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Candidate: mgr Maitrayee Gupta
PhD title: Comparison of AGN properties in luminous radio galaxies to their radio-quiet counterparts
Institution: CAMK
Supervisor: prof. Marek Sikora

PhD Thesis evaluation report

The PhD Thesis of mgr Maitrayee Gupta has been prepared consistently with the current law regulations. The Thesis consists of the Introduction, and three already published papers which appeared in the highly appreciated refereed journal *Monthly Notices of the Royal Astronomical Society*:

I. *Covering factors of the dusty obscurers in radio-loud and radio-quiet quasars*, M. Gupta, M. Sikora, K. Nalewajko
II. *Comparison of hard X-ray spectra of luminous radio galaxies and their radio-quiet counterparts*, M. Gupta, M. Sikora, K. Rusinek, G.M. Madejski
III. *Comparison of SEDs of very massive radio-loud and radio-quiet AGN*, M. Gupta, M. Sikora, K. Rusinek.

In all three papers mgr Gupta is the first author, and her contribution to all the papers has been dominating, accounting to 75 %, 60%, and 70 %, according to the statements of the co-authors. Therefore, the presented publications can certainly be considered as the achievements of the PhD candidate.

The Introduction presents the general scientific background as well as the short summary of the three publications. The Introduction is compact, but summarizes well the basic facts about active galaxies, the zoo of the classification schemes, and contains up to date references illustrating the current knowledge. Minor grammatical issues or the discussion of the figures not quite in the usual order (e.g. Fig. 1.2 is described before Fig. 1.1) do not pose a problem. This short presentation is complete, including the proper discussion of the geometry of the components, and the viscosity mechanism in the cold Keplerian disk. This part contains extensive bibliography (160 positions) which shows that mgr Gupta has a broad overview of the AGN literature. Section 1.5 gives additional details about the methodology (e.g. RL-RQ source matching, black hole mass determination etc.) which were not covered in such details in the published papers. This is an interesting supplement. In subsection 1.5.4 the author discusses a small error in derivation of the bolometric luminosity in the published version of Paper III. This error is not important since the incorrect definition was used both for RL and RQ objects, the error is small, and the estimate of Lbol is approximate anyway. There is also an error in the SED plots in Paper III, according to the Erratum published in MNRAS (as *Gupta et al, 2020, MNRAS, 499, 4024*), which somehow was not mentioned in the Introduction; indeed, the plotted hard X-ray spectra are too hard, but their normalizations were reproduced properly, so the conclusions do not depend on this problem. Also in the Introduction (page 14) and in the Abstract mgr Gupta mentions that the reflection fraction in RL and RQ sources were the same (Paper II) while in the published Paper II the authors argue that they are **significantly different - lower in RL** (Fig. 10 in Paper II and page 2869, left column). This is confusing. Further I assume that the statement from Paper II is correct, as the Introduction only plays a role of the supplementary material, not being the subject of evaluation.

The ambitious aim of the Thesis was to solve the most important problem of the AGN science - the physical nature of the radio-quiet (RQ) and radio-loud (RL) dichotomy and find strong arguments for the choice of the specific jet formation mechanism out of those proposed in the literature. These mechanisms, as stated in the Introduction are based either on Blandford-Payne magnetic wind, or Blandford-Znajek extraction of energy from the spinning black hole. Mgr Gupta approaches the issue through search for intrinsic differences between the radio-quiet and radio-loud objects which might shed light on this issue.

Apparently similar studies were performed before by many authors, but the first two papers differ from previous studies in a very careful matching between the RL and RQ sources. Earlier studies, which did not make such matching, claimed systematic differences between the broad band SED shapes, including X-ray slopes which created an impression that in RL objects additional jet contamination was present, leading to harder spectra. Mgr Gupta selected a sample of RL AGN, and then using much larger sample of RQ AGN choose for each RL object a corresponding (one or more) RQ counterpart matching the RL object relatively closely in the mass, Eddington radio and redshift. This approach, at the expense of reducing the size of the RQ sample removed the usual bias caused by RL objects having on average much larger masses and much lower Eddington ratios. The final sample is large, contains close to 800 FR II galaxies and the corresponding RQ counterparts.

The results of this approach are remarkable. In Paper I mgr Gupta showed that the outer boundary conditions seem to be the same in both types of objects. She measured the covering factor by the dusty/molecular torus through determination of the ratio of the IR to bolometric luminosity, which probed the conditions at a parsec scale, and derived the median value of the covering factor of 0.28 for RQ, and 0.32 for RL, and the difference is even much smaller (0.094 only) in the high Eddington ratio bin. This conclusion points towards the determination of the object radio loudness right close to the black hole, instead of imprinting it by the systematic differences in the AGN surrounding. If strong large scale magnetic field is the key element of the radio-loudness, it would also affect the torus which is most likely a from of a wind. Thus the Paper I favors the Blandford-Zajek mechanism. Additionally, Mgr Gupta finds no clear trends with redshift which implies no evolution of AGN torus, and, even more surprisingly, no dependence on the Eddington ratio. This last conclusion implies that the torus is not radiatively supported by the central source. There are numerous claims in the literature of the strong dependence of the covering factor on the bolometric luminosity (e.g. Hazinger 2008) but that might be caused by inclusion of much fainter sources than those in the sample of mgr Gupta, and in fainter sources host galaxy obscuration might be additionally important. Also mgr Gupta found no dependence on the black hole mass in the sample (from 10^8 Msun to 10^{10} Msun). Thus, for bright sources the outer region of an active nucleus looks universal.

In paper II, mgr Gupta again used a sample of RQ and RL sources matched in the black hole mass and Eddington ratio in order to see the systematic difference in their X-ray emission. This sample is smaller, contains 24 RL and 46 RQ sources, since more precise data was required to perform the analysis. And the result is surprising again. While the RL objects were found to be relatively brighter than RQ, as previously found in numerous works, this ratio of the hard X-ray flux to bolometric flux is only by a factor of 2 higher in RL subsample than in the RQ subsample. What is more, the spectral slope in the hard X-ray band as well as the high energy cut-off were found to be the same in RL and RQ sources. This is again a new and extremely important result, as it implies that there is a single mechanism operating in RL and RQ sources responsible for the X-ray emission, and this must be the Comptonization in the hot thermal plasma. No additional jet component is thus seen in this energy band. Selected RL sample excludes blazars, so we see in this case the true unbeamed emission of the nucleus. The bolometric luminosity has been determined from the mid-IR luminosity so the study included both Type 1 and Type 2 sources. The author argues that the emission in hard X-rays as well as in mid-IR is isotropic so the source orientation is unimportant.

However, the puzzling in this context is another conclusion from the data, namely relatively lower reflection fraction in RL sources than in RQ ones, despite their larger X-ray brightness. This was seen in the data in the past, but was usually interpreted as the argument is favor of strong jet contribution to the continuum. Now mgr Gupta argues that it has be connected with the larger emissivity in the hot medium, which again points toward the role of the black hole spin.

Paper III is devoted to study the sample of the RL and RQ sources with large black hole masses, and lower than before Eddington ratios. Here also AGN without good mass determinations are included, so in this paper the carefull cross-match of the RL and RQ objects could not be performed. On the other hand, larger sample allowed to study separately Type 1 and Type 2 sources, to get an insight into the viewing angle trends. In this sample the RL sources are again brighter by a factor 2 than RQ objects. In RL sources there is a negligible difference between Type 1 and Type 2 sources, implying no orientation effect; in RQ sources the difference between Type 1 and Type 2 sources is larger, top-view Type 1 sources are brighter by ~50%.

In my opinion the observational results of mgr Maitrayee Gupta represent the real break through in the field. The combination of the well posed scientific question and creative approach to the sample selection has lead to puzzling results: overall similarity of RL and RQ objects, no traces of difference in the outer boundary conditions at a parsec scale and overall the same geometry, even in the central region, as reflected in the X-ray properties.

The conclusion from the presented Thesis is that the Blanford-Znajek mechanism is more likely to be responsible for the jet formation but MAD-phase of accretion is also needed, so both the high spin and high large scale magnetic field are needed to power the relativistic jet.

However, I allow myself to express some reservations about the final interpretation of the results. In Paper I the author mentions at the very end of the discussion that the apparently the same conditions at the outer parsec scale in RL and RQ objects can be still consistent with the larger magnetic flux carried toward the nucleus. This, according to mgr Gupta, may happen either by accumulation of the magnetic flux prior to the active phase, or by longer activity of RL objects. The first argument is not quite convincing unless separate activity events happen inside the central parsec, without perturbing the outer torus zone. The second option - the argument about longer activity in RL objects found by other authors (e.g. Schwainsky et al. 2015) is based in my opinion on a sample of objects where RL sources show larger mass and lower Eddington ratio, and in that case the argument is natural. However, in carefully selected samples of mgr Gupta (same black hole mass and Eddington ratio) such trend would not be obvious. So in my opinion Paper I rather points toward RL/RQ dichotomy being born close to the black hole, just related to the spin and the stage of the accretion process right next to the black hole. If so, then the large scale magnetic field should be also created mostly in-situ. Perhaps some signatures of a specific process are in the soft X-ray band, which were not the subject of the study?

In Paper II mgr Gupta argued that both the mid-IR emission and X-ray emission are isotropic so there was no attempt to divide the sample into Type 1 and Type 2 objects, in order to test further the orientation effect. The models of the torus indicate that the torus is optically thin only above ~ 10 microns, so the band W3 might be somewhat affected, and in addition the torus is overall brighter by a factor of 2 when seen top-view (e.g. models by Stalevski 2012, 2016) due to scattering.

In Paper III again the mid-IR and X-rays in the interpretation of the results are treated as isotropic, while in the SED plots there is a clear difference in the IR shape of the AGN component, being much steeper in IR-opt_UV in Type 2 sources, and this does not seem to be the effected of the host galaxy contamination. So perhaps a more careful look into the issue of isotropy would help to reach the final conclusion with even stronger arguments.

In my opinion there is a possibility, not discussed in the presented publications but available in the literature that perhaps the X-ray emission in both RQ and RL objects actually comes (at least partially) from the base of the jet (e.g. Markoff & Nowak 2004, see also discussion in Zhou & Gu arXiv:2007.01049v1) in **BOTH** types of objects. RQ objects also show jets, but their jets are weak, not relativistic and do not propagate far into the galaxy. It may well be that, right from the start, RL objects show higher velocities of the corona/base jet, of order of 0.3 c, while RQ plasma has much smaller velocity. This would somewhat affect the emission isotropy, it would decrease the amout of the X-ray radiation intercepted by the torus. It could account for the higher X-ray loudness even without direct enhancement of the dissipation - the extra spin-related power would then go directly to kinetic energy and (mostly) Poynting flux. Those are just loose comments.

Overall, the Thesis presented by mgr Maitrayee Gupta is highly inspiring. For the first time it really pin-points the key issue in radio-loudness dychotomy in AGN - the differences in the RL and RQ source properties are much smaller than we thought, despite the orders of magnitude differences in the jet power. It does not fully solve the problem unambiguously, but we cannot expect that the problem present for the last 60 years in astronomy will disappear overnight. But this is fantastic step in the proper direction.

Summarizing, the presented Thesis fulfill all the formal and customary requirements, and I recommend to proceed to further steps required to award mgr Maitrayee Gupta the PhD title.
What is more, I am applying to the Scientific Council of CAMK for recognition of the work as outstanding, in recognition of the importance of the results for further studies of RL/RQ dichotomy.

B Czerny

Prof dr hab. Bożena Czerny