Haifa, 24/05/2023

Re: Review of the Ph.D. thesis of Mr. Mohammad Hassan Naddaf

Dear Members of the Scientific Council,

Below please find my assessment of the doctoral dissertation entitled "*Simulation of the Dynamics and Geometry of the Broad-Line Region in Active Galactic Nuclei*" by Mr. Mohammad Hassan Naddaf. To summarize, the dissertation, relying on published papers in leading journals in the field, constitute in my view an outstanding body of work, which significantly adds to our knowledge in the field of active galactic nuclei (AGN). Moreover, it provides a promising platform for further work, which would significantly contribute to the physical interpretation of upcoming datasets, as elaborated below.

Dissertation context

AGN are of great interest to (astro-)physical research as they are the means by which supermassive black-holes (SMBHs) may be identified out to cosmological distances, and their physics probed. The accompanying broad-line emission, which is a defining feature of (type-I) AGN, ties to two fundamental challenges in astrophysics: understanding the means by which SMBH form and grow, and revealing the geometry of our universe. Specifically, broad-line emission phenomenology in AGN is at the heart of SMBH mass estimation techniques, from which the cosmic SMBH census is derived. This, in turn, reflects on how SMBH grow over cosmological times, presumably by a combination of material accretion and merging with other black holes, with implications for structure formation and evolution, as well as for gravitational-wave detection in the LISA era. Further, with the discovery that the size of the broad-line region (BLR) scales with the AGN luminosity, the possibility of using AGN as cosmological rulers emerges. This is a particularly fascinating possibility as AGN can be viewed out to much larger distances than many other cosmological probes, and may add an independent cosmological measure, which is highly desirable given e.g. the lingering Hubble tension. Our ability to materialize the aforementioned science hinges upon our physical understanding of the BLR in AGN, which is currently phenomenological.

A significant challenge in the field of BLR study lies in the fact that the physics of the BLR ties together (magneto-)hydrodynamics, radiation transfer, and photoionization physics of dilute plasma near sources of intense radiation. The full solution is beyond the reach of current models since the range of characteristic timescales is huge, as is the density contrast in the medium (many orders of magnitude across). Also, the initial and boundary conditions of the problem (e.g. the magnetic field topology, and the gas origin and composition) are poorly known. It is therefore often the case that models in the field resort to a cartoonish modeling of the BLR, which is oversimplified and far from being realistic. Specifically, the BLR dynamics is at best phenomenologically modeled with little to no predictive power. The dissertation work of Mr. Naddaf is an important step in the right direction.

General impression

Originality: This dissertation work provides a first stab at a more comprehensive, kinematically sound treatment of one of the leading BLR models — the Failed Radiatively Accelerated Dusty Outflow (FRADO) model — aiming to shed light on BLR phenomenology in AGN of different properties (black hole mass, Eddington rate, material composition). While the exact general solution of the problem must tie the gas microphysics to its kinematics in a self-consistent way, this thesis' work is able to provide a smart effective prescription for the gas microphysics and kinematics, which reveals novel features of the FRADO model. The results seem to resonate with recent observational findings in the field, thereby providing a promising modeling platform for future study. The papers comprising this dissertation have been published in leading journals, attesting to their originality, and have been well received by the community given the number of citations since their publication.

Knowledge of the field: The thesis refers to much of the published work relevant to it (BLR phenomenology and modeling, as well as dust physics, and outflow physics) encompassing decades of research. In particular, it refers to historical works from the early days of AGN research to more contemporary work, highlighting the most recent findings, which reveal, for the first time, physical trends amidst the statistical noise. This leads me to conclude that the candidate has good command of the literature in the field.

Scientific independence: The thesis consists of published papers in leading journals in the field, in which the candidate is the leading author. All the papers are co-authored with his Ph.D. advisor, and two of which with a third co-author. From the appended declarations made by the co-authors, the contribution of Mr. Naddaf was pivotal and by far overwhelming to all three publications thereby attesting to his scientific independence.

Review of the results

The thesis provides a platform to explore some phenomenological aspects of the broad-line phenomenon in AGN — notably, kinematics and geometry — and their dependence on various attributes of the system, such as SMBH mass, Eddington rate, and gas composition, all of which have been assessed for a large sample of sources across a wide redshift range. With the advent in observational capabilities (e.g. high quality multi-epoch spectroscopy for numerous sources) the predictions from this work are of great interest to the community, whose physical interpretation is currently rather limited. Nevertheless, it is also clear that more meaningful predictions must also address the gas microphysics, which is currently largely ignored. Only then will it be possible to properly assess the model observables, such as emission-line spectrum, and the effective emission region size, and hence properly constrain the model. This is by no means a criticism of the submitted work, but rather a natural course for future work.

Below I summarize each of the chapters (papers) constituting this thesis' work, and some of my related musings.

Paper I: This paper provides a comprehensive outline of the BLR-model underpinnings. Existing literature is well covered, the model assumptions and formalism are clearly detailed, and the results comprehensively outlined. In a nutshell, the BLR geometry and kinematics within a more quantitative FRADO model are discussed as a function of key parameters (AGN and gas attributes, as well as shielding prescription). It is concluded that the BLR dynamics is heavily influenced by the Eddington rate, which could explain some recent findings in the field, and may have implications for the mass outflow rate from the outer accretion disk. Further, it implies a rather intricate structure of the velocity-resolved transfer function in those objects, which should be testable by state-of-the-art (e.g. STORM-like) datasets.

I agree with the notion of shielding promoted in this study, although the justification for it, which derives from Murray et al. (1995), is questionable; specifically, when a confining agent is present, over-ionization may be mitigated even in the absence of shielding. Generally, I am concerned about the efficiency of line emission in the model, and whether it can account for the observed line intensities, especially in low luminosity sources. For example, the total covering factor of clouds in the FRADO model, especially at low Eddington ratios, appears to be quite small (e.g. Fig. 7). Would the clouds intercept enough of the ionizing radiation and efficiently convert it to line emission? This issue is exacerbated by a) the dust content of the medium which competes with the gas over ionizing photons given the implied column densities, and b) the high inclination angles deduced in this work with respect to the inner disk (I note that some of these issues are alluded to in paper III). Further, the rationale behind the prescription used to assess the effective size of the emitting BLR in the model is unclear to me, nor is it clear that it is consistent between the papers/chapters of this thesis. Concerning the FRADO kinematics in the inner region, I'm wondering whether dust (re)formation could take place and be dynamically important for the inner clouds trajectories thereby leading to a non-failed configuration at small radii [see the inner trajectory in Fig. 3 whose height beyond the peak, $z(r)<S(r)$]. For the sake of completeness, I was missing some discussion, however brief, of the effect of the disk's self-gravity, which appears to be relevant given the range of cloud-ejection radii for the LIL-BLR.

Paper II: This paper provides an elaborate treatment of shielding and quantifies its effect on the BLR kinematics. It is shown that high-Eddington rate sources must be characterized by heavier levels of shielding, which could explain their measured BLR sizes with respect to those of the general population. I was missing a brief mention of how such an increased level of shielding might come about. As noted before, it is unclear to me whether the prescription used to assess the effective BLR radius of the simulations (given the lack of atomic physics in the model) is robust, and consistent across the chapters (papers) comprising this thesis' work. I note in passing that some of the text is unclear (e.g. referring to a model as being "too strong" in the sentence "Interestingly, while the Patch model… was too strong,…."). I also note that the notion of line driving of the high-ionization line (HIL) dust-free BLR gas has been alluded to several times in the text (e.g. in the conclusions section of this paper), and yet the importance of continuum driving (e.g. by bound-free processes) is not mentioned. This has been shown to be important when the optical depth in the lines (per unit thermal width) is considerable as may be the case here (Chelouche & Netzer 2001 for highly ionized gas). I am also missing a cautionary comment in the text stating that the actual BLR size, which is emissivity weighted, requires better knowledge of the gas properties (e.g. density structure) and photoionization physics.

Paper III: This paper provides detailed predictions of emission-line profiles for a range of object properties and gas compositions. An interesting conclusion is that much of the ionizing illumination of the clouds in the FRADO model must be indirect, possibly resulting from photons being scattered by an optically thin medium (is this enough to explain the flux in the LILs? I'm not sure). The model further suggests that clouds farther away are largely shielded from the scattered ionizing radiation. I am therefore wondering whether *a)* the equivalent width of the emission line in the RMS spectrum of quasars in this model is expected to be comparable to that measured in the mean spectrum (after host subtraction), and if *b)* the scattered UV emission, which is strong enough to boost line emission from the clouds, could also lead to further dynamical changes in the FRADO model via dust sublimation. Related to the above, I am also wondering what the required mass loss rate might be to effectively shield the rest of the BLR that lie at $z(r)<S(r)$ in region II (see Fig. 1) from the scattered radiation. Further, if scattering of the ionizing (EUV,UV) flux is indeed efficient then the UV signal reaching the observer will be a combination of direct and scattered flux. What would the implications be for the observed continuum variability across the UV-optical bands, and is this consistent with observations (e.g. interband time-delays, and the shape of the RMS spectrum)? Lastly, the author suggests the existence of a pressure equilibrium between the clouds and an intercloud medium, and I am left wondering whether this implies very significant columns of hot ionized medium, which could lead to significant continuum scattering with implications for the polarized signal from AGN (e.g. IXPE data).

Forthcoming work: some further work is outlined, specifically in relation to the formation of broad absorption line outflows in quasars. I am wondering whether such a model might be relevant given the fact that recent estimates for the location of the majority of these absorbers hover around 0.1-1kpc scales away from the central source. While it is possible that a two step mechanism is involved (compact wind ejection that subsequently impacts larger scale material à la the Faucher-Giguere et al. models), a single-step mechanism, wherein the clouds seen on large scales originate from accretion-disk scales and survive as coherent entities out to large scales seems less likely.

Personally, I would be very interested to see how the model extends to cases in which luminosity variations of the source can no longer be considered as small perturbations in the source parameters (changing-look AGN). Could such objects shed further light on the FRADO model for the BLR?

Summary

Summing up, I consider the doctoral thesis of Mr. Mohammad Naddaf to be a valuable contribution to the field, and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Sincerely,

Doron Chelouche

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