal enrichment in the interstellar medium of the host galaxy - one of the most pressing questions of modern astrophysics. These wide-ranging implications make the thesis's results only more valuable, even if the reviewer believes that they are not adequately stressed in the thesis.

The thesis shows an outstanding mastering of the astrophysical concepts underlying the physics of photoionized plasma, and of the usage of the main codes currently available to simulate their physical conditions (CLOUDY and TITAN). Mr. Adhikari shows in his thesis to have skilfully acquired this know-how. This constitutes a solid intellectual basis on which he can pursue his future development as a researcher.

I particularly commend the structure of the thesis, and the way he introduces the reader to understanding the physical basis of his research work.

Chapter 1 provides a broad introduction to the astrophysical of Active Galactic Nuclei (AGN). The presentation follows the traditional classification in radio-loud and radio-quiet objects, and the underlying interpretation of the variety of the AGN phenomenology in terms of orientation effects against an azimuthally-symmetric obscuring structure. While a few inaccuracies are present (see the last Section of this report), the presentation of the observational scenario is clear and useful. This Chapter allows also him to present the general properties of the gaseous regions in the AGN environment that are the main subject of the thesis: the Broad (BLR) and Narrow Line Region (NLR), as well as the elusive Intermediate Line Region (ILR).

Chapter 2 and **3** present the basic context of his research: the physics of photoionized nebulae. In Chapter 2 the main diagnostic tools underpinning the results in Chapter 4 are presented: the stability curve, and the

Absorption Measured Distribution (AMD). Chapter 3 shows a detailed comparison between the two main concurrent scenarios being used in the literature to simulate ionized outflows in AGN, the Constant Density (CD), and the Constant Pressure (CP). The former scenario represents the current mainstream paradigm (due to the relatively simpler ways it offers to observers to calculate its predictions and compare them with observations). The latter one is gaining recently more and more support, however. Mr. Adhikari's recent papers have been crucial in this paradigm's shift.

The results shown in **Chapter 4** of his thesis represent the first successful attempt of providing a comprehensive explanation of the observed AMD in AGN outflows. Some of these results have been published in Adhikari et al., 2016, ApJ, 815, 83. In the thesis the calculated AMD is compared to the nearby Seyfert Galaxy Mkn509 and a sample of six nearby Seyfert Galaxies (the "Behar's sample" thereafter). In both cases the observed AMD was extracted from high-quality high-resolution X-ray spectroscopic data. The AMD in Mkn509 is characterized by two deep minima and an overall normalization $\sim 10^{21}$ cm^{-2} for $\xi \sim 800$ erg cm s^{-1}, while the AMD in the Behar's sample exhibits a single minimum with an overall normalization about one order-of-magnitude higher. Both these cases can be reproduced by the models calculated in the thesis, even if the lower normalization in the former case remains challenging. These results go well beyond any prior attempts published in the literature, that were restricted to reproduce the overall power-law shape of the AMD. Furthermore, as Mr. Adhikari rightfully stresses in his thesis, his results have a more general bearing than those obtained hitherto using the Radiation Pressure Confinement (RPC) models because: a) the RPC model is just a special case of the CP scenario; b) Mr. Adhikari succeeds in reproducing not only the general shape of the AMD, but also subtle features thereof that had escaped full understanding so far. Furthermore, he explores how these localized features depends on a wide range of parameters (e.g. density and ionization parameter at the AGN-closest surface of the cloud, AGN Spectral Energy Distribution). This enables him to employ his results as a powerful tool to estimate the density of the gas.

The comparison with the observed AMD in Mkn509 (Fig.4.4) assumes an electron density of 10^{8} cm^{-3}. As shown in Fig.4.19, reducing further the density may yield models with an even lower normalization, and could help reconciling the existing normalization discrepancy. The reason why models with lower density were not explored and compared to the data is not explained in the thesis. Therefore, the thesis leaves open a further parameter space that could (and should) be investigated in future work. Another interesting aspect that I would recommend Mr. Adhikari to cover in future work is the comparison between the spectral prediction of the CP model (cf. Fig.4.5, right-bottom panel) and the properties of the Ultra Fast Outflow (UFO) detected by Tombesi et al. (2011, ApJ, 742, 44) in Mkn509.

Equally interesting is the comparison with the observed AMD in the "Behar's sample" (Fig.4.22). We stress once again the main novelty of the thesis: the results presented in this Section represent the first successful attempt to fit the overall shape of the AMD *as well as* the deep localized feature "dip" in the AMD distribution at $\xi \sim 10$ erg cm s^{-1}. This first encouraging result indicates also the direction of possible future refinements of the model. At the dip the model fits very well the NGC7469 data, but still exceeds the two lowest upper limits (MCG-6-30-15 and NGC5548). Other solutions could and should be explored, such as, *e.g.,* lower densities than assumed in the model applied to the data in Fig.4.22 (10^{12} cm^{-3}). Exploring a wider parameter space is also important to check a potentially important inference of these results. The best-fit density allows in principle to resolve the degeneracy with the distance between the source of ionizing continuum and the innermost nebular surface. This allows Mr. Adhikari to provide in his thesis an estimate of the launching radius of the ionized outflows. However, his estimate ($\sim 10^{15}$ cm) is much lower than typically associated to "warm absorbers". This is a potential issue, both form the theoretical point of view (stability of the outflowing clouds), and because it disagrees with other independent experimental estimates. This potential issue could be alleviated if lower density solutions would be consistent with the data. Another possible future improvement is calculating a source- (i.e. SED-) dependent AMD for each of the sources of the "Behar's sample".

Section 4 discusses extensively the dependence of the AMD on the AGN Spectral Energy Distributions (SEDs). The thesis explores two possible SED shapes. The so called "SED A" represents a typical Seyfert-like object similar to those on which experimental AMDs have been determined so far. "SED B" represents instead a low-luminosity AGN with accretion rate (in Eddington units) of $\sim 10^{-3}$, and high black hole spin (0.9). It is an important consistency check that the "SED B" AMDs disagrees with the observed AMDs (discussion at Pag.64 and Pag.65). "SED A", instead, leads to AMDs in agreement with observations. This is a first promising result that should be pursued further. Extending this study to "SED A"s corresponding to higher black hole spins (as typically measured in Seyfert X-ray spectroscopic observations) or closer-to-Eddington accretion rates (as expected in Narrow Line Seyfert Galaxies) would be an interesting extension of this work. In this context the reviewer is compelled to mention a potential issue with the calculation of the SEDs. The normalization of the "SED A" and "SED B" power-law components differ even if they correspond to the same X-ray luminosity and to the same range in photon index. The issue could be related to an inadequate definition of the energy range where the X-ray luminosity is estimated. Furthermore, is it really the "X-ray luminosity" the important parameter in this context? Shouldn't instead the luminosity associated to the power-law component to be used as the definition parameter for the high-energy part of the SED?

Chapter 5 (subject of two publications on refereed journals: Adhikari et al., 2016, ApJ, 831, 68; 2018, ApJ, 856, 78) revises a 25-year old problem that had found no clear solution so far: why does an apparent gap exist in the gas distribution between the BLR (sub-pc scale, high-density) and the NLR (pc-scale, low-density, related to the optical ionization cone)? This question is timely, due to the growing recent evidence of emission related to an intermediate region (ILR). The thesis shows that this issue can be solved by considering solutions of the radiation transfer across the gas structure in the AGN environment with a higher density than originally postulated by Netzer & Laor in 1993. This decreases the size of the ionization front in the ionized clouds (as shown in Chapter 3), reducing the effect of dust extinction on the emission lines. It is a quite elegant solution, that Mr. Adhikari explores thoroughly. Moreover, this solution allows him also to explain the separation of the BLR into a Low- and a High-Ionization Line gas, as well as the lower detection likelihood of ILR lines in low-luminosity AGN due to the flatter line emissivity profiles. Albeit elegant, however, this solution is affected by some potential shortcomings, the most important thereof, in the reviewer's opinion, is the difficulty in reproducing the [OIII] line luminosity when a physically-motivated disk-line density profile is assumed. This profile (see Fig.5.17) exceeds the critical density of the Narrow Line Region (10^8 cm^{-3}). These issues shall be addressed in future work. A possibility is considering a steeper density profile beyond the dust sublimation radius, constrained by the NLR astrophysics and based on the experimental evidence of a steeper-than-liner density profile of the NLR gas coming from spatially-resolved optical spectroscopy.

As far as the ILR emission is concerned, comparing the predictions of the line emissivity profile with reverberation mapping results is an important contribution of the thesis. For NGC5548, for instance – an AGN subject to one of the most extensive reverberation mapping campaigns – the derived line emissivity profiles show peaks coincident with the reverberation mapping measurements. Differences are still present, though: *e.g.*, the MgII profile is increasing up to $\sim 10^3$ light-days compared to a typical reverberation size ≤ 70

days; the Hβ profile in the model peaks at about 200 light-days, compared to a typical reverberation size about one order-of-magnitude smaller.

Main highlight of the thesis

- It is an important and timely thesis, addressing important questions on the structure model in the innermost region of AGN
- Its structure is straight and clear, the text is well written, the references are accurate and adequate
- It shows an outstanding mastering of the astrophysical concepts underlying the physics of photoionized plasma, and of the usage of the main codes currently available to simulate their physical conditions
- The results therein discussed have been crucial in enabling a – still continuing - paradigm shift in our understanding of the physics of ionized outflows in AGN. Mr. Adhakari has been a key player in this field of research in the last few years
- The modelling of the AMD in nearby Seyfert therein discussed is the first fully successful attempt at explaining all its features in a consistent interpretative scenario
- It describes an unprecedentedly extensive study of the dependence of the AMD on different physical (density and ionization parameter boundary conditions) and astrophysical (SED) conditions
- Its Sect.5 describe a novel solution to the physical origin of the "emission gap" between BLR and NLR – a 25 years old problem recently brought back to the attention of the science community by new experimental results on the ILR gas

Main issues with the thesis

- A few inaccuracies in the description of the AGN phenomenology are present in Chapter 1 (see some examples in the last Section of this report)
- The choice of model basic parameters (most notably, the density) does not always seem to be optimized to fit the observational data (see, *e.g.*, Fig.4.4 and Fig.4.22). The reviewer finds that a wide parameter space should have been explored or, if it was explored, described in more details in the text
- It does not discuss the comparison between AMD spectral predictions and literature results on the Mkn509 UFO (Sect.4.1.2)
- The disk-like density profile is inconsistent with the critical density constraint on the NLR (Sect.5.4), and the predicted [OIII] is too low. This casts some shadows on the self-consistency of the ILR modeling in this scenario
- The comparison between the line emissivity profile and the reverberation mapping results in NGC5548 requires a more careful assessment (Sect.5.4.2)

Minor/editorial issues

I list below a few suggestions on the presentations of the results in the thesis:

Pag.3: The definition of Narrow Line Seyfert Galaxies provided here is too qualitative, and does not take into account that these objects are defined not only on the basis of the width of their optical lines, but also on the basis of their strength and diagnostic ratio, e.g. the FeII and the [OIII] vs. H-beta

Pag.3: In the discussion of Radio-loud AGN, radio galaxies are incorrectly included among those objects where the jet points to the direction of the observers

Pag.4: The radio emission in radio-loud objects can come from "much larger [N.d.R: than what?] regions", as well as from the base of the jet, a few Gravitational Radii from the black hole

Pag.6, "*This is mostly ... the electron recoil*": I am not sure this explanation is complete. The presence of the high-energy cut-off is related to the Maxwellian thermal distribution of the relativistic electron responsible for the Comptonization

Pag.21, "*the density is ... the increasing order.*". I am not sure I understand this sentence. From the context, I guess the Mr. Adhikari means something along these lines: "The density increases when going deeper into the cloud."

Pag.26, *Eq. 2.15*: I assume that this equation refers to the calculation of the AMD based on observations. As discussed at Pag.54, this equation describes how for each ion a pair [N_H,ξ] is calculated. From an observed spectrum, a set of a few tens of these pairs can be calculated. It remains to be explained how from such a sparse set of data points the AMD function, entailing the derivative of the N_H vs. ξ function, can be calculated

Pag.28: in referring to the Laha et al. (2014) paper it may be worth stressing that this paper analysed the largest sample of AGN in the nearby Universe with available high-resolution X-ray spectra

Pag.79, "*The change of ... to dust sublimation*". I am not sure I understand this sentence. Perhaps Mr. Adhikari meant something along these lines: "... due to metals being locked in dust grains."

Pag.89: "rare" -> "rarefied"

Pag.105, "*In these type ... types of AGN.".* I am not sure I understand this sentence. Does Mr. Adhikari mean something along these lines: "The emissivity profile in Seyfert Galaxies is flat, while in LINER decreases with radius. It should be therefore comparatively more difficult to detected ILR in LINERs."

Summary

Overall, I consider Mr. Adhikari thesis excellent. It addresses important questions in modern astrophysics. In dealing thoroughly with them, it shows all the qualities of a mature researcher with a tremendous potential. Mr. Adhikari's research work has already had an important impact on the scientific community interested in AGN ejection phenomena and in "AGN feedback". The dissertation meets the formal requirements made to the PhD theses. Hence, I am requesting the admission of Mr. T.A.Adhikari to the subsequent stages of the procedure, including the public defence. I would also like to propose to award Mr. Adhikari's doctoral thesis with distinction due to the following aspects: scientific novelty, extensive research on a highly timely topic, good quality of the work, and a good number of first-author publications.

Faithfully,

European Space Agency
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