Pair-Matching of Radio-Loud and Radio-Quiet AGNs

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Active galactic nuclei (AGNs) are known to cover an extremely broad range of radio luminosities and the spread of their radio-loudness is very large at any value of the Eddington ratio. This implies very diverse jet production efficiencies which can result from the spread of the black hole spins and magnetic fluxes. Magnetic fluxes can be developed stochastically in the innermost zones of accretion discs, or can be advected to the central regions prior to the AGN phase. In the latter case there could be systematic differences between the properties of galaxies hosting radio-loud (RL) and radio-quiet (RQ) AGNs. In the former case the differences should be negligible for objects having the same Eddington ratio. To study the problem we decided to conduct a comparison study of host galaxy properties of RL and RQ AGNs. In this study we selected type II AGNs from SDSS spectroscopic catalogs. Our RL AGN sample consists of the AGNs appearing in the Best and Heckman (2012) catalog of radio galaxies. To compare RL and RQ galaxies that have the same AGN parameters we matched the galaxies in black hole mass, Eddington ratio and redshift. We compared several properties of the host galaxies in these two groups of objects like galaxy mass, color, concentration index, line widths, morphological type and interaction signatures. We found that in the studied group RL AGNs are preferentially hosted by elliptical galaxies while RQ ones are hosted by galaxies of later type. We also found that the fraction of interacting galaxies is the same in both groups of AGNs. These results suggest that the magnetic flux in RL AGNs is advected to the nucleus prior to the AGN phase.

Keywords: active galaxies, radio galaxies, jetted and non-jetted AGNs, radio-loudness, galaxy morphology

1. INTRODUCTION

Active galactic nuclei (AGNs) are powered by accretion on a supermassive black hole (BH). Although the first discovered AGNs were radio-loud (RL), most of AGNs are radio-quiet (RQ). The radio-loudness of RL AGNs, defined as the ratio of the radio flux to the optical flux (Kellermann et al., 1989), covers several orders of magnitude (e.g., Sikora et al., 2007; Lal and Ho, 2010) which implies very diverse jet production efficiencies. For jets powered by rotating BHs (Blandford and Znajek, 1977), the efficiency of the jet production can be related to the spread of the BH spins and the amount of magnetic fluxes accumulated in the central AGNs.

Magnetic fluxes can be developed stochastically in the innermost zones of accretion discs (Begelman and Armitage, 2014), or can be advected to the central regions of a galaxy prior to the AGN phase (Sikora et al., 2013; Sikora and Begelman, 2013). In the latter case there could be

systematic differences between the properties of galaxies hosting radio-loud and radio-quiet AGNs. Our aim is to compare the properties of the host galaxies of radio-loud and radio-quiet AGNs to distinguish which of these two scenarios is more probable. If we find that RQ and RL are hosted by different galaxies, we could discard the scenario where radio jets are stochastic.

Radio-loud (jetted) and radio-quiet (non-jetted) AGNs have already been studied extensively and some systematic differences were found between these two groups of objects:

- The most radio-loud AGNs are found in galaxies with black hole masses $\geq 10^8\, M_\odot$ (Laor, 2000; Dunlop et al., 2003; Floyd et al., 2004; McLure and Jarvis, 2004; Best et al., 2005).
- The fraction of radio-loud objects and radio loudness increases with decreasing Eddington ratio, $\lambda = L_{bol}/L_{Edd}$ (e.g., Terashima and Wilson, 2003; Kratzer and Richards, 2015), but there is a large scatter in radio loudness for AGNs with similar Eddington ratio.
- The fraction of galaxies with disturbed morphology is larger in RL than in RQ AGNs (Bessiere et al., 2012; Chiaberge et al., 2015).
- RL AGNs are located in denser environments (e.g., Mandelbaum et al., 2009; Ramos Almeida et al., 2013).
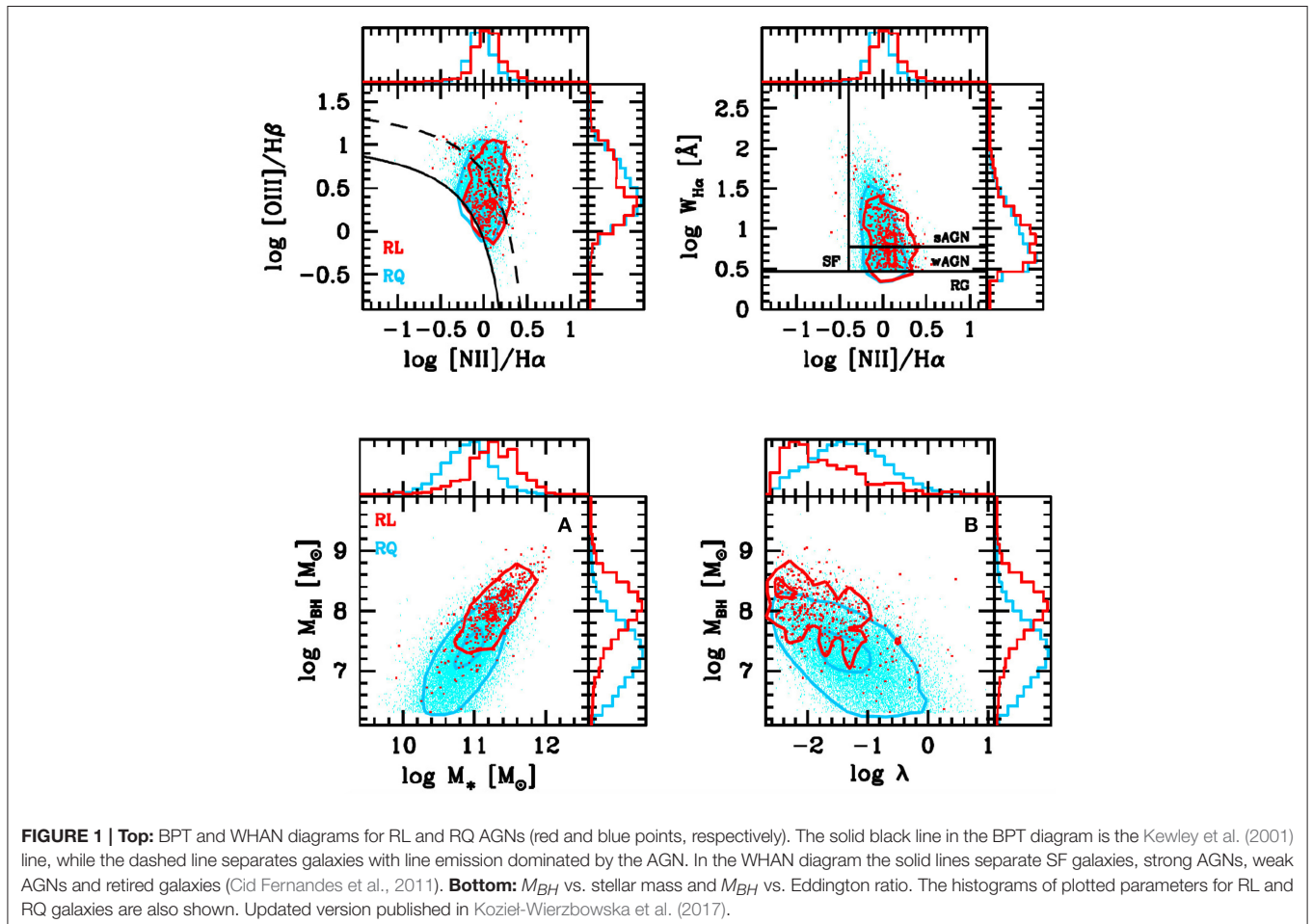
However, the differences listed above concern entire families of objects, but not objects that have the same accretion properties. Moreover, in catalogs of AGNs there are many objects with properties characteristic of RL objects like very massive black holes, low Eddington ratios, and disturbed morphologies, but they are radio-quiet. Therefore, we ask the question why is the efficiency of the jet production very different among otherwise similar objects?

In our project we concentrate on Type 2 (i.e., obscured) objects, to be able to study the properties of the host galaxies, with Eddington ratios $\lambda \geq 0.003$, and we seek the differences between radio-loud and radio-quiet AGNs to check if there are any generic differences between the host galaxies of these two groups of objects that can indicate different evolution histories of jetted and non-jetted AGNs.

2. METHODS

2.1. Selection of the Samples

The samples of radio-loud and radio-quiet galaxies were selected from the SDSS DR7 spectroscopic catalogs (Abazajian et al., 2009). Only galaxies with S/N ≥ 10 Å^{-1} in the region around $\lambda_0 = 4{,}020$ Å were chosen. We also applied the redshift cuts, low velocity dispersion limit and S/N limits in emission line fluxes as

FIGURE 1 | Top: BPT and WHAN diagrams for RL and RQ AGNs (red and blue points, respectively). The solid black line in the BPT diagram is the Kewley et al. (2001) line, while the dashed line separates galaxies with line emission dominated by the AGN. In the WHAN diagram the solid lines separate SF galaxies, strong AGNs, weak AGNs and retired galaxies (Cid Fernandes et al., 2011). **Bottom:** M_{BH} vs. stellar mass and M_{BH} vs. Eddington ratio. The histograms of plotted parameters for RL and RQ galaxies are also shown. Updated version published in Kozieł-Wierzbowska et al. (2017).

in Kozieł-Wierzbowska et al. (2017). Galaxies with faulty pixels in the area of emission lines were eliminated. After this step, AGNs were selected based on the BPT diagram and the Kewley et al. (2001) line. Using the WHAN diagram (Cid Fernandes et al., 2011), we removed those galaxies in which the emission lines could be produced by hot, low-mass, evolved stars (the retired galaxies defined in Stasińska et al., 2008). This procedure selected 19883 optical AGNs.

Among this sample of optical AGNs, we searched those which belong to the Best and Heckman(2012; BH12) catalog of radio galaxies and whose radio emission is considered by them to be produced by an AGN. The BH12 catalog flux limit is 5 mJy.

After limiting ourselves to AGNs with Eddington ratio $\lambda \geq 0.003$[1], i.e., focusing mostly on sources with radiatively efficient accretion, we obtained our RL AGN sample of 376 objects, and our RQ AGN sample of 10,918 objects.

The host galaxy stellar masses, velocity dispersions (used to calculate M_{BH}), nebular extinction, emission line fluxes and equivalent widths, and the Eddington ratios, λ, where obtained from the SDSS data after applying the STARLIGHT (Cid Fernandes et al., 2005) spectral model-fitting.

The upper panels of **Figure 1** show the BPT (Baldwin et al., 1981) and the WHAN (Cid Fernandes et al., 2011) diagrams for our RL and RQ samples. RL AGNs are shown in red and RQ AGNs in blue. On both axes the normalized histograms are presented. The black curve is the Kewley et al. (2001) line. The location of red and blue points is similar which shows that objects from both samples have similar ionization properties. The bottom panel in **Figure 1** shows M_{BH} as a function of the galaxy stellar mass M_*, and of the Eddington ratio, λ. In these diagrams RL and RQ galaxies are shifted relative to each other. On average, RL AGNs have higher black hole masses and higher stellar masses compared to RQ galaxies. RL objects have also lower λ. These observations are compatible with trends found by previous authors (see Introduction). These two panels clearly show that in order to compare RL and RQ AGNs it is necessary to match them in black hole mass and Eddington ratio.

2.2. Pair-Matching of RL and RQ Galaxies

To compare RL and RQ galaxies with the same AGN parameters, we applied a pair-matching technique. Galaxies were matched in redshift, black hole mass (M_{BH}) and Eddigton ratio (λ). In practice for each RL object we selected all RQ objects for which: $|\Delta z| \leq 0.01$, $|\Delta \log \lambda| \leq 0.09$, and $|\Delta \log M_{BH}| \leq 0.1206$. We computed the distance as $d^2_{match} = \sum \Delta^2$. For each RL AGN three RQ galaxies with the smallest d were included into the matched RQ sample (mRQ sample).

We defined the radio loudness parameter by $\mathcal{R} \equiv L_{1.4}[W\,Hz^{-1}]/L_{H\alpha}[L_\odot]$, where $L_{1.4}$ is the radio luminosity at 1.4 GHz. The classical criterion for radio-loud AGN, $\mathcal{R}^{(K)} > 10$ (Kellermann et al., 1989), translates into $\log \mathcal{R} > 15.8$. From the matched RQ sample we excluded galaxies that were undetected in radio and for which the radio-loudness (estimated from the

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[1]This step ensures us that we calculate the bolometric luminosity consistently and correctly for all studied sources.
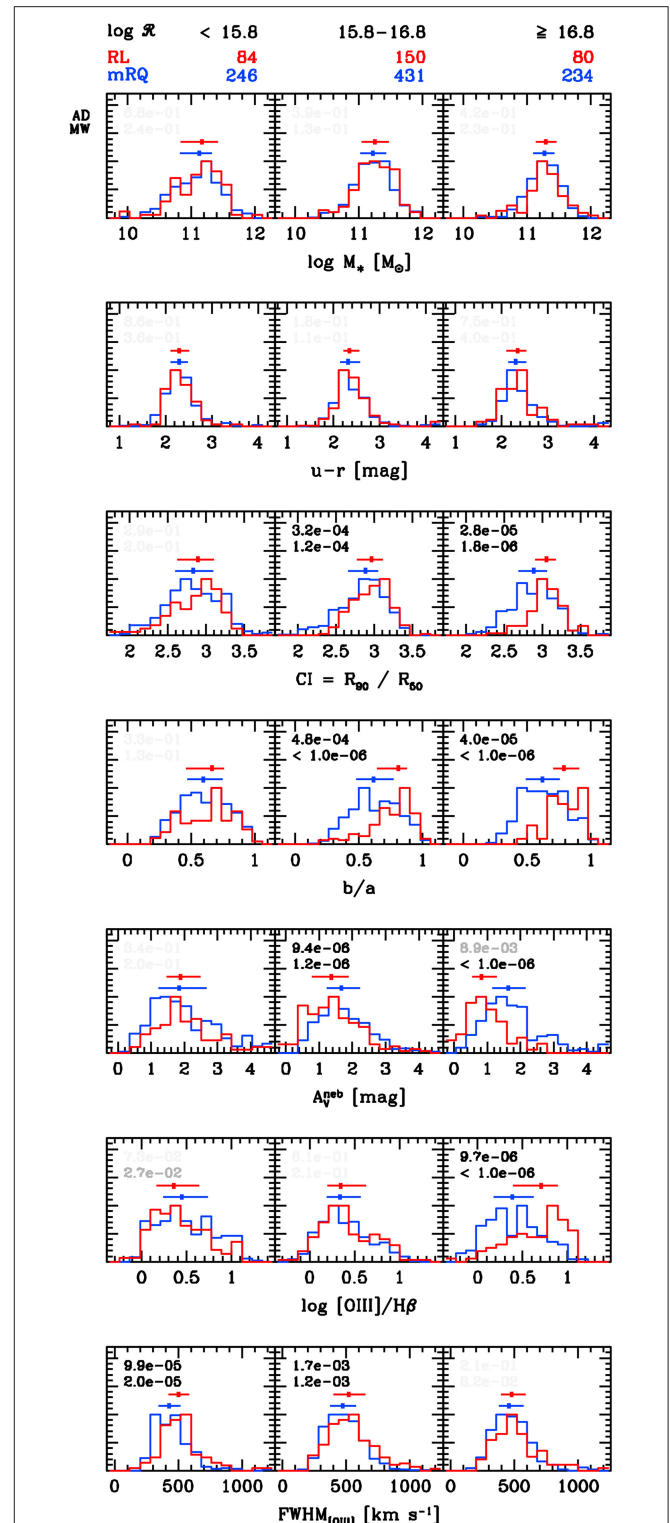

FIGURE 2 | Histograms of selected parameters of RL (red) and mRQ (blue) objects. In each panel we show the results of the Anderson-Darling and Mann-Whitney tests in terms of probabilities p that the samples could be drawn from the same population. Results with $p < 0.003$ are written in black, those with $p < 0.05$ are written in dark gray. Blue and red points at the top of each histogram indicate the median values and the horizontal lines indicate the quartiles. Published in Kozieł-Wierzbowska et al. (2017).

flux limit od 5 mJy in the BH12 catalog) is larger than 10 (log $\mathcal{R} > 15.8$).

3. RESULTS

We present our results in the form of histograms. **Figure 2** shows histograms of selected parameters of RL (red) and RQ (blue) galaxies. Results for RL AGNs and their matched RQ galaxies are presented separately for three bins in the value of the radio-loudness $\mathcal{R}$ of the parent RL object. $\mathcal{R}$ bins were chosen to represent classically radio-quiet (although jetted, log $\mathcal{R} < 15.8$) objects, intermediate radio-loud objects (15.8 < log $\mathcal{R} < 16.8$), and the most radio-loud ones (log $\mathcal{R} > 16.8$). In each bin, the tick mark with horizontal line shown on the top of the histograms represents the median value and the quartiles. We used two statistical tests to study the difference between RL and mRQ samples. These are the Anderson-Darling (AD) and Mann-Whitney (MW) tests. These tests give the probability that both samples are drawn from the same population.

Among the studied parameters, the stellar galaxy masses, M_*, and the colors, u-r, have very similar distributions for RL and RQ AGNs. In the case of galaxy mass this result is expected since we matched our objects in M_{BH} which correlates with M_*. The concentration index, CI, and the galaxy axes ratio, b/a, the two parameters associated with galaxy shape and morphology,

show significant differences. RL galaxies tend to have larger concentration index, and larger axes ratios in the two highest $\mathcal{R}$ bins. The lower values of CI and b/a ratio in the matched RQ sample indicate more disky galaxy morphology.

In the next two panels we present a comparison of the nebular extinction, A_V^{neb}, and of the [O III] to Hβ line fluxes ratio. The values of A_V^{neb} decrease with increasing $\mathcal{R}$. [O III]/Hβ differs significantly in the bin of the highest $\mathcal{R}$. These results may suggest some contribution from the H II regions to the line emission. The last panel shows histograms of [O III] line widths. We see that the line widths in RL galaxies tend to be larger then in RQ AGNs in the lowest $\mathcal{R}$ bins. We speculate that this can result from having at low R less collimated jets. Forming wider outflows such jets may affect the motion of the gas clouds in the narrow line region, and hence broaden the emission line profiles.

To eliminate the contribution of H II regions from our studies we decided to use "cleaned" samples. In these samples only galaxies that lie above the dashed curve shown in BPT diagram from **Figure 1** are included. In these galaxies the contribution from H II regions can be neglected. The results for the cleaned samples (see Kozieł-Wierzbowska et al., 2017) confirm our findings for the whole RL and mRQ samples concerning morphological properties.

From the comparison of CI and of the b/a ratio we see that there is a difference in morphology between RL and
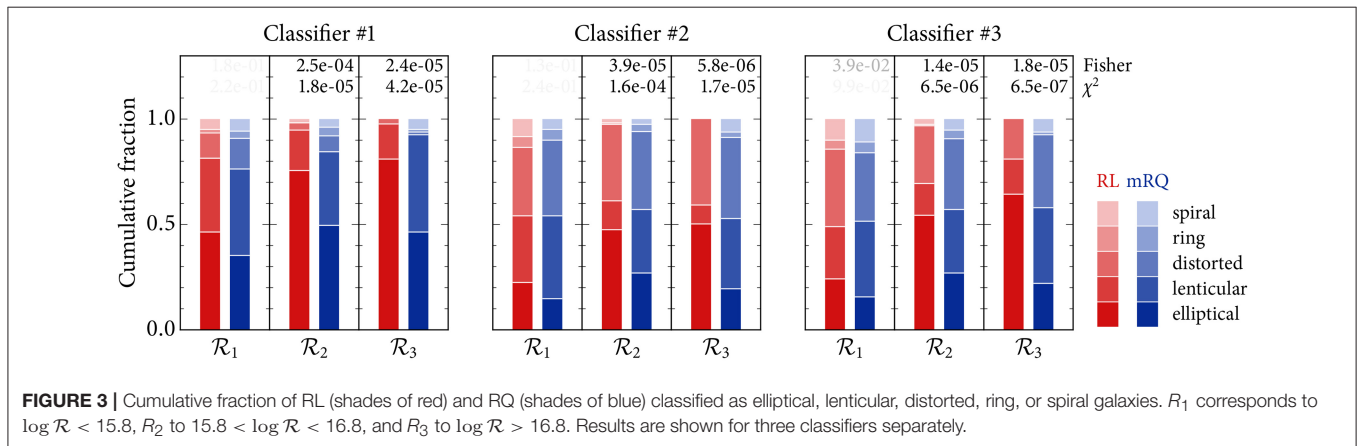

FIGURE 3 | Cumulative fraction of RL (shades of red) and RQ (shades of blue) classified as elliptical, lenticular, distorted, ring, or spiral galaxies. R_1 corresponds to log $\mathcal{R}$ < 15.8, R_2 to 15.8 < log $\mathcal{R}$ < 16.8, and R_3 to log $\mathcal{R}$ > 16.8. Results are shown for three classifiers separately.
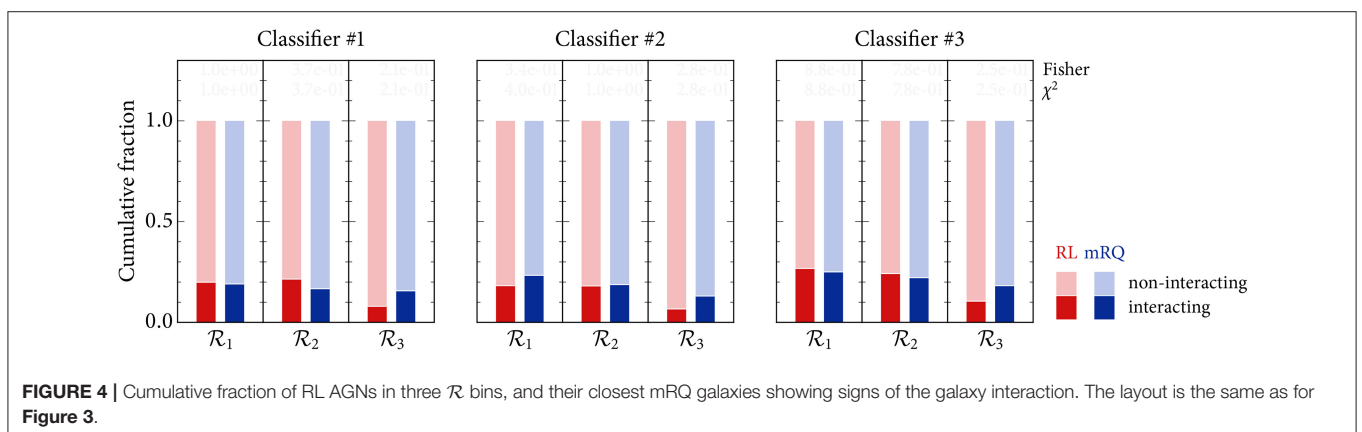

FIGURE 4 | Cumulative fraction of RL AGNs in three $\mathcal{R}$ bins, and their closest mRQ galaxies showing signs of the galaxy interaction. The layout is the same as for **Figure 3**.

mRQ galaxies. To confirm this result we decided to perform a morphological classification of all RL galaxies and the closest match from the RQ galaxies. Classifiers looked at the color SDSS images of these objects and attributed to each galaxy a morphological type. The results for the three classifiers are shown in **Figure 3**. The panels in this figure show in different shades of red (blue) the fraction of RL (mRQ) galaxies classified as elliptical, lenticular, distorted, ring, or spiral galaxies. As before, results are presented separately for three $\mathcal{R}$ bins. As we can see, the fraction of ellipticals among RL objects in all three radio-loudness bins is larger than among the matched RQ galaxies. Note that low-CI galaxies are not spirals, but lenticular or distorted galaxies. This result was confirmed using Galaxy ZOO data.

The classification scheme also included information about galaxy interactions like major or minor mergers, tail, or suspected interaction. **Figure 4** shows the results concerning the fraction of galaxies with interaction signatures considered as certain. Here, as interacting, we consider major or minor mergers and galaxies with a tail. In **Figure 4** we do not see any systematic difference between RL and RQ AGNs suggesting that galaxy interaction has no special effect on the radio activity of the AGN. Our result is in contradiction with Chiaberge et al. (2015) who found that all radio-loud galaxies in their sample are mergers, however their sample consisted of FRII radio galaxies at redshifts larger than 1, while in our sample we have only local AGNs mostly with compact morphologies.

4. SUMMARY

The results presented here clearly show that not only Eddington ratio and black hole mass determine the jet production efficiency. In the description of the jet production the accumulation of the magnetic flux in the AGN center and the BH spin have also to be taken into account. The fact that we find a higher fraction of

ellipticals among RL galaxies than among the matched RQ ones suggest that elliptical galaxies have already a sufficient amount of magnetic flux accumulated in the center to produce and collimate radio jets in the Blandford and Znajek, 1977 scenario. This is in agreement with findings of Sikora et al. (2013) and Sikora and Begelman (2013) on the RL AGN pre-phase.

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