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Examination of the doctoral dissertation of Anna Patrycja Wójtowicz, M. Sc., "RADIO EMISSION IN EARLY-TYPE GALAXIES: RADIO LOUDNESS, JET DUTY CYCLE, AND LARGE-SCALE ENVIRONMENT"

The PhD thesis of Anna Wójtowicz is devoted to studies of radio emission in elliptical (early-type) galaxies. Section 1 gives a concise introduction to the field, Sections 2 and 3 consist of two research papers published in The Astrophysical Journal, and Section 4 consists of a paper submitted (at the time of the thesis submission) to the same journal. Anna Wójtowicz is the first author of all three papers.

The first paper studies the jet production efficiency in very young radio galaxies, so-called Compact Symmetric Objects, which consist of two lobes on the opposite sides of a radio core (together forming a pair of jets), similarly to the Fanaroff-Riley type II (FR II) radio galaxies (which have the radio emission dominated by their lobes), but much smaller, with the sizes <1 kpc. The studied sample has measured redshifts, kinematic jet life times, radio fluxes and nuclear X-ray fluxes. The black-hole masses in the sample have been estimated using the black-hole mass – velocity dispersion relation, and the bolometric luminosities have been estimated using mostly the Hβ luminosity and a bolometric correction. The minimum jet power has been estimated calculating the energy content of the radio lobes assuming equipartition divided by the jet life time. These estimates are somewhat lower than those based on the scaling relation of Willott et al. (1999) and Osterero et al. (2010), but they provide conservative limits on the actual jet power. The authors then assume that the observed X-rays originate entirely from hot accretion flows in these systems. The accretion rates are calculated from the bolometric luminosity assuming a 10% accretion efficiency, and the jet production efficiency is defined in a usual way as the ratio between the jet and accretion powers.

Then, various relationships between the jet power and the X-ray, bolometric and Eddington luminosities are calculated. The jet production efficiency in the sample is found to be low, between $<10^{-2}$ and 0.2, which indicates that the accretion flows do not form magnetically arrested geometrically thick discs around maximally spinning black holes, in which case the jet production efficiency is of the order of unity. The other significant finding of the study is that systems with low ratio of the X-ray to bolometric luminosity have much lower both the jet power and the jet production efficiency than those with that ratio being high. This resembles the case of black-hole X-ray binaries, which have weak or no jets in their soft spectral state (with weak or absent accretion disc coronae) than in the hard spectral state, which have strong coronal emission always accompanied by jets.

The second paper proposes a new method for estimating the ambient medium density around lobes of distant radio sources. The method is based on the discovered correlation between the spectral indices of the spectra of the radio lobes of FR II radio galaxies and the density of the intergalactic medium (IGM) around their lobes. Such a correlation can arise if the efficiency of electron acceleration in termination shocks of their jets depends on the density of the shocked medium, with the increasing density decreasing the acceleration efficiency.

The study utilizes a large sample of FR II radio galaxies with good spectral and imaging data on their radio lobes. However, observational estimates of the IGM density are sparse and limited to a small number of nearby and/or brightest sources with deep-exposure data with either Chandra or XMM-Newton X-ray telescopes. Therefore, the authors use instead a theoretical method to measure that density based on a specific model, namely the DYNAGE code of Machalski et al. (2007). This code determines the jet kinetic power and life time and the density of the IGM based on the spectral and imaging data. The density profile is assumed to be a power law with the index of −3/2 and the jet inclination to be either 70º or 90º. The density from this model is then correlated with the observed radio spectral index. The authors find a good correlation when also the linear sizes of the sources are included, see fig. 2. Then, they search for correlations not including the linear size, and find the best one is between the spectral index and the theoretical central density of the host galaxy (fig. 6). That correlation is presented as the main result of the paper.

The goal of the third paper is to study the origin of the radio emission in galaxies with low/very low radio emission. The authors use a large sample of nearby early-type galaxies with good optical and X-ray data for which the black-hole masses are precisely determined with dynamical methods. The present paper adds to most of the objects in the original sample available archival VLA data at 1.4 GHz and IRAS infrared data. Various correlations between observables are then studied. A major finding of the study is that the histogram of the radio luminosities in units of the Eddington luminosity is clearly bimodal, which divides the sample into radio dim and radio bright objects. Another finding is that the radio emission is brighter than that expected from star-formation regions. On the other hand, most of the infrared fluxes can be accounted for by that process. The authors also find that the radio emission of radio-dim objects is much stronger than that following from the radio/X-ray scaling found for accreting black-hole binaries. The authors conclude that the radio emission of their radio-bright sources originates in relativistic jets, while the origin of the radio emission for their radio-dim remains uncertain, with a few possibilities discussed.

Overall, the thesis contains a large number of significant new results and is clearly sufficient for granting a PhD degree. The first paper (published in 2020) of the thesis has already had a significant impact on radio astronomy, as having 16 citations by mostly refereed papers in prestigious journals (according to the NASA Astrophysical Data System).

As for any research, one can have comments on the obtained results. My main caveat for the first paper regards the assumption that the X-ray emission is mostly from accretion. As the authors note themselves, this remains uncertain, and in a previous paper (Ostorero et al. 2010) the X-rays were assumed to originate in the radio lobes, which lead to estimates of the jet power very close to those obtained from the assumption of equipartition. The authors themselves point out that ambiguity.

In a number of formulae and tables in all three papers, the unit of the power of erg/s is mixed with that of Watt. While this is quite common in radio astronomy, strictly it is incorrect. With a little effort, one could convert the numerical coefficients to those using only one unit of power.

My main comment on the second paper is that the discovered correlation between the radio spectral index (observed) and the density of the surrounding medium uses the density as calculated in a theoretical model. The actual densities in the studied sample remain unknown. Only for several nearby sources the densities are estimated from studying of X-ray halos. However, those observed densities are all above the model values, as shown in fig. 7. Thus, the validity of the obtained correlation remains uncertain. I also note that this fact is not clearly stated, in particular in the abstract and the Conclusions.

Some quantities in that paper are not defined, e.g., a_0, which seems to be the radius of the host galaxy, and is a crucial quantity. The abbreviation of `PDF' (footnote 1) is not defined. The authors plot the density in an unobvious unit (10^{-28} g/cm^3), which is not stated in figure captions. Then, the label of the y axis in fig. 6 is ρ_0, while the caption gives it as $\rho_0 a_0^{3/2}$ (with the unit of a_0 remaining unknown). I guess the latter is true since the numbers of the y axis are lower than those on figs. 2, 4. As I understood the results, using $\rho_0 a_0^{3/2}$ instead of ρ reduces the scatter (as follows from comparing fig. 6 with fig. 4), while the Conclusions state it is ρ_0 vs. $\rho_0 a_0^{3/2}$.

In the third paper, the authors compare the radio fluxes in their sample to those predicted by the ADAF model for accreting black-hole binaries. They state that the observed fluxes to be much higher than those of the ADAF model. I note this is not the case. The radio emission in the ADAF model strongly depends on the black-hole mass, which can be expressed by the so-called Fundamental Plane (which the authors use in their first paper). The supermassive black-hole sources have then much higher radio loudness than those with stellar-mass black holes. The physical cause of that is the dependence of the magnetic field strength on the size different from the linear scaling for the luminosity. I propose that the authors compare the observed radio emission with that predicted by the Fundamental Plane.

I find their definition of the flux ratio of equation (4) to be rather obscure. I understand it was introduced long time ago (in 1985) by other authors, but a much more physical quantity would be a simple comparison of the νF_ν values. I also don't understand the meaning of the coefficient of 2.58 in front of the 60 μm flux. The authors mix the unit of Jansky with W/m^2.

I note that the authors use commas in a non-standard way. That usage in English is quite different from that in Polish. In the former, an appearance of a comma depends whether the clause is defining (no comma then) or non-defining.

Still, the issues discussed above are relatively minor. Concluding, the included papers form a high-quality PhD thesis as well as show the intellectual potential of the candidate. The papers are relatively well organized. The thesis satisfies all of the customary and legal requirements for PhD theses. I recommend admitting the candidate to a public defence of the thesis.

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