

Jet-accretion system in the nearby mJy Radio Galaxies

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ABSTRACT

It is generally thought that FR II Radio Galaxies host thin optically thick disks, while FR I are powered by Advected Dominated Accretion Flows. The 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 fluxes 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. \(2017a,b\)](#) and [Baldi et al. \(2018\)](#) have allowed us to explore this issue in the local ($z \leq 0.15$) 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, exhausted the cold fuel, have changed their accretion regime or a separate LERG class particularly efficient in launching jets. Exploiting the empirical relations which convert $L_{[\text{OIII}]}$ and $L_{1.4 \text{ GHz}}$ into accretion power and jet kinetic power, respectively, we observed that LERGs with similar masses and accretion rates seem to expel jets of different power. 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. FR0s) should host extremely slow black holes and/or weak magnetic fields.

Keywords: galaxies: active-galaxies: galaxies:-galaxies:jet

1. INTRODUCTION

Radio Galaxies (RGs) are historically divided in core-brightened FR I and bright edge-brightened FR II ([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_R). As the host galaxy luminosity traces the black hole mass (Magorrian et al. 1998) and the radio power is proportional to the accretion luminosity (Willott et al. 1999), the FRI-FRII separation was later re-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, Marchesini 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 [OIII] equivalent width $< 10 \text{ \AA}$ and/or [OII]/[OIII] ratios > 1 . More recently, Buttiglione et al. (2010) proposed a combination of emission lines, the excitation index (EI^1), to distinguish the classes: LERGs have $EI < 0.95$ and HERGs $EI > 0.95$.

As FRIIs are generally associated to 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 Jy 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 $EW_{[OIII]} < 10 \text{ \AA}$. 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 kpc radio morphology has become more evident in recent years when large-area radio (NVSS, FIRST) and optical (SDSS and 6dFGRS) spectroscopic surveys have allowed expanding the study of radio galaxies 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,b; 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 black hole 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; Gawroński et al. 2006; Croston et al. 2008; Gendre et al. 2013; Ineson et al. 2017; Croston et al. 2018; Mingo et al. 2019; Macconi et al. 2020) seem to suggest. Finally, we could be observing different phases that AGN 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_H) than FRII-HERGs. A possible suggestion is that a transition occurs from a thin disk to a thick flow in FRIIs when the cold fuel has been depleted. Incidentally, this leads to speculate that FRIs could switch from 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 (Jy) radio sources

¹ $EI = \text{Log}([OIII]/H\beta) - 1/3(\text{Log}([NII]/H\alpha) + \text{Log}([SII]/H\alpha) + \text{Log}([OI]/H\alpha))$

Table 1. Sample selection criteria: $F_{1.4\text{GHz}} > 5\text{mJy}$

Sample	z	Optical Class	Extension (kpc)
FR0cat	< 0.05	LERG	< 2.5
FRIcat	< 0.15	LERG	> 30
sFRIcat	< 0.05	LERG	> 10 and < 30
FRIIcat	< 0.15	LERG/HERG	> 30

which 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 FR catalogs FRcat (Capetti et al. 2017a,b; Baldi et al. 2018) that include sources well characterized both in the radio and optical bands.

A cosmology with $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.32$, 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 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 AGN in the sample, Best & Heckman (2012) provided an optical classification (LERG/HERG) assuming different criteria (Buttiglione et al. 2010; Kewley et al. 2006; Cid Fernandes et al. 2010) depending on the signal to noise ratio of emission lines (e.g. H_α , H_β , OIII, OI, NII, SII) 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 kpc². 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 $\sim 90\%$ in the optical range and have a flux limit of $\sim 50 \text{ mJy}$ 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 ≤ 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 on 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 $\sim 4\%$ (see Figure 1). Interestingly enough, Miraghaei & Best (2017) provided the radio classification of another BH12 subsample

² 1" corresponds to 2.72 kpc at $z=0.15$.

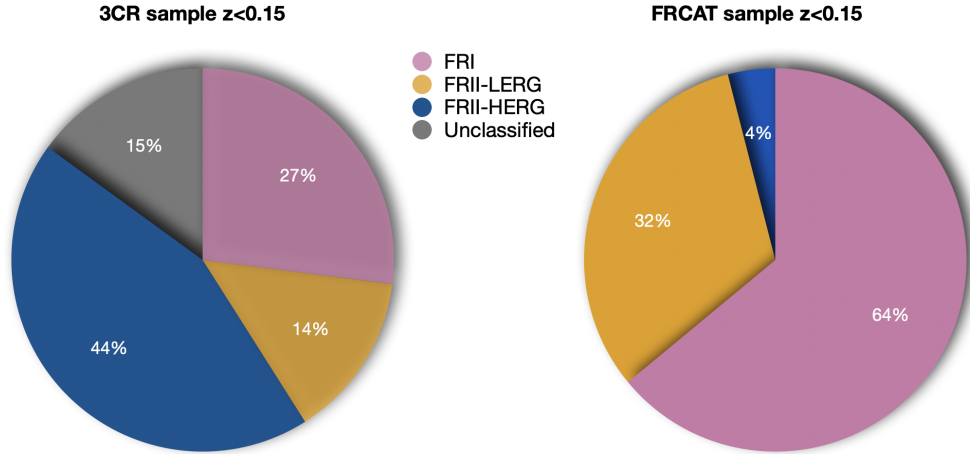


Figure 1. Fraction of FRI and FRII radio galaxies with $z < 0.15$ in the 3CR (*left pie*) and in the FRcat (*right pie*) catalogs. The number of LERGs increases going down to mJy fluxes.

adopting slightly different selection criteria. Despite the different approaches, they confirm the predominance of LERGs in the FRII population.

2.1. SDSS observables and derivated quantities

Thanks to the MPA-JHU DR7 release of spectrum measurements³, we could estimate black hole mass and radiative luminosity for each source of the FR catalogs. The velocity dispersion (σ_*) was converted into BH mass using the relation $\text{Log}(M_{BH}/M_\odot) = 8.32 + 5.64 \times \text{Log}(\sigma_*/200 \text{ km s}^{-1})$ (McConnell & Ma 2013) and the [OIII] λ 5007 luminosity into radiative luminosity (hereafter named accretion luminosity, L_{acc}) using the multiplicative factor 3500, $L_{\text{acc}} = 3500 \times L_{[\text{OIII}]}$ (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_n4000 . The stellar masses are obtained fitting a large grid of models from Bruzual & Charlot (2003) to the broad-band 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_n4000 jump is considered an indicator of the 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 ionised atoms).

2.2. Checking the FRO 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 smaller samples. This is particularly true for the FROs 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 for possible spurious sources exploring the WISE color-color diagram. Three infrared bands, w1(3.4 μ m), w2(4.6 μ m), and w3(12 μ m) 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

³ <https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/>

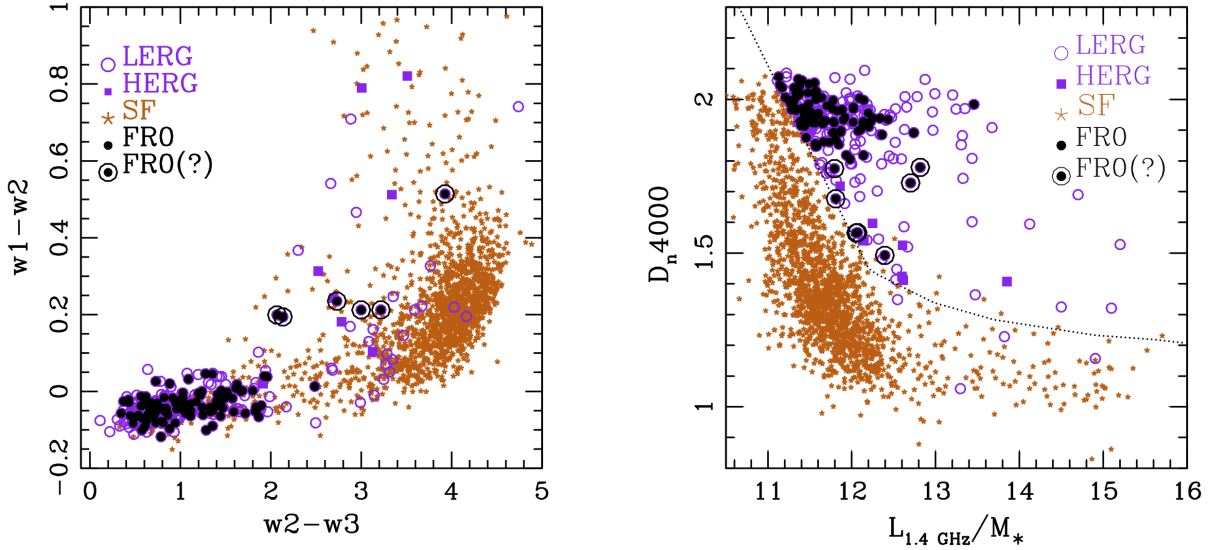


Figure 2. Diagnostic diagrams of radio sources with $z \leq 0.05$ of the sample of Best & Heckman (2012). LERGs are purple open circles, HERGs purple squares and Star-forming galaxies (SF) orange stars. FR0s from Baldi et al. (2018) are marked by black points. *Left panel* – WISE color-color diagram. LERGs are in the lower right corner, while the few HERGs are shifted towards redder colours. SF on the left are spread on a wide zone. FR0s mainly fall in the LERG zone. Those with $w3-w2 > 2$ and $w2-w1 > 0.1$ (open black squares) are excluded by the sample as possible spurious objects. *Right panel* – D_n4000 versus $L_{1.4\text{GHz}}/M_*$ diagnostic plane. The majority of FR0s are clustered in the AGN region with $D_n4000 \sim 2$. The sources with $D_n4000 < 1.8$ are rejected as possible Star-forming galaxies or BL Lacs.

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 AGN with efficient accretion disks and dusty screens are in between (see Fig. 12 of Wright et al. (2010)).

Figure 2 (*left panel*) shows all the objects of the B12 sample with $z \leq 0.05$ 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 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 bulk of the FR0 population in the D_n4000 versus $L_{1.4\text{GHz}}/M_*$ diagram (Fig. 2–*right panel*), one of the diagnostic plots proposed by Best & Heckman (2012) to divide AGN from star-forming galaxies.

Taking a conservative approach, we then decided to exclude from our statistical analysis those FR0s with redder WISE colours ($w3-w2 > 2$ and $w2-w1 > 0.1$). These have a not negligible probability to be star forming galaxies. Also, we also excluded FR0s with $D_n4000 < 1.8$. As pointed out by Capetti & Raiteri (2015), a small amplitude of the 4000\AA break could be a signature not only of young stars but also of a jet. The non-thermal radiation can indeed dilute the optical continuum reducing the D_n4000 depth. Finally, we note that the not genuine FR0 nature is certain for, at least, two compact radio galaxies. They have red WISE colours, small calcium break, a BH mass less than $10^8 M_\odot$ (typical of radio-quiet AGN), and a high probability to reside 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 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 Kolmogorov-Smirnov 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 and FRIs are distinct populations. FRII-HERGs have smaller black holes, a larger accretion rate expressed in terms of $L_{\text{acc}}/L_{\text{Edd}}$ and more stellar activity. They are younger systems. More interesting is that our analysis 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 Fig. 3), i.e. are more similar to FRIs. Indeed, FRI and FRII-LERG classes are almost completely overlapped in the histograms of Fig. 3.

The nuclear properties of mJy LERG sources, independently of their radio morphology, are very similar, at odds with the trend observed in Jy radio galaxies. As shown by Macconi et al. (2020), the FRII-LERGs of the 3C sample have indeed accretion rates ($L_{\text{acc}}/L_{\text{Edd}}$) 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 Tab 2). Although potentially interesting, we do not further speculate on this result, as still missed outliers in the FR0 sample can not 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.

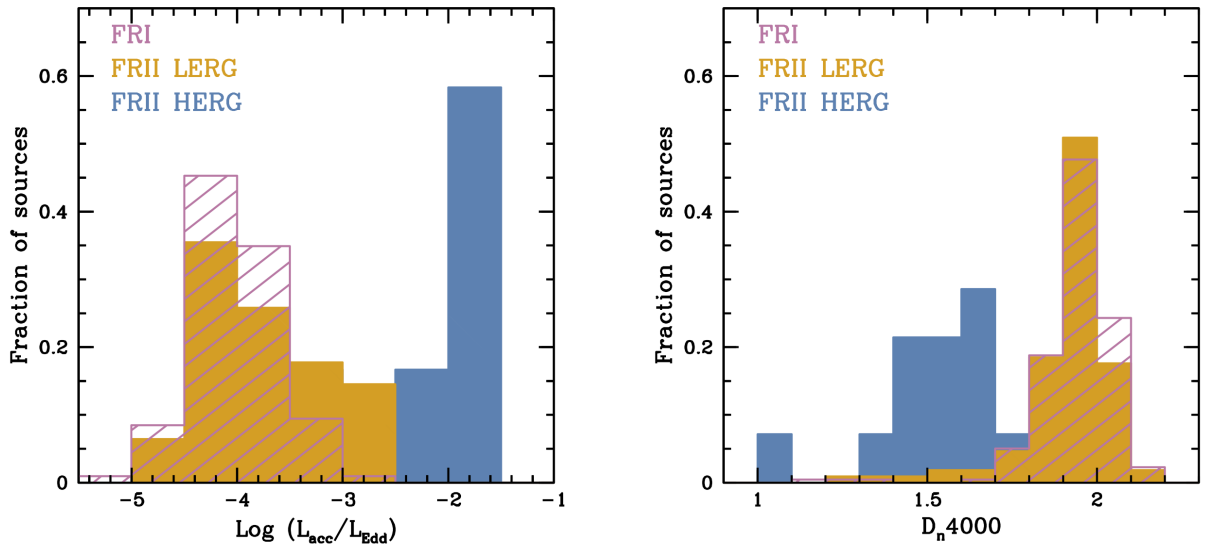


Figure 3. Eddington-scaled radiative luminosity (*left panel*) and calcium break (*right panel*) histograms. FRII-LERGs are similar to FRIs. Both live in old galaxies and are powered by hot accretion flows. FRII-HERGs are more radiatively efficient and show signs of star-forming activity.

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:

Table 2. FRCat Average Properties

Class	median	average	std	N. objects	Class	median	average	std	N.objects
($z < 0.15$)	Log($L_{1.4GHz}$) (erg s ⁻¹)				($z < 0.05$)	Log($L_{1.4GHz}$) (erg s ⁻¹)			
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
	Log(L_{OIII}) (erg s ⁻¹)					Log(L_{OIII}) (erg s ⁻¹)			
FRI	39.87	39.86	0.23	107	FR0	39.60	39.58	0.27	98
FRII-LERG	39.91	39.95	0.39	66	FRI	39.51	39.50	0.17	9
FRII-HERG	41.42	41.30	0.52	14	small FRI	39.39	39.37	0.15	12
	Velocity Dispersion σ_* (km s ⁻¹)					Velocity Dispersion σ_* (km s ⁻¹)			
FRI	254	256	35	218	FR0	231	237	38	97
FRII-LERG	246	243	39	102	FRI	270	276	31	9
FRII-HERG	209	204	23	12	small FRI	253	261	32	14
	Stellar Mass Log(M_*) (M_\odot)					Stellar Mass Log(M_*) (M_\odot)			
FRI	11.38	11.38	0.19	214	FR0	11.15	11.13	0.22	97
FRII-LERG	11.33	11.33	0.31	107	FRI	11.32	11.34	0.13	9
FRII-HERG	11.09	11.08	0.25	14	small FRI	11.22	11.23	0.17	14
	Calcium break (D_n4000)					Calcium break (D_n4000)			
FRI	1.96	1.94	0.12	218	FR0	1.96	1.95	0.06	99
FRII-LERG	1.96	1.94	0.14	108	FRI	1.95	1.91	0.07	9
FRII-HERG	1.59	1.53	0.19	14	small FRI	1.96	1.94	0.09	14
	Log(BH) (M_\odot)					Log(BH) (M_\odot)			
FRI	8.91	8.91	0.39	218	FR0	8.67	8.71	0.39	97
FRII-LERG	8.83	8.77	0.41	102	FRI	9.06	9.10	0.27	9
FRII-HERG	8.43	8.36	0.28	12	small FRI	8.89	8.95	0.29	14
	Log(L_{acc}/L_{Edd})					Log(L_{acc}/L_{Edd})			
FRI	-4.03	-4.03	0.40	106	FR0	-3.99	-4.04	0.47	96
FRII-LERG	-3.85	-3.74	0.55	62	FRI	-4.38	-4.50	0.32	12
FRII-HERG	-1.84	-2.1	0.57	12	small FRI	-4.38	-4.50	0.32	12

Table 3. FRCat Kolmogorov Smirnov test results

Classes	KS probability					
$z < 0.15$	$\text{Log}(L_{1.4\text{GHz}})$	$\text{Log}(L_{\text{OIII}})$	$\text{Log}(\text{BH})$	$\text{Log}(L_{\text{acc}}/L_{\text{Edd}})$	$\text{Log}(M_*)$	D_n4000
FRI vs FRII-LERG	$< 10^{-3}$	0.18	3.7×10^{-3}	3.5×10^{-3}	5.7×10^{-2}	0.06
FRI vs FRII-HERG	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
FRII-LERG vs FRII-HERG	1.9×10^{-2}	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	3.2×10^{-3}	$< 10^{-3}$
$z < 0.05$	$\text{Log}(L_{1.4\text{GHz}})$	$\text{Log}(L_{\text{OIII}})$	$\text{Log}(\text{BH})$	$\text{Log}(L_{\text{acc}}/L_{\text{Edd}})$	$\text{Log}(M_*)$	D_n4000
FR0 vs small FRI	–	8×10^{-3}	3.2×10^{-2}	$< 10^{-3}$	0.33	0.33
FR0 vs FRI	–	0.34	2.1×10^{-3}	0.20	0.01	0.37
small FRI vs FRI	$3.8 < 10^{-3}$	0.19	5.7×10^{-2}	0.42	0.06	0.84

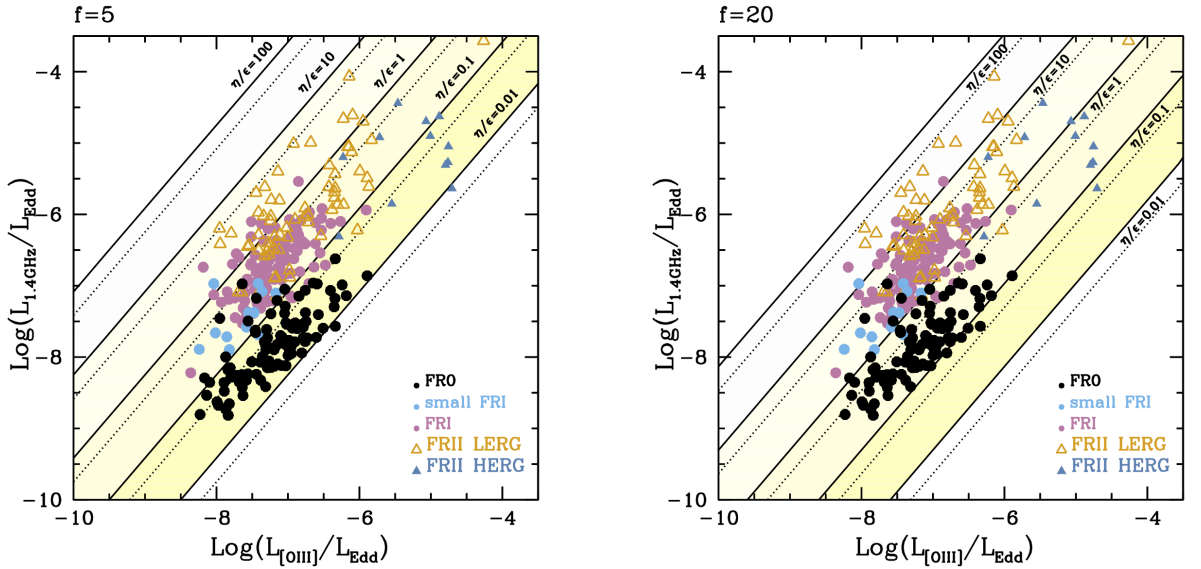


Figure 4. $L_{1.4\text{GHz}}/L_{\text{Edd}}$ versus $L_{\text{[OIII]}}/L_{\text{Edd}}$ of FRCat sources compared to the predicted values estimated by equation (2) assuming $f = 5$ (left panel) and $f = 20$ (right panel). Each line in the plots corresponds to a different value of η/ϵ . Solid and dotted lines corresponds to $M_{\text{BH}} = 10^{7.5} M_{\odot}$ and $M_{\text{BH}} = 10^{9.5} M_{\odot}$, respectively.

$P_{\text{jet}} = \eta \dot{M} c^2$ and $L_{\text{acc}} = \epsilon \dot{M} c^2$, being η and ϵ , the fraction of gravitational energy converted into jet power and thermal radiation, respectively. Combining the two relations we obtain:

$$P_{\text{jet}} = (\eta/\epsilon) L_{\text{acc}} \quad (1)$$

The (η/ϵ) 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 [OIII] luminosity through: $L_{\text{acc}} = L_{\text{OIII}} \times 3500$ (see Section 2), while the kinetic power, expressed as a function of the radio luminosity (L_{rad}), is generally written as: $P_{\text{jet}} = K L_{\text{rad}}^{\Gamma}$.

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

$$P_{jet} = 4 \times 10^{35} f^{3/2} L_{1.4}^{0.86} \quad (2)$$

Here the original relation, that uses the radio luminosity at 151 MHz, is re-scaled to 1.4 GHz adopting a radio spectral index $\alpha=0.8$ (Heckman & Best 2014). The luminosity is in units of 10^{25} Watt 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 magnetic field and relativistic particles) and then divided this quantity by the source age. The f factor (included in the normalization) absorbs all 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 FR II and Steep Spectrum Radio Quasars, constrained f between 1 (light jet) and 20 (heavy jet). Later, Daly et al. (2012), investigating 31 FR II radio galaxies with an accurate radio characterization, found a P_{jet} relation in substantial agreement with equation (2) and a value of $f \sim 5$.

The extension of these studies to sources in gas-rich environments (mainly FR I) 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 Bîrzan 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 FR I) and found $P_{jet} \propto L_{1.4}^{0.75(\pm 0.14)}$, in quite agreement with the 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, $P_{jet} \propto L_{core}^{0.8}$, similar to those deduced by Willott et al. (1999) and Cavagnolo et al. (2010) allowing to extend the study of jet kinetic power to also small and unresolved Radio Galaxies. The assumption here is that beaming Doppler boosting effects do not amplify the 1.4 GHz radiation. We are quite confident that this condition is satisfied by our Radio Galaxies, considering that suspected BL LAC objects have been excluded by the FR 0 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 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 FR I and FR II sources. The luminosities generally changed less than 0.2 dex on 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 FR 0s and small FR I, their NVSS luminosities will be treated as upper limits.

4.1. Predicted luminosities in systems with different accretion efficiency ratios

Relation (2) can be re-written in order to have the 1.4 GHz luminosity as subject: for an [OIII] luminosity as input, it then allows to estimate the expected radio luminosity for any value of f and η/ϵ .

The **predicted** $L_{1.4\text{GHz}}$ values, obtained assuming $L_{[\text{OIII}]}$ 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_{Edd}), using two different black hole 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 . 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, being unconstrained the contribution of the radio core to the total $L_{1.4\text{GHz}}$ luminosity. Comparing the two panels, it appears also 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 $L_{[\text{OIII}]} / L_{\text{Edd}}$), occupy different parts of the plot. FROs, 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 favour 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 classes.

4.2. Exploring the $[\eta/\epsilon-f]$ parameter space of the FRcat sources

In order to better investigate the problem, we then decided to explore the $[\eta/\epsilon-f]$ parameter space of each class. This time, the η/ϵ values were determined via equation (2) utilizing the **observed** average $L_{[\text{OIII}]}$, $L_{1.4\text{GHz}}$ and L_{Edd} luminosities in Table 2 and running f from 1 to 20. The $(\eta/\epsilon-f)$ 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 $\text{Log}(L_{[\text{OIII}]} / L_{\text{Edd}}) = -6.7$ 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 only assuming that jets are lighter in the former sources. Although not completely rejectable (our understanding of the particle acceleration near the black hole is really poor), this hypothesis does not seem to be supported by the observations of radio structures on kpc 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 η/ϵ 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 η/ϵ) are preferentially found in groups or clusters when bright (Jy) radio galaxies are considered (Gendre et al. 2013). Moreover, no environmental difference between FRIs and FRIIs is observed in the Local mJy 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 jets power and FRII-HERGs into thermal radiation.

FRII-LERGs represent a more complex class. They have radio morphologies and particle content (Ineson et al. 2017) similar to FRII-HERGs but habit older galaxies, have more massive black holes and a smaller accretion rate. In addition, they have the largest η/ϵ ratios (Fig. 4) despite their marked similarity with FRIs. As proposed by Macconi et al. (2020), a possibility is that FRII-LERGs are old HERGs that, exhausted their fuel, have changed the accretion mode. In this case, the values of η/ϵ are meaningless, as Equation (2) cannot be applied anymore being 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 reasons 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 in 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-LERGs are a separate class and not a product of the FRII-HERG evolution. The observed $L_{\text{OIII}}/L_{\text{Edd}}$ spread of FRII-LERGs (see Fig. 4) could then be simply due to the co-existence of ADAF configurations with different electron cooling. The high η/ϵ ratios are however difficult to explain, unless, for example, more extreme conditions of the black hole 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 Fig. 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 η/ϵ values would require f changing from a class to another one, implying possible different intrinsic (jet content) or external (environment) conditions. FR0s, that are less able to channel energy into the jets (η/ϵ 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, the observations do not support this view. A study based on the galaxy richness around the FRCat sources at $z \leq 0.05$ does not reveal any FR0 over-density (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 A&A submitted, Ubertosi Master Thesis⁴) 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

⁴ <https://amslaurea.unibo.it/21460/>

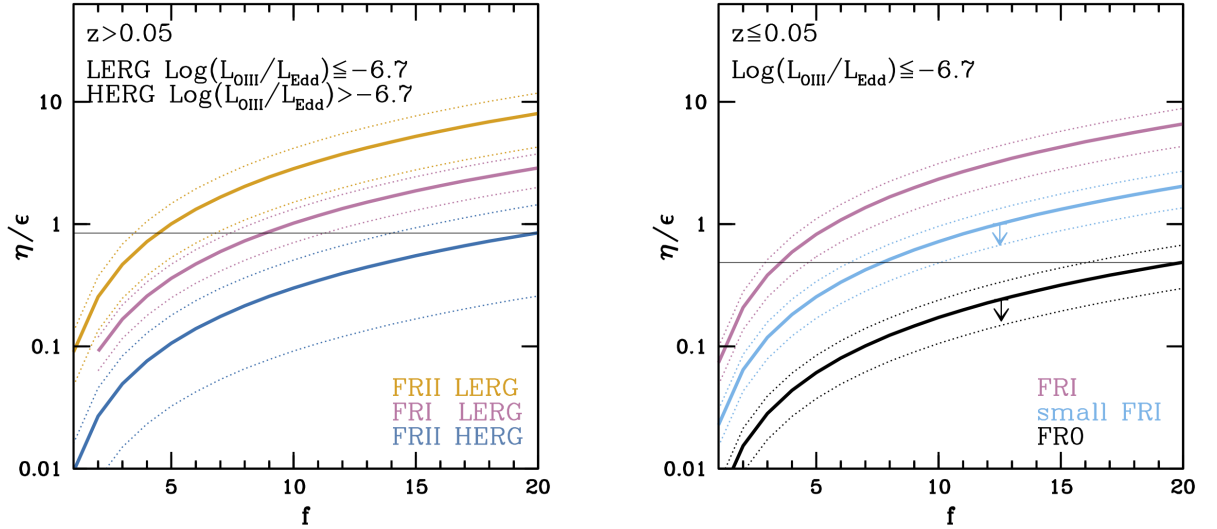


Figure 5. *Left Panel* – $[\eta/\epsilon - f]$ parameter space for FRIs, FRII-LERGs and FRII-HERGs with $z > 0.05$. The curves are obtained via equation (2) assuming the average $L_{[\text{OIII}]}$ and L_{NVSS} luminosities (and standard deviation σ) in Table 2. Dotted lines correspond to $1\text{-}\sigma$ uncertainty. The separation at $\text{Log}(L_{[\text{OIII}]} / L_{\text{Edd}}) = -6.7$ between HERGs and LERGs is based on Figure 4. The intersections of the horizontal line with the curves mark the f values required to have a same efficiency ratio ($\eta/\epsilon = 0.98$ in this case) in each class. *Right Panel* – Same plot for FROs, small FRIs and FRIs with $z \leq 0.05$. The horizontal line corresponds to $\eta/\epsilon = 0.49$. Vertical arrows indicate that the η/ϵ values traced by the curves have to be intended as upper limits.

diverse accelerations to the outflowing plasma. One of the most accredited model for the jet production (Blandford & Znajek 1977) links the jet kinetic power to the properties of the black hole, i.e. mass, spin (a) and magnetic field at its horizon (Φ): $P_{\text{BZ}} \propto \Phi^2 a^2 M_{\text{BH}}^2$. Since LERGs have similar accretion rates and black hole masses (Table 2), the vertical displacement of the FRcat $[\eta/\epsilon - f]$ curves could directly map different values of a and/or Φ . In this view, FROs (at least those with $\text{Log}(L_{[\text{OIII}]} / L_{\text{Edd}}) < -6.7$) should have extremely slow black holes and/or weak magnetic fluxes, while FRII-LERGs, assumed not evolved HERGs, the largest values of a and/or Φ .

Finally, we noted 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 black hole horizon, favours a low accretion rate. Magneto-hydrodynamic (MHD) simulations of ADAF (Sądowski et al. 2013) also predict winds. These are expected to be less energetic than jets unless the black hole spin and/or the magnetic flux are small⁵. 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. (2020), exploring the innermost jet profile of several radio-loud AGN using VLBI data, has confirmed the existence of thick disk-launched layers surrounding the HERG jets and of

⁵ FROs could be in this condition and dissipate more of their gravitational power into winds.

less prominent sheaths, anchored to the innermost accretion regions, in LERGs. X-ray studies also confirm the co-existence 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 transiency of the event. However, if consolidated, they will attest to the important 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 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:

- FRIs compared to FRII-HERGs show more massive black holes, smaller accretion rates (expressed in terms of $L_{\text{acc}}/L_{\text{Edd}}$), larger stellar masses, and a more evolved stellar population;
- FRII-LERGs are more similar to FRIs than FRII-HERGs;
- No significant difference is observed between small FRIs and FRIs at $z < 0.05$. All the local sources are hosted in massive galaxies with no recent star forming activity and have comparable low accretion rates and black hole masses;
- FR0s show M_* and D_n4000 typical of evolved system. Their $\text{Log}(L_{\text{acc}}/L_{\text{Edd}})$ ratio extend to values higher than local ($z \leq 0.05$) FRIs.

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 Jy 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 (Macconi et al. 2020). This points towards 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 the past activity. It has been shown that a wide range of configurations between 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 origin to more luminous hot accretion flows. Similar accretion configurations could account for the wide range of $\text{Log}(L_{[\text{OIII}]} / L_{\text{Edd}})$ in Fig. 4, and even more for the higher [OIII] luminosities observed in the 3C FRII-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 (η/ϵ), that quantifies the capability of a source to convert gravitational energy into jet power rather than in thermal radiation. We

exploited the relations $P_{jet} = K(f)L_{radio}^{0.86}$ and $L_{acc} = 3500 \times L_{[OIII]}$ that, although empirical and affected by several uncertainties (absorbed by the f parameter) allow to directly relate jet kinetic and accretion powers to observed luminosities. Aware of the intrinsic limitation of this approach, we compared the η/ϵ 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:

- FRIs and FRII-HERGs have different efficiency ratios. A similar η/ϵ 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 mainly dissipated by thermal photons. Although our study does not include sub-relativistic/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 co-exist 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 (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 disc. The recent VLBI study of inner jet profiles of radio galaxies (Boccardi et al. 2020) strongly supports this scenario.
- The wide range of $\text{Log}(L_{1.4\text{GHz}}/L_{\text{Edd}})$ observed in radio galaxies with similar Eddington normalized [OIII] luminosities ($L_{[OIII]}/L_{\text{Edd}} \leq -6.7$) might indicate that neither the black hole 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 spin of the black hole and/or the magnetic field threading its horizon are fundamental ingredients. Following Blandford & Znajek (1977) the jet propulsion could be less potent in FR0s than in FRIs, because the black hole 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 black holes with the fastest spin and/or most intense magnetic field.
- Assuming typical values of $\epsilon \sim 0.1$ for efficient disks and $\epsilon \sim 10^{-2}-10^{-3}$ 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 $\eta < \text{a few } 10^{-3}$.

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