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# The new class of FR 0 radio galaxies

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Are the FR I and FR II radio galaxies representative of the radio-loud (RL) AGN population in the local Universe? Recent studies on the local low-luminosity radio sources cast lights on an emerging population of compact radio galaxies which lack extended radio emission. In a pilot JVLA project, we study the high-resolution images of a small but representative sample of this population. The radio maps reveal compact unresolved or slightly resolved radio structures on a scale of 1–3 kpc. We find that these RL AGN live in red massive early-type galaxies, with large black hole masses ( $\gtrsim 10^8 M_\odot$ ), and spectroscopically classified as Low Excitation Galaxies, all characteristics typical of FRI radio galaxies which they also share the same nuclear luminosity with. However, they are more core dominated (by a factor of  $\sim 30$ ) than FRIs and show a clear deficit of extended radio emission. We call these sources 'FR0' to emphasize their lack of prominent extended radio emission. A posteriori, other compact radio sources found in the literature fulfill the requirements for a FR 0 classification. Hence, the emerging FR0 population appears to be the dominant radio class of the local Universe. Considering their properties we speculate on their possible origins and the possible cosmological scenarios they imply.

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## 1 Introduction

Classical radio catalogs (e.g. 3C, 2Jy...) are set at low radio frequencies and limited by high flux density. These selection criteria favor the inclusions of extended steep spectrum sources, Fanaroff-Riley classes (FR I and FR II), where the core emission contributes  $\sim 1\%$  of their total emission and their sizes are of tens or hundreds of kpc (e.g. Morganti et al. 1997). Furthermore, they produce a bias, since the high core-dominant sources are excluded. In fact, when the selection biases used are less severe (lower flux threshold and/or higher frequency), core dominated radio-galaxies (RGs), generally too faint to be detected in the existing low-frequency limited surveys, emerge as the dominant constituent of the RL AGN population (Baldi & Capetti, 2010). Hence, do the classical FR I and FR II RGs represent the real picture of RL AGN? In this contribution to the Proceedings, we want to address this question in the context of the jet formation in the local Universe.

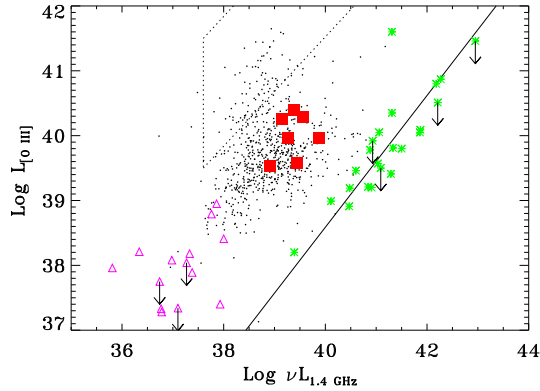
We investigate the properties of the local RL AGN population, selected by Best et al. (2005) (hereafter B05), a sample of RGs by cross-correlating the SDSS (DR2), NVSS, and FIRST datasets. This sample is highly (95%) complete down to the flux threshold of 5 mJy and provides a very good representation of RGs in the local Universe, up to a redshift of  $\lesssim 0.3$ , covering the range  $10^{38-42} \text{ erg s}^{-1}$  in

radio power. All morphologies are represented, including twin-jets and core-jet FR Is, narrow and wide angle tails, and FR IIs. However, most of them  $\sim 80\%$  are compact, unresolved or barely resolved at the  $5''$  FIRST resolution, corresponding to a limit to their size of  $\sim 10$  kpc. This sample does not mostly overlap with previous classical radio catalogs because of their low radio flux density and is more numerous than 3C sample of a factor of  $\sim 100$  in space density.

Baldi & Capetti (2010) analyzed their spectrophotometric properties and they found that they display a strong deficit of radio emission with respect to their nuclear emission-line luminosity up to a factor 1000, when compared to FR I and FR II matched in line luminosity (Fig. 1). Most of them live in red massive ( $\sim 10^{11} M_\odot$ ) early-type galaxies (ETGs), with large BH masses ( $\gtrsim 10^8 M_\odot$ ), and spectroscopically classified as Low Excitation Galaxies, all characteristics typical of FR Is.

A similar radio behavior is also noted in the 'miniature' RGs, i.e. Core Galaxies (CoreG), nearby giant ETGs of extremely low radio luminosity ( $10^{20-22} \text{ W Hz}^{-1}$  at 1.4 GHz) (Balmaverde & Capetti, 2006). Despite their low total radio power, they host RL nuclei and produces jets on a scale of  $\sim 20$  kpc, smaller than the typical size of  $\sim 100$  kpc of the FR Is. Their host and nuclear properties are indistinguishable from the FR Is (e.g. Baldi & Capetti 2009; Balmaverde et al. 2006, 2008). However, CoreG show a core dominance up to  $\sim 100$  times higher than FR Is, but

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**Fig. 1** FIRST vs. [O III] line luminosity ( $\text{erg s}^{-1}$ ). The small points correspond to the B05 sample. The solid line represents the correlation between line and radio-luminosity derived for the 3CR/FR I sample. The dotted lines include the region where Seyfert galaxies are found. The empty pink triangles are the CoreG, and green stars the 3CR/FR Is. The red squares are the FR 0s.

similar to the B05 sample (Baldi & Capetti, 2009). A high core dominance is generally interpreted as evidence of Doppler boosting in a radio source oriented at a small angle with respect to the line of sight. The correlation found with the core radio power and emission line luminosity (independent of orientation) indicates that this is a genuine deficit of extended radio emission and that no geometric effect is present.

The smaller jets produced by the CoreG compared to FR Is might be ascribed to their lower AGN luminosity, although they have similar properties. However, the B05 sample, which show a similar radio deficit to the CoreG, have optical luminosities similar to the FR Is and their nuclei and hosts are statistically indistinguishable from those of 3C sources from the point of view of morphology, color, stellar and BH masses. Therefore, this radio behavior cannot be ascribed to differences in their hosts, but to other mechanisms.

In conclusion, the properties of the bulk of the population of RL AGNs (with a space density  $\sim 100$  times higher than 3C sources) are virtually unexplored. This severely limits our ability to understand their nature and the jet formation in low-luminosity AGN. An improvement of the radio data is needed to provide a more complete view of the radio emission phenomenon. For this purpose, we start a project with the JVLA aimed at study the high-resolution properties of the RL AGN population, represented by the B05 sample. Here, we present the results from a pilot sample, largely discussed in Baldi et al. (2015).

## 2 Sample

We observe with the JVLA at three frequencies (1.4, 4.5, and 7.5 GHz) twelve objects selected from the B05 sample

with the following criteria: redshift  $z < 0.1$ ; the main optical emission lines detected at least  $5\sigma$  significance; equivalent width for the [O III] lines larger than  $3\text{ \AA}$ .

We will study the RL AGN objects present in this sample, since a contamination from radio-quiet (RQ) AGN is expected to be present in the B05 sample.

## 3 Results

### 3.1 Spectro-photometric properties

We now explore the physical properties of the present sample based on the optical spectroscopic and photometric information available from the SDSS survey, similarly to the study performed on the B05 sample by Baldi & Capetti (2010).

We estimated the BH masses from the stellar velocity dispersion adopting the relation of Tremaine et al. (2002). They range from  $\sim 10^7$  to  $\sim 10^9 M_\odot$ . The sources are associated with galaxies with a distribution of masses in the range  $10^{10}$ - $10^{11.5} M_\odot$ .

Studying their concentration index  $C_r$  (defined as the ratio of the radii including 90% and 50% of the light in the  $r$  band) to carry out a morphological classification of the hosts (e.g. Shen et al. 2003), either early- and late-type galaxies are present in the sample. We also use the 4000Å break strength,  $D_n(4000)$  (defined as the ratio between the fluxes in the wavelength range 3850-3950Å and 4000-4100Å), sensitive to the presence of a young stellar population (Balogh et al., 1999). A further diagnostic panel tool enables us to qualitatively measure the amount of contamination in radio emission in the galaxy that is due to star formation. This method is based on the location of a galaxy in the  $D_n(4000)$  versus  $L_{1.4\text{ GHz}}/M_*$  plane, where  $M_*$  is the galaxy's stellar mass (Fig. 6 from Baldi et al. 2015). Nine sources are above the curve corresponding to the prediction of a star formation event lasting 3 Gyr and exponentially decaying. According to B05, their radio emission is associated with the AGN.

We used the spectroscopic diagnostic diagrams defined by Buttiglione et al. (2010) for the 3CR sample to recognize the nature of their nuclear emission. These diagnostics are formed by pairs of nuclear emission line ratios to separate active nuclei from star-forming galaxies (e.g. Baldwin et al. 1981) and, furthermore, to separate AGN into branches of different excitation level, that is Low- and High-excitation galaxies (LEG and HEG). So, we classify the spectra of our sample in nine LEGs and three HEGs (Fig. 1 from Baldi et al. 2015).

Based on the spectro-photometric properties, we can distinguish the presence of two groups. The first group consists of four sources that are characterized by their low BH masses, mostly  $\sim 10^7 M_\odot$  and their blue color. Their radio and spectrophotometric properties indicate that they are RQ AGN. The presence of an active nucleus is evidenced by their optical line ratios and equivalent widths, which are

characteristic of AGN. Nonetheless, three of them show a substantial contamination from star formation to their radio emission and are in late-type galaxies.

Conversely, the second group includes eight sources with high BH masses ( $\gtrsim 10^8 M_\odot$ ) whose radio emission is dominated by the radio AGN and are considered as the RL counterpart of the sample. With the sole exception of 625, they are associated with red massive ETGs belonging to the LEG spectroscopic class, similar to the vast majority of the B05 sample.

### 3.2 Radio data

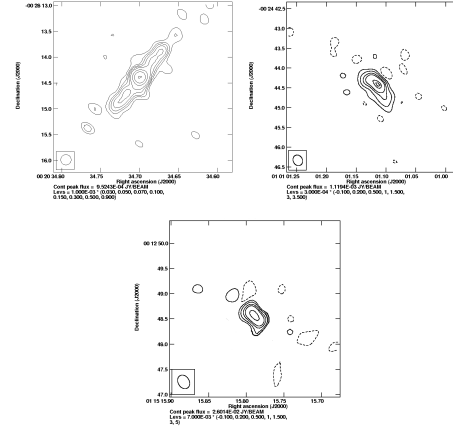
Let us focus on the new high-resolution JVLA observations at 1.4, 4.5, and 7.5 GHz of the eight RL objects. One object, 625, shows a FRI/FRII radio morphology extended over  $\sim 40$  kpc and has a HEG optical spectrum. We exclude it from the final sample, consisting of 7 objects (see the luminosities and properties in Table 1). The new JVLA maps of these objects revealed that they show a compact morphology, unresolved or only slightly resolved (core-jet) down to a resolution of  $\sim 0''.2$  (Fig. 2). The total morphology shows structure on a scale of 1-3 kpc. The sources which show an interesting morphology are: 547 (a twin-jet source), and 590 (with an elongated radio morphology on a scale of  $0''.8$ , possibly due to a bent two-sided jet structure).

We measure the spectral slope  $\alpha$  ( $F_\nu \propto \nu^\alpha$ ), obtained between 1.4 and 4.5 GHz: they range from -1.00 to -0.04, indicative of steep and flat spectra. For most of the objects, the spectra show a flattening at 7.5 GHz (Fig. 4 from Baldi et al. 2015, sign of an emerging radio core component).

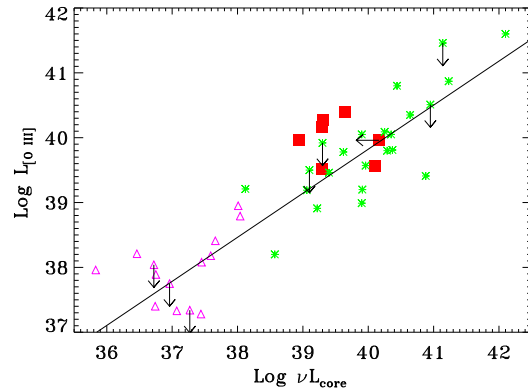
One of the main purposes of our program is to isolate the radio core component and to measure the core dominance of the sources of our sample. The high-resolution radio maps at 7.5 GHz reveal an unresolved radio core component for three sources (519, 537, and 547). For the remaining sources, we can use the radio spectra to measure the core emission, at the frequency where the spectra flatten. The radio core luminosities are in the range  $\sim 10^{39-40}$  erg s $^{-1}$ , similar to the cores of 3CR/FR Is.

After measuring the radio core component thanks to the new observations, we can include our sources in the  $L_{core}$  vs.  $L_{[O III]}$  plane (Fig. 3), similarly to what was done for CoreG in Baldi & Capetti (2009). The seven sources lie on the  $L_{core}$  vs.  $L_{[O III]}$  correlation found for the 3CR/FR Is. This strongly indicates their radio-loudness and their genuine lack of substantial large-scale radio emission since no geometric effect is present (Fig 1).

The core dominance of our sources is defined as the ratio between the source nuclear emission at 7.5 GHz and the total flux density, for which we adopted the NVSS measurement. The core dominance ranges between 0.05 and 0.86 (Fig. 7 from Baldi et al. 2015) and is consistent with the core dominance of CoreG and higher than 3CR/FR Is by a factor  $\sim 30$ .



**Fig. 2** The JVLA maps at 7.5 GHz of the three FR 0s, (from left top 547, 590, and 605) which show extended structure (resolution of  $\sim 0''.2$ ). See Baldi et al. (2015) for the expanded radio maps.



**Fig. 3** Core radio power vs. [O III] line luminosity (erg s $^{-1}$ ). The line indicates the best linear fit for 3CR/FR I. The color symbols are like in Fig. 1

## 4 Discussion

The results discussed in the previous sections indicate that these seven objects (together with the powerful source 625 discussed above) are the genuine RL AGN in the pilot sample selected from B05. They are located in red massive ( $\sim 10^{11} M_\odot$ ) ETGs, have BH masses  $\gtrsim 10^8 M_\odot$  (Chiaberge & Marconi, 2011) and are spectroscopically classified as LEGs. All these (host and nuclear) properties are shared with FR I RGs (e.g., Baldi & Capetti 2008, 2009; Baldi et al. 2015; Balmaverde et al. 2006; Chiaberge et al. 1999). Furthermore, their radio core and [O III] luminosities lie in the range typical of FR Is. The JVLA observations show compact radio structures (with a limit to their size of  $\sim 0.5$  kpc or, in a few cases, extending by at most 1-3 kpc) and lead to an estimate of their (average) core dominance a factor of  $\sim 30$  higher than FR Is. The only feature distinguishing them from FR Is is then the substantial lack of extended radio emission. For this paucity we call them *FR 0* in

**Table 1** Spectroscopic and photometric properties of the FR 0s

ID	z	opt. class	Log $M_*$	Log $M_{BH}$	Log $L_{[O III]}$	Log $L_{FIRST}$	Log $L_{NVSS}$	Log $L_{core}$
519	0.076	LEG	11.30	8.67	40.28	39.50	39.56	39.31
524	0.093	LEG	11.07	8.32	39.96	39.89	39.87	<40.16
535	0.076	LEG	11.48	8.76	40.26	38.96	39.14	39.29
537	0.061	LEG	11.09	7.72	39.52	38.90	38.90	39.29
547	0.072	LEG	11.18	7.64	39.97	39.22	39.27	38.93
590	0.097	LEG	11.42	8.43	40.39	39.22	39.37	39.64
605	0.045	LEG	11.15	8.57	39.57	39.47	39.44	40.10

Column description: (1) name; (2) spectroscopic redshift; (3) optical spectroscopic classification; (4) galaxy stellar mass  $M_*$  ( $M_\odot$ ); (5) black hole mass  $M_{BH}$  ( $M_\odot$ ); (6) [O III] luminosity ( $\text{erg s}^{-1}$ ); (7) 1.4 GHz FIRST luminosity ( $\text{erg s}^{-1}$ ); (8) 1.4 GHz NVSS luminosity ( $\text{erg s}^{-1}$ ) used as total radio luminosity  $L_{tot}$ ; (9) 7.5 GHz JVLA luminosity ( $\text{erg s}^{-1}$ ) used as radio core luminosity  $L_{core}$ .

opposition to the jetted FR radio classes (Fanaroff & Riley, 1974) and in agreement with Ghisellini (2011).

#### 4.1 The FR 0 population

The FR 0 classification then corresponds to a combination of radio and spectro-photometric (both nuclear and of the host) properties. FR 0s and FR Is are indistinguishable in terms of nuclear and host properties (color, BH mass, optical spectra). They show compact radio structures on scale of some kpc. The high FR 0 core dominance appears to be due to the genuine paucity of extended radio emission, rather than to an enhanced radio core, since FR 0s and FR Is show similar ratios of radio-core to emission line luminosity.

The CoreG fulfill the requirements for a FR 0 classification: they show kpc scale radio structures and are of high core dominance, they are hosted in red giant ellipticals and are characterized by LEG line ratios. They are  $\sim 100$  times less luminous than the FR 0s studied here. They smoothly extend the various nuclear multi-wavelengths relations seen in FR Is. In this sense, they represent the low-luminosity end of the FR 0 population that therefore extends at least down to a radio power of  $\sim 10^{36}$   $\text{erg s}^{-1}$ .

Since the vast majority of the B15 sample fulfills the FR 0 definition (a deficit of radio emission and similar spectro-photometric properties to FR Is), this strongly indicates that the FR 0 population is the dominant radio class in the local Universe. However, a detailed radio study of a large portion of this sample is needed to put these results on a firmer ground. This conclusion was also recently claimed by Sadler et al. (2014), who found that the bulk of the 20-GHz RG population consists of compact radio sources lacking extended radio emission, analogous to our FR 0s.

This new class of RGs is similar to the low-luminosity radio sources hosted in ETGs, studied by Slee et al. (1994), which contain parsec-scale radio cores and do not produce extended radio emission. The presence of a large population of low luminosity compact sources has been recently unveiled by Kunert-Bajraszewska et al. (2010), similar to FR 0s but much brighter. This new RG class is also consistent with a subclass of low-luminosity Gigahertz-Peaked Spectrum (GPS) radio sources proposed by Tingay & Edwards (2015), which show jet-dominated

compact morphologies similar to FR Is, but lacking extended radio emission.

What causes the radio deficit in FR 0s? In CoreG small scale jets and plumes are the dominant radio morphology. This favors the idea that their jets suffer deceleration and disruption before escaping the host core radius, slowly burrowing their way into the external medium and accounting for their small sizes. Furthermore, the similarity of the host and nuclear properties of FR Is and FR 0s constrain two scenarios that can explain their extended radio difference.

In the first scenario, the central engines of FR 0s and FR Is are indistinguishable and the paucity (and small size) of the extended radio emission is ascribed to an evolutionary effect. Since FR 0s appear small and compact, they might be young and will possibly evolve into more extended FR I and FR II. However, this implies that their number density should be much lower than that of FR Is, but this is the opposite of what is observed. This scenario can still hold if FR 0s are intermittent sources. Rapid intermittency, e.g., with a timescale of  $\sim 10^{4-5}$  years would prevent FR 0s from becoming well developed FR Is. Several suggestions in this direction have been proposed (e.g. Reynolds 1997) based on various physical mechanisms, such as disk (or jet) instabilities or discontinuous accretion. The drawback of this scenario is that it does not explain why these mechanisms should be at work only in FR 0s. Furthermore, this scenario is in contradiction with the studies on FR Is and CoreG (Allen et al., 2006; Balmaverde et al., 2008), which indicate that accretion is provided by the X-ray emitting hot gas of the corona, which slowly cools, shrinks and supplies the central BH. This implies a long-lasting continuous inward transfer of gas related only to the host properties and then no differences would be expected between FR 0s and FR Is.

As a second scenario, we suggest that the differences between FR 0s and FR Is are driven by a different value of the jet bulk speed  $\Gamma$ , with FR 0s having lower  $\Gamma$  values with respect to FR Is. In this scheme, FR 0s and FR Is share a common range of accretion rate (as proved by their similar line emission luminosity and similar optical line ratios) and of radio core power (which represents the synchrotron emission from the base of the jet). Therefore, the innermost regions of FR 0 and FR Is are not expected to differ significantly. The different radio behaviors should arise on a

larger scale. In the hypothesis that jets in FR 0s are slower than FR 1s, they are more subject to instabilities and entrainment (Bodo et al., 2013; Perucho, 2012) and this causes their premature disruption. Indeed, the typical scale of the radio emission in FR 0s is usually smaller than the core size of their host galaxies coronae, a region characterized by a dense interstellar medium that easily may obstruct the passage of the jet. This hypothesis is supported, albeit with a small number statistics, by the absence of one-sided kpc scale morphologies among the FR 0s observed, the typical sign of relativistic jet boosting.

The ultimate origin of this effect is apparently not related to any directly observable quantity. We speculate that this could be due to a different spin of their central BH. A broad and continuous distribution of BH spin is a indeed natural consequence of galaxy evolution via both BH mergers and gas accretion (e.g., Volonteri et al. 2013). By assuming that dependence between the BH spin (and the BH mass) and jet bulk Lorentz factor  $\Gamma$  exists (e.g., Chai et al. 2012; Liu et al. 2015), this would result in the needed spread of  $\Gamma$  values. The FR 1s might represent the cases where the efficiency in the mechanism of launching of a relativistic jet is maximized. The FR 1 radio morphology is produced only when the BH spin is close to its maximum value, while smaller spin values could be associated with FR 0s. Another benefit of this scenario is that, since FR 1s represent the cases with extreme values of spin, the broad range of BH spins would account for the more numerous population of FR 0s than FR 1s. Circumstantial evidence in favor of this speculation comes from the slight differences in large scale environment between FR 0s and FR 1s. The latter class is generally ( $\gtrsim 70\%$ ) associated with clusters or rich groups (e.g. Wing & Blanton 2011). Conversely, although FR 0s avoid regions of low galaxies density and are located in a richer environment than RQ AGN (B05), they are also found outside clusters. This could alter slightly their evolution with respect to FR 1s (i.e., from the point of view of merger rate and/or merger type), leading to a difference in the BH spin distribution.

## 5 Summary and Conclusions

The most studied catalogues of RGs are severely biased against the inclusion of objects with high core dominance, since a large contribution from extended emission is needed to fulfill the stringent flux requirements of low frequency, high flux threshold samples. Conversely, recent studies on low-luminosity RGs (e.g., Baldi & Capetti 2009, 2010; Baldi et al. 2015; Sadler et al. 2014) have been converging to an opposite picture: the local RL AGN population is dominated by compact high core-dominated weak RGs, the FR 0s, which show a lack of prominent extended radio structures with respect to other FR classes. Such a dominant population is still unexplored, casting shadow on our present knowledge about the radio-AGN phenomena.

The FR 0 radio structures are not small because of a low-power engine or because of geometrical effects, and their different radio properties cannot be ascribed to differences in their hosts. Our preferred scenario to account for their radio behavior is the slow jets, associated with small jet Lorentz factors ( $\Gamma \lesssim 2 - 3$ ), probably due to small BH spins. Furthermore, this conjecture matches with the idea of recent studies on the radio-mode feedback which have been gradually oriented to low-power/compact jets (e.g. Cielo et al. 2014; Perucho et al. 2014; Shabala et al. 2011), because they appear to be more efficient to deposit energy on the galaxy scale rather than powerful radio galaxies which flow faster out from the galaxy.

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