Jet–Accretion System in the Nearby mJy Radio Galaxies

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Abstract

It is generally thought that FRII radio galaxies host thin optically thick disks, while FRIs are powered by advection-dominated accretion flows. Sources with an efficient engine are optically classified as high-excitation radio galaxies (HERGs) and those with an inefficient motor as low-excitation radio galaxies (LERGs). Recently, the study of radio galaxies down to mJy flux has cast serious doubts on the LERG-FRI and HERG-FRII correspondence, revealing that many LERGs show FRII radio morphologies. The FR catalogs recently compiled by Capetti et al. and Baldi et al. have allowed us to explore this issue in the local (z ≤ 0.15) mJy universe. Our statistical study shows that the majority of nearby mJy objects are in a late stage of their life. FRII-LERGs appear more similar to the old FRI-LERGs than to the young FRII-HERGs. FRII-LERGs may be aged HERGs that, having exhausted their cold fuel, have changed their accretion regime or are a separate LERG class particularly efficient in launching jets. Exploiting the empirical relations that convert L1.4 GHz into accretion power and jet kinetic power, respectively, we observed that LERGs with similar masses and accretion rates seem to expel jets of different powers. We speculate that intrinsic differences related to the black hole properties and jet kinetic power, respectively, we observed that LERGs with similar masses and accretion rates seem to expel jets of different powers. We speculate that intrinsic differences related to the black hole properties (spin and magnetic field at its horizon) can determine the observed spread in jet luminosity. In this view, FRII-LERGs should have the fastest spinning black holes and/or the most intense magnetic fluxes. On the contrary, compact LERGs (i.e., FRBs) should host extremely slow black holes and/or weak magnetic fields.

Unified Astronomy Thesaurus concepts: Radio active galactic nuclei (2134)

1. Introduction

Radio galaxies (RGs) have historically been divided into core-brightened FRI and bright edge-brightened FRII (Fanaroff & Riley 1974), on the basis of their extended radio morphology that approximately changes at a critical power \( P_{1.4 \text{ GHz}} \sim 3 \times 10^{25} \text{ W Hz}^{-1} \). Ledlow & Owen (1996) refined the classification showing that the break between FRIs and FRIIs is a strong function of the host galaxy absolute magnitude \( M_B \). As the host galaxy luminosity traces the black hole (BH) mass (Magorrian et al. 1998) and the radio power is proportional to the accretion luminosity (Willett et al. 1999), the FRI–FRII separation was later interpreted in terms of accretion rates (Ghisellini & Celotti 2001). The less powerful radio galaxies (i.e., FRIs) host an inefficient hot thick flow, while the more powerful sources (i.e., FRIIs) have an efficiently accreting cold disk. In support of this interpretation, Marchisini et al. (2004) found an accretion rate gap between FRIs and FRIIs, suggestive of a different accretion regime. From the optical point of view, radio galaxies are split into high-excitation radio galaxies (HERGs) and low-excitation radio galaxies (LERGs; Jackson & Rawlings 1997), with LERGs characterized by \([\text{O III]} \) equivalent width \(< 10 \text{ Å} \) and/or \([\text{O II}] / [\text{O III}] \) ratios \(> 1 \). More recently, Buttiglione et al. (2010) proposed a combination of emission lines, the excitation index \((\text{Ei})^\text{5}\), to distinguish the classes: LERGs have \( \text{Ei} < 0.95 \) and HERGs \( \text{Ei} > 0.95 \).

As FRIIs are generally associated with HERGs and FRIs to LERGs, it is almost natural to consider the nuclear engine as the main driver of the FRI–FRII dichotomy. However, this one-to-one correspondence (FRI-LERGs versus FRII-HERGs), based on the study of powerful sources with Jansky flux densities, is probably a simplification.

For example, 24 FRII sources in the 3CR sample (Buttiglione et al. 2010) lack high-excitation emission lines and are classified as LERGs. Similarly, Tadhunter et al. (1998), studying the 2Jy sample (Wall & Peacock 1985), found that 23% of the FRIIs are weak-line radio galaxies (WLRGs), i.e., objects with \( \text{EW}_{[\text{O III}]} < 10 \text{ Å} \). As discussed by Tadhunter (2016), WLRGs generally correspond to LERGs, although the classification criteria are slightly different. Moreover, some FRIs have efficient accretion disks (i.e., they are FRI-HERGs). 3C 120, with broad and intense optical lines, a prominent UV bump, and an iron line in the X-ray spectrum (Torresi 2012), is a typical example. The difficulty in reconciling accretion mode and kiloparsec radio morphology has become more evident in recent years when large-area radio (NVSS, FIRST) and optical (SDSS and 6dFGRS) spectroscopic surveys have allowed the study of radio galaxies to be expanded down to mJy fluxes (see Heckman & Best 2014 for a review). Several studies show that radio galaxies with FRII morphologies preferentially host low-efficient accretion flows (i.e., they are classified as LERGs) at low flux densities (Capetti et al. 2017a, 2017b; Miraghaei & Best 2017). Finally, a recent analysis of low-luminosity radio galaxies observed by LOFAR (Mingo et al. 2019) has questioned the FRI/FRII break based on the radio power. At low fluxes, any association between morphology and radio
luminosity seems to disappear. If radio galaxies of similar radio morphology (radio power) can come into different “accretion flavors,” new scenarios have to be considered. The accretion rate could not be the driving parameter, and something else related to the BH could play a major role in launching the jet (Ghisellini et al. 2014). The environment could be also important, as radio, optical, and X-ray studies (Croston et al. 2005, 2008, 2018; Gawroński et al. 2006; Gendre et al. 2013; Ineson et al. 2017; Mingo et al. 2019; Macconi et al. 2020) seem to suggest. Finally, we could be observing the different phases that active galactic nuclei (AGNs) pass through their life. For example, a recent X-ray analysis of 3C radio galaxies (Macconi et al. 2020) has shown that FRII-LERG nuclei have less cold gas, i.e., smaller column densities ($N_{\text{HI}}$) than FRI-HERGs. A possible suggestion is that a transition occurs from a thin disk to a thick flow in FIRs when the cold fuel has been depleted. Incidentally, this leads us to speculate that FRIs could switch from an LERG to HERG if a sudden replenishment of fresh cold gas occurs, maybe due to a galaxy merger (see, for example, Garofalo & Singh 2019). However, most of the results (and controversial interpretations) are based on the study of very bright (Jansky) radio sources that make up only a small fraction of the total radio galaxy population. In order to shed light on these open questions, the jet–accretion system is explored through the study of local faint (mJy) radio galaxies, taking advantage of the recently compiled radio catalogs FRcat (Capetti et al. 2017a, 2017b; Baldi et al. 2018) that include sources well characterized both in the radio and optical bands.

A cosmology with $H_0 = 67$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\text{m}} = 0.32$, and $\Omega_{\Lambda} = 0.68$ (Planck Collaboration et al. 2014) is assumed in this paper.

2. The FRcat Samples

The FR0 (Baldi et al. 2018), FRI (Capetti et al. 2017a), and FRII (Capetti et al. 2017b) catalogs include 108, 219, and 122 radio galaxies, respectively. They are part of a large sample assembled by Best & Heckman (2012, hereafter the B12 sample), cross-correlating the seventh data release of the Sloan Digital Sky Survey (SDSS) with the NRAO (National Radio Astronomy Observatory) VLA (Very Large Array) Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey. For all the AGNs in the sample, Best & Heckman (2012) provided an optical classification (LERG/HERG) assuming different criteria (Kewley et al. 2006; Buttiglione et al. 2010; Cid Fernandes et al. 2010) depending on the signal-to-noise ratio of emission lines (e.g., $H_{\alpha}$, $H_{\beta}$, O III, O I, N II, S II) revealed in the SDSS spectra.

The FRI and FRII catalogs are limited to local radio galaxies (maximum distance $z < 0.15$) with an NVSS flux density larger than 5 mJy and a (one-side) extension of at least 30 kpc. The radio classification was performed by a visual inspection of the FIRST images. If a radio galaxy showed a higher surface brightness near the core (edge darkness), it was defined as FR Type I. On the contrary, if it appeared brighter at the end (edge brightened), the associated radio class was FR Type II. An additional sample of 14 small FRIs (sFR) was also included in the FRICat. It consists of sources located at $z \leq 0.05$ and with a radio extension between 10 and 30 kpc. As stressed by Capetti et al. (2017b), the FRI and FRII catalogs are statistically complete at a level of ~90% in the optical range and have a flux limit of ~50 mJy at 1.4 GHz.

The FR0 catalog (Baldi et al. 2018) consists of FIRST compact radio galaxies with a minimum flux density of 5 mJy at 1.4 GHz, at redshift $\leq 0.05$ (i.e., with a maximal radio extension of 2.5 kpc), all optically classified as LERGs (see Baldi et al. 2019 for a review of this class of objects). Four compact sources with HERG properties were also revealed but not included. A summary of the selection criteria is reported in Table 1.

While in the 3CR catalog more than 40% are powerful radio galaxies with an efficient accretion disk, in the FR catalogs, radio galaxies with high-excitation emission lines are a minority, ~4% (see Figure 1). Interestingly enough, Miraghaei & Best (2017) provided the radio classification of another B12 subsample, adopting slightly different selection criteria. Despite the different approaches, they confirm the predominance of LERGs in the FRII population.

2.1. SDSS Observables and Derived Quantities

Thanks to the MPA-JHU DR7 release of spectrum measurements, we could estimate the BH mass and radiative luminosity for each source in the FR catalogs. The velocity dispersion ($\sigma_*$) was converted into BH mass using the relation $\log(M_{\text{BH}}/M_\odot) = 8.32 + 5.64 \times \log(\sigma_*/200 \text{ km s}^{-1})$ (McConnell & Ma 2013) and the $O$ III] $\lambda$5007 luminosity into radiative luminosity (hereafter named accretion luminosity, $L_{\text{acc}}$) using the multiplicative factor 3500, $L_{\text{acc}} = 3500 \times L_{\lambda}$ (Heckman et al. 2004).

Other important DR7 quantities, useful to characterize the galaxies hosting different FR classes, are the stellar mass and the calcium break $D_{4000}$. The stellar masses are obtained by fitting a large grid of models from Bruzual & Charlot (2003) to the broadband $u, g, r, i, z$ photometry of SDSS. The calcium break values are derived considering the ratio of the flux in the red continuum (4000–4100 Å) to that in the blue continuum (3850–3950 Å; Balogh et al. 1999). The $D_{4000}$ jump is considered an indicator of stellar activity (Worthey & Ottaviani 1997). Being due to metal absorption, it is expected to be smaller in galaxies with young stars (i.e., with highly ionized atoms).

2.2. Checking the FR0 Sample

The selection and classification of large samples of objects necessarily imply the inclusion of a small fraction of spurious sources. As noted by Best & Heckman (2012), this is not a problem if the number of sources is large (of the order of several hundreds or more), but it could have an impact on

| Sample | $z$ | Optical Class | Extension (kpc) |
|--------|-----|---------------|-----------------|
| FR0cat | $<0.05$ | LERG | $<2.5$ |
| FRIcat | $<0.15$ | LERG | $>30$ |
| sFRcat | $<0.05$ | LERG | $>10$ and $<30$ |
| FRICat | $<0.15$ | LERG/HERG | $>30$ |

Table 1 Sample Selection Criteria: $F_{1.4\,GHz} > 5$ mJy

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6 $1^\circ$ corresponds to 2.72 kpc at $z = 0.15$.

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https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/
smaller samples. This is particularly true for the FR0s that are not resolved in the FIRST survey and could be misclassified.

Low radio flux density sources without any resolved jet structure could hide a weak BL Lac nucleus or a radio-quiet LINER with intense star formation.

We sought possible spurious sources by exploring the WISE color–color diagram. Three infrared bands, w1(3.4 μm), w2(4.6 μm), and w3(12 μm), were considered. The color w3 − w2 was plotted versus the color w2 − w1. It is known that different sources occupy different regions of the plot, with redder objects characterized by higher values of w3 − w2 and w1 − w2. Elliptical galaxies are expected to have colors near zero while star-forming galaxies (SF) are very red in both w3 − w2 and w2 − w1. Radio-quiet and radio-loud AGNs with efficient accretion disks and dusty screens are in between (see Figure 12 of Wright et al. 2010).

Figure 2 (left panel) shows all the objects of the B12 sample with z ≤ 0.05 together with FR0s marked as black points. LERGs are in the elliptical region, star-forming galaxies mainly above w3 − w2 > 2, and the few HERGs are in the AGN area. As expected, there is overlapping between FR0s and LERGs, although a handful of compact radio sources are shifted to redder colors (w3 − w2 > 2 and w2 − w1 > 0.1). Some of them are also clearly separated from the bulge of the FR0 population in the D4000 versus L1.4 GHz/M* diagram (Figure 2, right panel), one of the diagnostic plots proposed by Best & Heckman (2012) to divide AGNs from star-forming galaxies.

Taking a conservative approach, we then decided to exclude from our statistical analysis those FR0s with redder WISE colors (w3 − w2 > 2 and w2 − w1 > 0.1). These have a negligible probability to be star-forming galaxies. Also, we also excluded FR0s with D4000 < 1.8. As pointed out by Capetti & Raiteri (2015), a small amplitude of the 4000 Å break could be a signature not only of young stars but also of a jet. The nonthermal radiation can indeed dilute the optical continuum, reducing the D4000 depth. Finally, we note that the not genuine FR0 nature is certain for, at least, two compact radio galaxies. They have red WISE colors, a small calcium break, a BH mass less than 10^8 M_☉ (typical of radio-quiet AGNs), and a high probability of residing in spiral galaxies (Huertas-Company et al. 2011; Tempel et al. 2017).

At the end of this selection, the “clean” sample consisted of 99 FR0s with only 9 rejected sources (less than 1% of the sample).
### 3. Comparison among the Different Classes

Table 2 reports the median, average, and relative standard deviation of all the studied quantities. A comparison among the different classes was performed by applying a Kolmogorov–Smirnov (KS) test. We conservatively assumed that two data sets are different if the KS probability is less than $\times 10^{-3}$. In other words, we reject the null hypothesis that the two data sets are drawn from the same distribution at a confidence level $>3\sigma$. The KS results are in Table 3. In Figure 3, the most interesting histograms are shown.

As expected, FRII-HERGs have smaller black holes, a larger accretion rate, and more stellar activity. They are younger systems. More interesting is that our analysis reveals that the relative standard deviation of the mass in the central black hole is lower for FRII-HERGs than for FRIs, while it is higher for FRII-LERGs. Moreover, the relative standard deviation of the stellar mass is larger for FRII-LERGs than for FRIs and FRII-HERGs.

#### Table 2

| Class       | Median | Average | std   | No. Objects | Class       | Median | Average | std   | No. Objects |
|-------------|--------|---------|-------|-------------|-------------|--------|---------|-------|-------------|
| ($z < 0.15$) |        |         |       |             | ($z < 0.05$) |        |         |       |             |
| FRI         | 40.32  | 40.34   | 0.34  | 219         | FR0         | 38.87  | 38.96   | 0.36  | 99          |
| FRII-LERG   | 40.77  | 40.75   | 0.49  | 108         | FRI         | 40.12  | 40.13   | 0.40  | 9           |
| FRII-HERG   | 41.37  | 41.26   | 0.55  | 14          | small FRI   | 39.52  | 39.60   | 0.34  | 14          |
|             |        |         |       |             | FRII-LERG   | 40.77  | 40.75   | 0.49  | 108         |
|             |        |         |       |             | FRI         | 40.12  | 40.13   | 0.40  | 9           |
|             |        |         |       |             | FRII-HERG   | 41.42  | 41.30   | 0.52  | 14          |
|             |        |         |       |             | small FRI   | 39.39  | 39.37   | 0.15  | 14          |
|             |        |         |       |             | FRII-LERG   | 39.91  | 39.95   | 0.39  | 66          |
|             |        |         |       |             | FRI         | 39.51  | 39.50   | 0.17  | 9           |
|             |        |         |       |             | FRI         | 40.32  | 40.34   | 0.34  | 219         |
|             |        |         |       |             | FR0         | 38.87  | 38.96   | 0.36  | 99          |
|             |        |         |       |             | FRII-LERG   | 40.77  | 40.75   | 0.49  | 108         |
|             |        |         |       |             | FRI         | 40.12  | 40.13   | 0.40  | 9           |
|             |        |         |       |             | FRII-HERG   | 41.42  | 41.30   | 0.55  | 14          |
|             |        |         |       |             | small FRI   | 39.52  | 39.60   | 0.34  | 14          |

#### Table 3

| Class     | $\log(L_{1.4 \text{ GHz}})$ | $\log(L_{\text{O III}})$ | $\log(BH)$ | $\log(L_{\text{acc}}/L_{\text{Edd}})$ | $\log(M_*)$ | $D_{\text{KS}}$ |
|-----------|-----------------------------|---------------------------|-------------|----------------------------------------|-------------|-------------|
| ($z < 0.15$) | $<10^{-3}$                  | 0.18                      | $3.7 \times 10^{-3}$ | $3.5 \times 10^{-3}$ | $5.7 \times 10^{-2}$ | 0.06 |
| FRI vs. FRII-LERG | $<10^{-3}$                  | $<10^{-3}$                | $<10^{-3}$    | $<10^{-3}$                            | $<10^{-3}$  |
| FRII-LERG vs. FRII-HERG | $1.9 \times 10^{-2}$     | $10^{-3}$                | $10^{-3}$    | $3.2 \times 10^{-3}$ | $<10^{-3}$  |
| ($z < 0.05$) | $<10^{-3}$                  | 0.18                      | $3.2 \times 10^{-2}$ | $<10^{-3}$                            | 0.33        | 0.33        |
| FR0 vs. small FRI | ...                        | $8 \times 10^{-3}$        | $2.1 \times 10^{-3}$ | 0.20                                   | 0.01        | 0.37        |
| small FRI vs. FRI | $3.8 < 10^{-3}$             | 0.19                      | $5.7 \times 10^{-2}$ | 0.42                                   | 0.06        | 0.84        |

Notes. Bold values underline the physical quantities that are different, with a large level of confidence.
shows that FRII-HERGs and FRII-LERGs are also different. FRIIs with an inefficient engine have more massive black holes and a more evolved stellar population (Table 2 and Figure 3), i.e., are more similar to FRIIs. Indeed, FRI and FRII-LERG classes are almost completely overlapped in the histograms of Figure 3.

The nuclear properties of mJy LERG sources, independently of their radio morphology, are very similar, at odds with the trend observed in Jansky radio galaxies. As shown by Macconi et al. (2020), the FRII-LERGs of the 3C sample indeed have accretion rates \( \dot{L}_{acc} / L_{44\alpha} \) generally lower than FRII-HERGs but higher than FRIs.

At \( z \leq 0.05 \), no significant difference is observed between small and extended FRIs. FR0s have accretion rates slightly higher than FRIs (see Table 2). Although potentially interesting, we do not further speculate on this result, as still missed outliers in the FR0 sample cannot be definitively excluded. However, recent stellar activity is not observed in any classes, suggesting that all the LERGs in the local universe are in a late stage of evolution.

4. Jet Power versus Accretion Power

In this section, we explore the jet–accretion link in mJy radio galaxies to find possible intrinsic differences in their nuclear engine. Following Shankar et al. (2008), we define the jet and the radiation power as \( P_{jet} = \eta M c^2 \) and \( L_{acc} = \epsilon M c^2 \), with \( \eta \) and \( \epsilon \) the fraction of gravitational energy converted into jet power and thermal radiation, respectively. Combining the two relations, we obtain

\[
P_{jet} = (\eta / \epsilon) L_{acc}.
\]

The \( (\eta / \epsilon) \) ratio directly measures the ability of the system to channel gravitational energy into the jet rather than to dissipate it in thermal radiation.

The radiative power can be related to the [O III] luminosity through \( L_{acc} = L_{[O\text{ III}]} \times 3500 \) (see Section 2), while the kinetic power, expressed as a function of the radio luminosity \( (L_{rad}) \), is generally written as \( P_{jet} = KL_{rad}^{\alpha} \).

A jet power–radio luminosity relation was first proposed by Willott et al. (1999):

\[
P_{jet} = 4 \times 10^{35} f^{3/2} L_{1.4}^{0.86}.
\]

Here the original relation, which uses the radio luminosity at 151 MHz, is rescaled to 1.4 GHz by adopting a radio spectral index \( \alpha = 0.8 \) (Heckman & Best 2014). The luminosity is in units of \( 10^{25} \text{ W Hz}^{-1} \).

As a starting point, Willott et al. (1999) assumed that the jet energy is mainly stored in the lobe and/or utilized to expand the radio source and considered the radiative losses negligible. They provided a minimal estimation of the internal energy in an equipartition regime (i.e., the internal energy is almost equally distributed between the magnetic field and relativistic particles) and then divided this quantity by the source age. The \( f \) factor (included in the normalization) absorbs all of the uncertainties on the physical state of the lobes, such as the particle composition and their spectral distribution, volume filling factor, possible deviation from the equipartition condition, presence of internal turbulence, and fraction of internal energy lost as work done during the lobe expansion (assumed to be \( \sim 50\% \) of the internal energy). Among these, the number of protons per electron present in the relativistic plasma is the most relevant one. The analysis of Willott et al. (1999), based on FRI and steep-spectrum radio quasars, constrained \( f \) between 1 (light jet) and 20 (heavy jet). Later, Daly et al. (2012), investigating 31 FRII radio quasars, constrained \( f \) and a value of \( f \sim 5 \).

The extension of these studies to sources in gas-rich environments (mainly FRIs) was viable after the launch of the Chandra satellite. The discovery of X-ray cavities around radio lobes suggested a different approach to estimate \( P_{jet} \). The jet power could be deduced considering the energy spent by lobes to displace the surrounding gas and the age of the cavity (see Birzan et al. 2008 for details on the age calculation). The required energy (i.e., the enthalpy \( H \)) to excavate the medium is the sum of the work done by the lobes \( (pV) \) and their thermal energy. The enthalpy is assumed to be \( H = 4pV \) if the lobe is dominated by relativistic particles (McNamara & Nulsen 2007).

Cavagnolo et al. (2010) studied 16 giant radio galaxies (mainly FRIs) and found \( P_{jet} \propto L_{0.75}^{0.14} \), in some agreement with Willott’s relation. Finally, we mention a study of 15 radio galaxies (Merloni & Heinz 2007) where a relation between the jet power, estimated from X-ray cavities, and the radio core luminosity was explored. The authors reported a relation, \( P_{jet} \propto L_{0.8} \), similar to those deduced by Willott et al. (1999) and Cavagnolo et al. (2010), allowing the study of jet kinetic power to also be extended to small and unresolved radio galaxies.

The assumption here is that beaming Doppler boosting effects do not amplify the 1.4 GHz radiation.
are quite confident that this condition is satisfied by our radio galaxies, considering that suspected BL LAC objects have been excluded by the FR0 cleaned sample. Incidentally, we note that the core contribution does not significantly affect the extended radio galaxies. As a check, we obtained a rough estimation of the “extended” 1.4 GHz luminosity by subtracting the FIRST peak flux (assumed to be a proxy of the core emission) from the total NVSS flux. This test was possible for more than 90% of FRI and FRII sources. The luminosities generally changed less than 0.2 dex on a logarithmic scale with no significant impact on our study (see next section).

Considering the above-mentioned caveats, we will handle the f parameter as an unknown variable in the following. Moreover, when Equation (2) is exploited to estimate the η/ε ratios of FR0s and small FRIs, their NVSS luminosities will be treated as upper limits.

4.1. Predicted Luminosities in Systems with Different Accretion Efficiency Ratios

Relation (2) can be rewritten in order to have the 1.4 GHz luminosity as the subject: for an [O III] luminosity as input, it then allows the expected radio luminosity to be estimated for any value of f and η/ε. The predicted $L_{1.4\text{GHz}}$, obtained assuming $L_{[\text{O III}]}$ ranging from 39 to 45, are shown in Figure 4 for $f=5$ (left panel) and $f=20$ (right panel). The luminosities are rescaled to the Eddington luminosity ($L_{\text{Edd}}$), using two different BH masses ($M_{\text{BH}}=10^{7.5}$ $M_{\odot}$ and $M_{\text{BH}}=10^{9.5}$ $M_{\odot}$) to cover the mass range observed in the FRcat sources. Each line in the plots corresponds to a different value of η/ε. The solid and dotted lines correspond to $M_{\text{BH}}=10^{7.5}$ $M_{\odot}$ and $M_{\text{BH}}=10^{9.5}$ $M_{\odot}$, respectively. Note that a change of the black hole mass has not an important impact on the predicted η/ε curves. As stressed in the previous section, the FRI and FRII radio luminosities could be overestimated by ~0.2 dex. Considering the intrinsic spread of each class in each plot, this effect is negligible. For small and compact sources, the η/ε values should be considered upper limits, with the contribution of the radio core to the total $L_{1.4\text{GHz}}$ luminosity being unconstrained. Comparing the two panels, it also appears evident that a variation of f only translates the η/ε curves, preserving the relative position of the different classes.

As expected, LERGs and HERGs, having different accretion rates (i.e., different $L_{[\text{O III}]}/L_{\text{Edd}}$), occupy different parts of the plot. FR0s, being compact radio sources by definition, populate the lower-left corner. However, a more careful inspection of Figure 4 shows that FRIs and HERGs preferentially fall in different η/ε strips and that LERGs are spread along the y-axis. It seems that jet–disk systems in HERGs favor a thermal dissipation of the gravitational power, while jets of different powers can be launched by very similar inefficient accretion flows. However, the implicit assumption here is that the normalization (i.e., f) of Equation (2) is the same for each FR class.

4.2. Exploring the [η/ε − f] Parameter Space of the FRcat Sources

In order to better investigate the problem, we then decided to explore the [η/ε − f] parameter space of each class. This time, the η/ε values were determined via Equation (2) by utilizing the observed average $L_{[\text{O III}]}$, $L_{1.4\text{GHz}}$, and $L_{\text{Edd}}$ luminosities in Table 2 and running f from 1 to 20. The (η/ε − f) pairs that do not satisfy the condition $L_{\text{acc}} \leq L_{\text{Edd}}$ were excluded.

In Figure 5 (left panel), the f and η/ε permitted values for FRII and FRI radio galaxies at $z > 0.05$ are shown for two different accretion rates. The separation at Log($L_{[\text{O III}]}/L_{\text{Edd}}$) = −6.7 is based on Figure 4. As already noted, the efficiency ratio increases from FRII-HERGs to FRII-LERGs if f is kept constant. Different classes could have the same η/ε ratio only if the normalization of Equation (2), i.e., f, is allowed to vary.

If the main source of uncertainty included in f is the plasma particle content (Willott et al. 1999), the condition of equal η/ε could be reached in FRIs and FRII-HERGs by assuming that jets are lighter in the former sources. Although not completely rejectable (our understanding of the particle acceleration near the BH is really poor), this hypothesis does not seem to be supported by observations of radio structures on kiloparsec scales. The decelerated and less collimated jets seen in FRIs are indeed suggestive of strong interactions with the environment and mass loading through mixing in turbulent layers (Perucho 2020). X-ray studies of radio lobes and gaseous environments of FRIs and FRIIs (Ineson et al. 2017; Croston et al. 2018) indicate indeed that core-brightened radio galaxies contain more protons than edge-brightened radio galaxies.
Another source of uncertainty that could be invoked to satisfy the equal $\eta/\epsilon$ condition is the ambient medium (Cavagnolo et al. 2010). Jets that propagate in a dense environment have to spend more internal energy pushing away the surrounding gas. A larger corrective factor (thus a larger $f$) should then be included in the normalization of Willott’s relation (2) if a radio source lives in a rich environment. Again, this conflicts with the observations. FRIs (that should have a smaller $f$ than HERGs for equal $\eta/\epsilon$) are preferentially found in groups or clusters when bright (Jansky) radio galaxies are considered (Gendre et al. 2013). Moreover, no environmental difference between FRIs and FRIs is observed in the local mly universe (Massaro et al. 2019).

In summary, it seems unlikely that radio galaxies, powered by different accretions, choose the same dissipative channel. It is more plausible that FRIs convert most of their gravitational energy into jet power and that of FRII-HERGs into thermal radiation.

FRII-HERGs represent a more complex class. They have radio morphologies and particle content (Ineson et al. 2017) similar to FRII-HERGs but inhabit older galaxies, have more massive black holes, and a smaller accretion rate. In addition, they have the largest $\eta/\epsilon$ ratios (Figure 4) despite their marked similarity with FRIs. As proposed by Maccioni et al. (2020), a possibility is that FRII-HERGs are old HERGs that, having exhausted their fuel, have changed the accretion mode. In this case, the values of $\eta/\epsilon$ are meaningless, as Equation (2) can no longer be applied with the nuclear region and the extended radio structures temporarily disconnected. On the other hand, theoretical studies show that inefficient accretion configurations between an ADAF and a cold efficient disk can exist (see Figure 1 of Yuan & Narayan 2014). If, for some reason, more viscous dissipated energy is transferred into electrons and radiated away, the ADAF accretion flow can enter into a more luminous hot accretion flow regime (Xie & Yuan 2012). If the electron cooling becomes too strong, the matter in accretion collapses into a cold disk or in cold dense clumps embedded in a hot flow (Yuan & Narayan 2014). We could then be observing the inverse trend.

Another option is that FRII-HERGs are a separate class and not a product of the FRII-HERG evolution. The observed $L_{\text{OIII}}/L_{\text{Edd}}$ spread of FRII-HERGs (see Figure 4) could then be simply due to the coexistence of ADAF configurations with different electron cooling. The high $\eta/\epsilon$ ratios are however difficult to explain, unless, for example, more extreme conditions of the BH properties are assumed for this class (see discussion below).

The $[\eta/\epsilon − f]$ parameter space of radio galaxies at $z \leq 0.05$ (i.e., FR0, small FRIs, and local FRIs) is shown in Figure 5 (right panel).

The plot is similar to that observed for sources at higher redshift: the efficiency ratio increases from FR0s to extended FRIs if $f$ is kept fixed. Also, in this case, equal $\eta/\epsilon$ values would require $f$ changing from a class to another one, implying possible different intrinsic (jet content) or external (environment) conditions. FR0s, which are less able to channel energy into the jets ($\eta/\epsilon$ is always less than 1), should expel heavier jets or be embedded in a very dense environment. The first hypothesis is difficult to test (in particular if the radio emission is not extended on large scales). The second one is more intriguing. The idea that a hostile ambient inhibits the jet expansion of small/compact radio galaxies is indeed plausible. However, observations do not support this view. A study based on the galaxy richness around the FR0 sources at $z \leq 0.05$ does not reveal any FR0 overdensity (Capetti et al. 2020). In addition, an X-ray study of the galaxy cluster Abell 795 having a FR0 at its center (Ubertosi et al. 2021, Ubertosi Master Thesis) found gas density and temperature typical of clusters hosting more extended central radio galaxies.

Figures 4 and 5 are suggestive of another viable interpretation. The different radio luminosities observed in LERGs having comparable accretion rates ($L_{\text{OIII}}/L_{\text{Edd}}$) might indicate that similar nuclear engines impart diverse accelerations to the outflowing plasma. One of the most accredited models for jet production (Blandford & Znajek 1977) links the jet kinetic power to the properties of the BH, i.e., mass, spin (a), and magnetic field at its horizon ($\Phi$): $P_{\text{BH}} \propto \Phi^2 a^2 M_{\text{BH}}^2$. Because LERGs have similar accretion rates and BH masses (Table 2), the vertical displacement of the FRCat $[\eta/\epsilon − f]$ curves could directly map different values of $a$ and/or $\Phi$. In this view, FR0s

\footnote{https://amslaurea.unibo.it/21460/}
(at least those with $\log(L_{\text{OIII}}/L_{\text{Edd}}) < -6.7$) should have extremely slow BHs and/or weak magnetic fluxes, while FRII-LERGs, assumed to be not evolved HERGs, have the largest values of $a$ and/or $\Phi$.

Finally, we note that Equation (2) does not take into account mildly relativistic winds that could contribute to the total kinetic budget ($P_{\text{tot}} = P_{\text{jet}} + P_{\text{winds}}$).

An advection-dominated inflow–outflow solution (ADIOS) proposed by Blandford & Begelman (1999) predicts the presence of matter outflows that, exceeding the amount of material crossing the BHH horizon, favors a low accretion rate. Magnetohydrodynamic (MHD) simulations of ADAF (Sadowski et al. 2013) also predict winds. These are expected to be less energetic than jets unless the BH spin and/or the magnetic flux is small.\(^9\) Moreover, Liska et al. (2019) showed that both jets and magnetically driven winds can be produced by AGNs with a thin accretion disk (and a fast-spinning black hole).

On the observational side, several works attest to the existence of outflows in bright radio galaxies. A very recent work by Boccardi et al. (2021), exploring the innermost jet profile of several radio-loud AGNs using VLBI data, has confirmed the existence of thick disk-launched layers surrounding the HERG jets and of less prominent sheaths, anchored to the innermost accretion regions, in LERGs. X-ray studies also confirm the coexistence of jets and outflows in the nuclear region of powerful radio galaxies (Torresi et al. 2012; Tombesi et al. 2014; Mehdipour & Costantini 2019). The velocity of these winds covers a wide range of possible values—in some cases, it can be as fast as $\sim 0.2c$. The measures of very fast outflows with velocities reaching an appreciable fraction of $c$ are technically difficult and probably limited by the transience of the event. However, if consolidated, they will attest to the importance role of the winds in the energy balance.

5. Conclusions

In this paper, the study of the mJy sources of the FRCat catalogs was performed following two different approaches. At first, we performed a statistical analysis of the main observables and compared the average properties of the different classes. Then, we explored the jet–accretion system by exploiting the known relations that link $L_{\text{OIII}}$ and $L_{1.4 \text{GHz}}$ to the accretion (thermal) and jet kinetic power, respectively.

The main results of our statistical analysis are summarized below:

1. FRIs compared to FRII-HERGs show more massive BHs, smaller accretion rates (expressed in terms of $L_{\text{acc}}/L_{\text{Edd}}$), larger stellar masses, and a more evolved stellar population;

2. FRII-LERGs are more similar to FRIs than FRII-HERGs;

3. No significant difference is observed between small FRIs and FRIs at $z < 0.05$. All of the local sources are hosted in massive galaxies with no recent star-forming activity and have comparable low accretion rates and BH masses;

4. FR0s show $M_*$ and $D_\text{4000}$ typical of evolved systems. Their $\log(L_{\text{acc}}/L_{\text{Edd}})$ ratio extends to values higher than local ($z \ll 0.05$) FRIs.

\(^9\) FR0s could be in this condition and dissipate more of their gravitational power into winds.

These results suggest that, in the mJy universe, the majority of radio galaxies within $z \leq 0.15$ are in a late stage of their life. The only exception is represented by the FRII-HERG class, which is, however, poorly populated.

From a comparison between Jansky and mJy FRII-LERGs, it emerges that lower radio flux density sources have, on average, FRI-like characteristics, while FRII-LERGs of the 3C sample are more “active” with intermediate properties between FRIs and FRII-HERGs (Maccioni et al. 2020). This points toward an evolutionary scenario in which FRII-LERGs are aged FRII-HERGs. Once the nuclear cold fuel has been consumed, the accretion configuration becomes hot and inefficient while the extended radio structures conserve traces of past activity. It has been shown that a wide range of configurations between the thick hot flow and thin cold disk is stable. If, for example, a strong and turbulent magnetic field permeates the accreting matter, MHD instabilities/magnetic reconnections can further heat the electrons that can radiate away, giving rise to more luminous hot accretion flows. Similar accretion configurations could account for the wide range of $\log(L_{\text{OIII}}/L_{\text{Edd}})$ in Figure 4, and even more for the higher $[\text{O III}]$ luminosities observed in the 3C FRI-LERGs.

We cannot however reject the hypothesis that FRII-LERGs are a separate and independent class with an inefficient accretion regime able to produce extended FRII radio structures. This breaks the correspondence between efficient/inefficient accretion and strong/weak jets, making appealing other options directly involving the black hole spin and/or the magnetic field at its horizon.

To further investigate this possibility we focused on the efficiency ratio parameter ($\eta/e$), which quantifies the capability of a source to convert gravitational energy into jet power rather than thermal radiation. We exploited the relations $P_{\text{jet}} = K(f)L_{\text{radio}}^{0.86}$ and $L_{\text{acc}} = 3500 \times L_{\text{OIII}}$ that, although empirical and affected by several uncertainties (absorbed by the $f$ parameter) allow us to directly relate jet kinetic and accretion powers to observed luminosities. Aware of the intrinsic limitation of this approach, we compared the $\eta/e$ ratios of the different classes considering two main sources of uncertainties: the particle composition of the relativistic plasma (Willott et al. 1999) and the work done by the jets on the surrounding medium (Cavagnolo et al. 2010).

We observe that:

1. FRIs and FRII-HERGs have different efficiency ratios. A similar $\eta/e$ in the two classes would require jet compositions and environment conditions not supported by the observations. In FRIs, the gravitational energy is preferentially channeled into the jets, in FRII-HERGs, it is mainly dissipated by thermal photons. Although our study does not include subrelativistic/mildly relativistic matter outflows, winds probably contribute to the total energy budget. In FRIs, jets launched by the Blandford & Znajek (Blandford & Znajek 1977) process should coexist with winds produced by the ADAF itself. Outflows of matter are indeed theoretically predicted in the inefficient accretion regimes (see the ADIOS model) and are also revealed in MHD simulations. In FRII-HERGs, both the Blandford & Znajek (Blandford & Znajek 1977) and the Blandford & Payne (1982) mechanisms could then be at work. The former launches jets extracting energy by the spinning black hole, the latter produces centrifugally driving outflows of matter
from a magnetized disk. The recent VLBI study of the inner jet profiles of radio galaxies (Boccardi et al. 2021) strongly supports this scenario.

2. The wide range of Log(L1.4 GHz/Ledd) observed in radio galaxies with similar Eddington-normalized [O III] luminosities (L([O III])/Ledd ≲ 6.7) might indicate that neither the BH mass nor the rate of the mass accretion are the key parameters to explain the class segregation of LERGs. If the difference originates in the nuclear engine, then the BH spins and/or the magnetic field threading their horizon are fundamental ingredients. Following Blandford & Znajek (1977), the jet propulsion could be less potent in FR0s than in FRIs, because the BH spins are slower and/or the magnetic field is weaker. Extending this interpretation to radio sources at z > 0.05, the high Eddington-normalized radio luminosities of FRII-LERGs (assumed as a class on its own) would imply BHs with the fastest spin and/or most intense magnetic field.

3. Assuming typical values of ε = 0.1 for efficient disks and ε ∝ 10^{-2} – 10^{-3} for ADAFs, an average η via Equation (2) can be derived for each class. In mJy sources, the fraction of gravitational power conveyed by the jets is modest, at most 10% in HERGs (excluding winds) and a few percentages in LERGs (despite their larger η/ε ratios). FR0s are the more extreme case, with η < a few 10^{-3}.

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