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Confrontation of the Magnetically Arrested Disc Scenario with Observations of FR II Sources

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The main aim of our work was to check whether powers of jets in FR II radio galaxies (RGs) and quasars (QSOs) can be reproduced by the Magnetically Arrested Disc (MAD) scenario. Assuming that established in the recent numerical simulations of the MAD scenario the $(H/R)^2$ dependence of the jet production efficiency is correct, we demonstrate that in order to reproduce the observed jet powers in FR II sources: (i) accretion discs must be geometrically much thicker than the standard ones; (ii) and/or that the jet production is strongly modulated.

Keywords: active galactic nuclei (AGN), quasars, relativistic jets, accretion discs, magnetically arrested disc (MAD)

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1. INTRODUCTION

The primary division of Active Galactic Nuclei (AGNs) is based on their radio loudness which is defined as the ratio of radio luminosity (typically 5 GHz) to the optical luminosity (typically in B band). Minority of AGNs are known to be radio-loud (10% in case of QSOs, Kellermann et al., 1989) and their radio loudness is sometimes even up to 3–4 orders of magnitude higher than that of radio-quiet AGNs. Moreover, which was found in last years (Rawlings and Saunders, 1991; Punsly, 2007; Fernandes et al., 2011; Sikora et al., 2013), jet powers P_j of many radio galaxies reach values comparable to the accretion powers $\dot{M}c^2$, where $\dot{M}$ is the mass accretion rate. In order to produce jets with such high efficiencies, $\eta_j \equiv P_j/(\dot{M}c^2) \simeq 1$, by the Blandford and Znajek (1977) mechanism, the amount of the magnetic flux required to be accumulated on the black hole (BH) is so large that it can only be maintained if it is confined by the ram pressure of the accreting plasma (Sikora and Begelman, 2013). This affects the accretion flow in such a way that the innermost portion of the accretion flow is dynamically dominated by the poloidal magnetic field causing that accretion proceeds via interchange instabilities. This scenario is called Magnetically Arrested Disc (MAD, Narayan et al., 2003; Igumenshchev, 2008; Punsly et al., 2009; Tchekhovskoy et al., 2011; McKinney et al., 2012).

Even though the MAD scenario appears to be an attractive and plausible way to explain the existence of the most powerful jets in radio-loud FR II AGNs (which as described by Fanaroff and Riley, 1974, are characterized by edge-brightened radio structures in contrast to centre-brightened RGs of class I), there are still some open problems. One of them is to establish which parameters truly decide on the MAD occurrence. Assuming that the jet production efficiency depends mostly on the BH spin, van Velzen and Falcke (2013) showed that in fact it is not a dominant parameter for powering jets. Furthermore, since the observed mean efficiency of their FR II quasars sample is much lower than maximal predicted by the MAD model, they concluded that this mechanism does not occur in these sources. On the other hand, in their recent studies, Avara et al. (2016) performed numerical simulations of thin MADs in order to investigate its efficiencies. They found

that not only BH spin a but also a geometrical thickness H/R (where H is the disc height and R is the distance from the black hole) contributes to the jet power efficiency as $\eta_j \sim a^2(H/R)^2$. Their results confirm that the MAD scenario can be responsible for explaining powerful jet systems but also point out that at moderate accretion rates discs must be geometrically thicker than the standard theory predicts.

Given the above we checked whether jet powers in FR II radio galaxies and quasars can be reproduced by the MAD scenario. Our studies were thoroughly described in Rusinek et al. (2017). In this paper we briefly outline samples we used and discuss the origins of results we obtained, especially focusing on the importance of geometrical thickness of accretion discs and modulation of jet production.

2. SAMPLES AND ANALYSIS

In order to adequately assess the distribution of radio galaxies and quasars in the P_j/L_d – $\lambda_{\rm Edd}$ plane (where L_d is the bolometric disc luminosity and $\lambda_{\rm Edd}$ is the Eddington ratio) we have combined four different samples of these sources. We used radio and optical data to calculate necessary values. Including both low- as well as high-redshift objects allowed us to check if cosmological evolution of jet production may have an impact on our final results.

2.1. Samples

1. FR II Narrow-Line Radio Galaxies (NLRGs) were extracted from the sample of $z < 0.4$ radio galaxies with extended radio structure selected by Sikora et al. (2013). The objects are taken from Cambridge catalogues and matched with the SDSS (Sloan Digital Sky Survey), FIRST (Faint Images of the Radio Sky at 20 cm) and NVSS (National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey) catalogues. Due to the available optical data, this sample contains 152 sources;
2. FR II quasar sample was obtained by van Velzen et al. (2015) on the selection of double-lobed radio sources from the FIRST survey catalog, and cross-matching with SDSS quasars. The BH masses and Eddington ratios, when available, were taken from Shen et al. (2011) thereby reducing the sample from 458 to 414 objects;
3. FR II NLRGs selected in $0.9 < z < 1.1$ were taken from Fernandes et al. (2011, 2015). The main reason of adding these sources was to verify how much the incompletness of very massive BHs in the local Universe affects the jet production efficiency FR II NLRGs (the first sample). This sample contains 27 objects;
4. Low-redshift Broad-Line Radio Galaxies (BLRGs) and radio-loud quasars (RLQs) were used by Sikora et al. (2007) to study radio loudness of these objects. We decided to add this sample (86 sources) to check if the incompletness of SDSS quasars at moderate accretion rates (the second sample) can significantly influence the average value of P_j/L_d of the FR II quasar sample.

2.2. Jet Production Efficiency

For each of mentioned in the previous paragraph samples we calculated the following properties:

– The jet power P_j was obtained from the different radio luminosities (from the range of 151 MHz to 5 GHz) according to the formula based on calorimetry of radio lobes which was proposed by Willott et al. (1999) as

$$P_j[\mathrm{erg\,s^{-1}}] = 5.0 \times 10^{22}(f/10)^{3/2}(L_{1.4}[\mathrm{W\,Hz^{-1}}])^{6/7}, \quad (1)$$

where f is the parameter accounting for errors in the model assumptions. Its value (typically between 10 and 20, Blundell and Rawlings, 2000) is established based on comparing jet powers of luminous FR II sources calculated from the model of hotspots Godfrey and Shabala (2013) and the one provided by Willott et al. (1999), and is adpoted as $f = 10$;
– The bolometric disc luminosity L_d which is related to the line or optical/IR luminosities via respective bolometric corrections. It is used as a proxy of the accretion power $\dot{M}c^2 = L_d/\epsilon_d$ where ϵ_d is the disc radiation efficiency depending on BH spin. In standard disc theory it is assumed to be $\epsilon_d = 0.1$;
– The Eddington luminosity $L_{\rm Edd}$ which is necessary to establish the Eddington ratio $\lambda_{\rm Edd} \equiv L_d/L_{\rm Edd}$ describing the accretion rate, $L_{\rm Edd} \propto M_{\rm BH}$ where $M_{\rm BH}$ is the BH mass.

We have adopted the Λ cold dark matter (ΛCDM) cosmology with $H_0 = 70\mathrm{km\,s^{-1}}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Uncertainties of P_j/L_d and $\lambda_{\rm Edd}$, calculated as standard deviations of ratios of two independently determined quantities, are not bigger than 0.4 dex for each of the samples. All details about samples and methods used to estimate our calculations are described in Rusinek et al. (2017).

2.3. Results

The dependence of P_j/L_d on the $\lambda_{\rm Edd}$ for all four samples is presented in **Figure 1**. The distribution of all objects confirms the trend of the increase of P_j/L_d with decreasing Eddington ratio (Sikora et al., 2007). All samples are pretty consistent with each other: $z < 0.4$ FR II NLRGs and $0.9 < z < 1.1$ NLRGs samples have similar median of P_j/L_d at moderate accretion rates (which corresponds to $\lambda_{\rm Edd} > 0.003$); FR II quasars and BLRGs+RLQs samples overlap each other.

The horizontal dashed line marks the upper limits for P_j/L_d predicted by the MAD model for the maximal BH spin and adopting $\epsilon_d = 0.1$. The inclined dashed line results from the dependence of the jet production efficiency on H/R given as

$$\eta_j \simeq 4a^2\left(1 + \frac{0.3a}{1 + 2(H/R)^4}\right)^2 (H/R)^2 \quad (2)$$

(Avara et al., 2016). For $0.03 < \lambda_{\rm Edd} < 1.0$ discs have $H/R \geq 1$ and then such a dependence disappears. The existence of objects in the shaded area, which represents a significant fraction of all studied sources, contradicts with the above predictions and challenges current jet production theories.

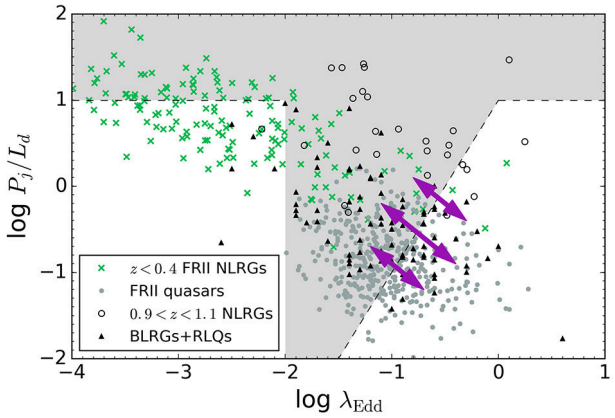

FIGURE 1 | The dependence of P_j/L_d on the $\lambda_{\rm Edd}$ for all samples: $z < 0.4$ FR II NLRGs as green crosses; FR II quasars as grey dots; $0.9 < z < 1.1$ NLRGs as empty circles; BLRGs+RLQs as black triangles. The horizontal dashed line corresponds to $P_j = (\epsilon_d/0.1)\dot{M}c^2$. The inclined dashed line is derived from the Equation (2) for $a = 0.5$ and assuming a correct normalization. The presence of objects in the shaded region of the plot calls into question our underlying assumptions. Purple arrows show how the modulation of jet production affects the $P_j/L_d - \lambda_{\rm Edd}$ distribution.

3. DISCUSSION

Depending on the Eddington ratio few different explanations for obtained by us jet powers can be proposed. The transition from Radiatively Inefficient, optically thin Accretion Flows (RIAF) to the standard, optically thick accretion discs occurs at $\lambda_{\rm Edd} \simeq 0.01$ (Best and Heckman, 2012). At lower Eddington ratios the disc radiative efficiency ϵ_d is expected to be much lower than usually assumed 0.1 and this can explain the presence of objects with $P_j/L_d > 10$ in this area. At higher Eddington ratios there are still some sources with $P_j/L_d > 10$. All of them belong to the $0.9 < z < 1.1$ NLRGs sample for which the bolometric disc luminosity was calculated from the mid-IR data. As it was pointed out by Ogle et al. (2006) this method is not very accurate and therefore discs luminosities of sources taken from Fernandes et al. (2011) may be overestimated.

The presence of objects in the shaded area corresponding to moderate accretion ratios and above the sloping dashed line may indicate that the accretion discs are thicker than the standard ones or/and that the jet production is modulated. However it should be noted here that the extension of the shaded area towards $P_j/L_d \ll 1$ on the **Figure 1** may be inappropriate by noting that the dependence of the jet production efficiency on geometrical thickness of the disk given by Equation (2) can be overestimated resulting from the very approximate treatment of the radiative transfer in Avara et al. (2016) simulations and by not including contribution to the vertical pressure in the MAD zone from toroidal magnetic fields.

3.1. Thicker Accretion Discs

Assuming maximally rotating black hole with $a = 1$ and producing radiation at a rate $\lambda_{\rm Edd} \sim 0.01$, the standard accretion disc model (Novikov and Thorne, 1973; Laor and Netzer, 1989) predicts that the maximal value of geometrical thickness of the disc is $H/R \sim 0.4$ which gives the jet production efficiency equal to 0.01 (from the Equation 2). This value is much lower than the median value of FR II quasars sample as well as its upper bound in the $P_j/L_d - \lambda_{\rm Edd}$ plot. This discrepancy can be explained if instead of optically thick, geometrically thin standard disc the thicker ones will be considered. These kind of discs have been proposed to avoid gravitational and thermal instabilities in gas and radiation pressure supported discs and they can be formed in presence of strong toroidal magnetic fields (e.g., Begelman and Pringle, 2007; Sądowski, 2016).

Different approach assumes the existence of moderately hot, optically thick and massive layer on top of the relatively colder, accretion disc which stays geometrically thin and optically thick as it was originally developed by Shakura and Sunyaev (1973). Różańska et al. (2015), and Begelman et al. (2015) proved that the model of heavly, viscously driven corona is real if the disc/corona system is stabilized by either strong magnetic fields or vertical outflows. The massive, dense coronas can also arise during the transition from Shakura and Sunyaev (1973) discs to Advection-Dominated Acretion Flows (ADAFs, Abramowicz et al., 1995; Narayan and Yi, 1995) which the transition coincides with the Luminous Hot Accretion Flow (LHAF, Yuan, 2003; Yuan and Narayan, 2014).

3.2. Modulation of Jet Production

Another worth considering idea which may explain the visible $P_j/L_d - \lambda_{\rm Edd}$ distribution is taking into account the variability of accretion rate. The method we used to establish jet powers is based on the total energy content of the radio lobes. Their lifetime is long (even up to 10^8 years, Komissarov and Gubanov, 1994) so the only possibility of observing variations of jet powers is connected with the hotspot luminosity which may vary on much shorter time-scales. Hotspots however make a small contribution to the total radio luminosity (Mullin et al., 2008) as a result of which jet powers from integrated lobe luminosities are not significantly affected by the variability of the accretion rate. This property may be noticed in the disc luminosity though, which is a direct measure of instantaneous accretion rate. Taken together these findings implicate a modulation of both, the "apparent" jet production efficiency as well as the Eddington ratio in such a way that with decreasing $\lambda_{\rm Edd}$ the P_j/L_d increases. This causes the stretching with the slope -1 on the plot which is presented as the set of arrows on the **Figure 1**. just as the sources are distributed. Variability of accretion rate may be naturally caused by the viscous instabilities in accretion discs (Janiuk et al., 2002; Janiuk and Czerny, 2011).

4. SUMMARY

In this proceeding we argue that jets in FR II radio galaxies and quasars accreting at moderate accretion rates are not only powered by MAD scenario but they are also much more powerful than this mechanism predicts. We highlight two possible reasons for this discrepancy. The first one indicates that the geometrical thickness of accretion flows can have much bigger impact on jets formation and evolution than it was originally considered. Here we point out that the future work should concentrate on

the existence of thicker than the standard accretion discs as well as on systems with massive, hot coronas. The second solution focuses on the variability of accretion rate which can significantly influence observed $P_j/L_d - \lambda_{\rm Edd}$ distribution. Since estimated by us jet powers are based on the calorimetry on the radio lobes and thereby they are averaged over the lifetime of the source, an important issue to resolve for future studies is to check if using different methods for calculating jet powers such as X-ray cavities (Cavagnolo et al., 2010; Nemmen and Tchekhovskoy, 2015) or model of hotspots (Godfrey and Shabala, 2013) such a trend of decreasing $\lambda_{\rm Edd}$ with increasing P_j/L_d will be still visible.

AUTHOR CONTRIBUTIONS

Both authors made substantial, direct and intellectual contribution to the work. KR collected and analyzed presented data. MS formulated the original problem, provided direction and guidance. Both authors contributed to the discussion of the obtained results.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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