Report on Ph.D. Thesis

Title: Observational constraints on jet production efficiency in Active Galactic Nuclei

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Reviewer: Mitchell Begelman

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This dissertation, consisting of a well-researched introduction and three published papers, provides an important advance in unraveling the phenomenology of radio loudness in AGN, and speculates on some interesting theoretical ideas for its origin.

The most robust conclusions are drawn in Papers II and III, which are based on samples that are carefully selected for homogeneity and completeness. Most importantly, they include only Type I AGN (i.e., with broad emission lines and thus presumably UV-emitting thin disks), which means that one can be confident about the methods used to obtain the bolometric luminosities that factor into the radio loudness calculations. Paper II provides the most convincing evidence yet that radio loudness (R) is bimodal, indicating that the production of a powerful jet either depends on the properties of the flow nonlinearly (more nonlinearly than the a^2 dependence of the spin paradigm) or that there is some kind of “switch” that sends an AGN into a radio loud state. The large values of R found for radio loud sources seem to be consistent only with the extreme magnetic fluxes associated with magnetically arrested disks (MADs), which are saturated at the maximum values capable of being confined dynamically by the accretion flow. The paper also confirms the association of radio loudness with elliptical galaxy morphology.

Paper III goes on to examine the correlation of radio loudness with redshift, black hole mass, and Eddington ratio, finding a strong anti-correlation with z but positive correlation with M_{BH}. Since there is a weak correlation of M_{BH} with z in the sample, the actual anti-correlation with z may be even stronger. Interestingly, they find no significant correlation with the Eddington ratio λ_E.

The strong dependence on z suggests that the dominant factors determining radio loudness are related to the cosmic evolution of galaxies. Since it is suspected that galaxy mergers are a key factor in triggering powerful episodes of activity, the authors make the very plausible suggestion that spiral-spiral mergers (i.e., “wet” mergers, which are relatively more frequent at higher z) favor radio quiet activity, while spiral-elliptical mergers (which are relatively more frequent at low z) favor radio loud activity. This idea also would explain the preference of strong radio sources for ellipticals.

Given their conclusion that the main requirement for high radio loudness is a MAD, they focus their theoretical argument on processes that could accumulated flux close to the black hole, which plausibly include a hot, quasi-spherical or thick disk accretion phase following a spiral-elliptical merger but preceding the most luminous activity. The idea that flux accumulation would be much less effective (or slower) following a spiral-spiral merger is reasonable but speculative. I find their third suggestion – that the MAD forms in situ due to the "cosmic battery effect" – much less plausible because this mechanism requires that the rotating, accreting gas be subject to an intense radiation field over a long period of time, yet they find (in Paper I) many instances of very low-luminosity sources with extremely high radio loudness. These would all have had to be extremely luminous for a sustained period in the past.

Paper I is indeed very intriguing but less conclusive than Papers II and III because it relies on a very heterogeneous sample. The additional parameter space covered in Paper I consists of FR II NLRGs, i.e., they are not Type I AGN so it is difficult to know how accurate the conversion is from H-alpha luminosity to disk bolometric luminosity. The total sample shows a strong anti-correlation between R and Eddington ratio, which is not seen in the Type I-only sample studied in Paper III. They argue that this anti-correlation is not due mainly to decreasing disk efficiency or the appearance of a radiatively inefficient inner torus at low λ_E because the trend appears already at values of λ_E that are not too low. They instead suggest that this is due to disk thickness, quoting the claims by Avara et al. that the BZ jet power scales as $(H/R)^2$. Note, however, that other authors (e.g., Tchekhovskoy) quote a weaker dependence (~H/R), which is also adopted later in the thesis. I think this result is still really uncertain – especially since the proposed explanations in the literature are very tentative, to say the least. In particular, it is not clear what happens to the remaining BZ power that does not go into the jet when H/R is small. If it couples to the disk, does it propel a sub-relativistic disk wind that in turn could help to collimate the jet? Does it heat a corona? Or does it couple to the main body of the disk, increasing its luminosity. These questions are still completely unanswered.

Compared to the other papers in the thesis, Paper I also might suffer from its relatively early publication date (it was competed in 2016 and published in 2017). There has been some progress on understanding MADs that might have affected the authors' interpetations had it been available sooner. For example, it is now generally thought that MADs are relatively radiatively efficient, even when the gas is hot and two-temperature. PIC simulations suggest that at high levels of magnetization a significant fraction of dissipated energy goes directly to electrons and does not need to be transferred from the ions by Coulomb collisions. Another, very recent result is that MADs with high gas pressure are not dominated by the vertical magnetic flux but rather by the toroidal magnetic field, which is convectively unstable (Begelman et al. 2021).

Thus, the most lasting contribution of the work described in this thesis is likely to be the empirical correlations, which together present a much more convincing picture than previously available. The theoretical ideas presented to explain these correlations are very intriguing but should be regarded as preliminary, especially given the rapid development of theoretical work on MADs and magnetically elevated disks. The empirical results presented here, however, provide important suggestions for further theoretical work.

Summing up, I consider the doctoral thesis of Katarzyna Rusinek-Abarca to be a valuable contribution 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.