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The nature of compact radio sources: the case of FR 0 radio galaxies

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Abstract Radio-loud compact radio sources (CRS) are characterised by a morphological *compactness* of the jet structure centred on the active nucleus of the galaxy. Most of local elliptical galaxies are found to host a CRS with nuclear luminosities lower than those of typical quasars, $\lesssim 10^{42}$ erg s^{-1}. Recently, low-luminosity CRS with a LINER-like optical spectrum have been named Fanaroff-Riley (FR) type 0 to highlight their lack of substantially extended radio emission at kpc scales, in contrast with the other Fanaroff-Riley classes, FR I and FR II. FR 0s are the most abundant class of radio galaxies in the local Universe, and characterised by a higher core dominance, poorer Mpc-scale environment and smaller (sub-kpc scale, if resolved) jets than FR Is. However, FR 0s share similar host and nuclear properties with FR Is. A different accretion-ejection paradigm from that in place in FR Is is invoked to account for the small FR 0 jets. This review revises the state-of-the-art knowledge about FR 0s, their nature, and which open issues the next generation of radio telescopes can solve in this context.

Keywords galaxies: active – galaxies: jets – radio continuum: galaxies

Contents

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1 Introduction

A controversial minority of Active Galactic Nuclei (AGN), named radio-loud AGN (RLAGN) (e.g. Urry and Padovani 1995; Kratzer and Richards 2015; Macfarlane et al. 2021), is known to launch relativistic collimated jets from parsec (pc) to Mpc scales, which connect the active supermassive black hole (BH) with the interstellar medium (ISM) to the furthest intra-cluster medium (ICM). A significant excess of radio emission over that expected from star formation (SF) processes is attributed to non-thermal jet emission in RLAGN, which then satisfy the criteria of radio-loudness[1] (Kellermann et al., 1989b; Terashima and Wilson, 2003). However, a fraction of radio-quiet (RQ) AGN can also emanate jets, which are, though, uncollimated and sub-relativistic. The jet kinetic energy released by RLAGN in the surrounding medium is generally indicated as the main responsible for the radio-mode feedback, crucial to the maintenance of massive galaxies in the present-day Universe (Fabian, 2012). RLAGN are typically associated with the most massive early-type galaxies (ETGs, and mostly ellipticals) and the most massive BHs in rich environments, although a small number of exceptions has been found (e.g. Hota et al. 2011; Singh et al. 2015a; Kaviraj et al. 2015; Kotilainen et al. 2016; Mao et al. 2018; Webster et al. 2021b; Davis et al. 2022). One of the most historically important classification of RLAGN was introduced by Fanaroff and Riley (1974), based on the extended radio structure: edge-darkened sources were classified as Fanaroff-Riley type I (FR Is), while edge-brightened as type II (FR IIs): the latter generally more radio luminous ($> 2 \times 10^{25}$ W Hz^{-1} at 178 MHz) than the former. Extended plumes, lobes, and tails account for typically 90% of their total radio emission (Miley, 1980). Other than the radio

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[1] Radio loudness, R, is defined as ratio between the flux densities in the radio (6 cm, 5 GHz) and in the optical band (∼4400 Å) (Kellermann et al., 1989a): RLAGN have $R \geq 10$, whereas radio-quiet AGN have $R < 10$. See also Terashima and Wilson (2003) for a radio loudness definition based on radio and X-ray (2-10 keV) luminosity ratio.

linear size and morphology, the orientation with respect to the line of sight is another important variable: extended sources inclined at small angles may appear compact due to projection effects and their radio emission can be boosted due to relativistic beaming of the nuclear jets moving at relativistic velocities. A further crucial aspect of RLAGN is the radio spectrum (flux density S_ν, varies with frequency ν as $\nu^{-\alpha}$ and α is the spectral index): steep-spectrum sources ($\alpha > 0.5$) are typically associated with optically-thin emission from extended jets, while flat/inverted-spectrum sources ($\alpha < 0.5$) are largely due to (synchrotron-self or free-free) absorption process involved in compact cores and jet knots. While misaligned RLAGN (with respect to the line of sight, e.g. FR I/II), commonly named as radio galaxies (RGs) in general, are typically dominated by their extended emission, aligned RLAGN (Blazars: BL Lacs and flat-spectrum radio quasars) show flat, inverted or complex radio spectra of the dominant cores. Traditionally, (misaligned) RL compact radio sources (CRS) are believed to represent the early stages of evolution of fully-fledged RLAGN (FR I/IIs, O'Dea 1998) and are characterised by a peaked radio spectrum (see Sect. 2). Recently, Baldi et al. (2015) introduced a new class of *low-power CRS*, named *FR 0* RGs, whose compact radio emission is dominated by the core and not related to a juvenile radio activity. The characteristic property of such an abundant class of RGs is the lack of substantial extended jet emission, that has changed the current view on the RLAGN phenomenology, particularly at low luminosities, where jets are scarcely studied. An increasingly-incomplete list of RLAGN classes is given in Table 1.

The complex radio taxonomy of RLAGN needs to find a correspondence with the optical classification schemes to modes of accretion onto the BHs (e.g., Jackson and Rawlings, 1997; Heckman and Best, 2014; Hardcastle and Worrall, 2000). Based on their optical spectra, RGs have been classified into Low Excitation Radio Galaxies (LERGs) and High Excitation Radio Galaxies (HERGs) (Tab. 1), which basically reflect two BH accretion states (Buttiglione et al., 2010; Tadhunter, 2016a) with distinct distributions of Eddington ratios[2]. LERGs are typically accreting below 1% of their Eddington luminosity, while HERGs have typical accretion rates between 1 and 10% (or higher) (Heckman and Best, 2014). HERGs, accretion-dominated RLAGN, are characterized by radiatively efficient accretion flows (REAF), i.e. standard optically thick, geometrically thin discs (Shakura and Sunyaev, 1973). LERGs, jet-dominated RLAGN, are powered by radiatively inefficient accretion flows (RIAF), which include the disc solutions of geometrically thick advection-dominated accretion flows (ADAF) (e.g., Narayan and Yi 1994a, 1995; Narayan et al. 2000; Yuan and Narayan 2014). LERGs prefer redder, gas-poorer, more massive ETGs with lower star-formation rates, which inhabit richer and more dynamically relaxed environment and feed more massive BHs than HERGs (Heckman and Best, 2014). LERGs are thought to be fuelled by the cooling hot gas from haloes present in their massive host galaxies, whereas the HERGs tend to

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[2] The Eddington ratio $\dot{L_E}$ gauges the BH accretion properties and is defined by the ratio between the bolometric AGN luminosity and the Eddington luminosity given its BH mass.

Table 1 radio-optical AGN taxonomy.

Acronyms	Main properties	Reference
Quasar	Quasi-stellar radio source	1
RLAGN	radio-loud AGN (relativistic collimated jets)	2
RQAGN	radio-quiet AGN (thermal/non-thermal emission, uncollimated sub-relativistic jet)	2,3
CRS	RL or RQ radio compact source	4
FR I	Fanaroff-Riley class I radio source; radio core-brightened	5
FR II	Fanaroff-Riley class II radio source; radio edge-brightened	5
FR 0	Fanaroff-Riley class 0 radio source; RL CRS lacking kpc-scale extended emission	6
RG	Radio galaxy, misaligned RL AGN	7
BL Lac	aligned RL AGN (BL Lacertae object)	7
Blazar	aligned RL AGN (BL Lac and quasar)	7
REAF	radiatively-efficient accretion disc	8
RIAF	radiatively-inefficient accretion disc	9
LERG	Low-Excitation Radio galaxies	10
HERG	High-Excitation Radio galaxies	10
LLAGN	Low-luminosity AGN	11
CSS	Compact steep spectrum radio source; young RG	12
GPS	Gigahertz-peaked radio source; young RG	12
HPF	High frequency peakers; young RG	12
CSO	Compact symmetric object; young RG	12
MSO	Medium-sized symmetric object; young RG	12
Seyfert	High-ionisation nuclear emission-line regions, RQ AGN	13
LINER	Low-ionisation nuclear emission-line regions, RQ or RL AGN	13,14
CoreG	Core Galaxies, nearby low-luminosity FR 0-like RGs	15

The complex radio-optical AGN taxonomy includes several acronyms. Here a partial but helpful list of labels for AGN, their properties and references (first/key papers or recent papers, which give up-to-date details). References: 1. Schmidt (1963), 2. Padovani (2016), 3. Panessa et al. (2019), 4. Kellermann and Pauliny-Toth (1981), 5. Fanaroff and Riley (1974), 6. Baldi et al. (2015), 7. Urry and Padovani (1995), 8. Shakura and Sunyaev (1973) 9. Yuan and Narayan (2014), 10. Heckman and Best (2014), 11. Ho (2008), 12. O'Dea and Saikia (2021), 13. Kewley et al. (2006), 14. Heckman (1980), 15. Balmaverde and Capetti (2006a).

accrete efficiently cold gas, from processes external or internal to the galaxy (Hardcastle et al., 2007). Several radio-optical studies of RGs concluded that the two FR radio morphologies are not representative of two distinct accretion states, but can co-exist in the same optical class (e.g., Gendre et al. 2013; Mingo et al. 2019, 2022). In fact, local LERGs are associated with FR I or FR II morphology, whereas HERGs, which are on average of higher luminosity, are generally FR IIs. The new low-power FR 0 class has thus further entangled, although already complex, the radio-optical classification scheme (Tab. 1).

Other than radio and optical bands, decades of observations of accreting BHs at different wavelengths have shed new light on specific aspects of the accretion-jet phenomena (e.g. X-ray emission, broad/narrow optical emission lines, IR excess emission), collecting evidence for an anisotropic AGN emission. The attempt to unify all the AGN classes in one single picture concluded with the Unification Model (UM, e.g. Barthel 1989; Antonucci 1993; Urry and Padovani 1995), which states that despite their differences, RLAGN have the same basic structure (attested for powerful sources): optically-thick circumnuclear matter (torus) obscuring the accretion disc in an edge-on view,

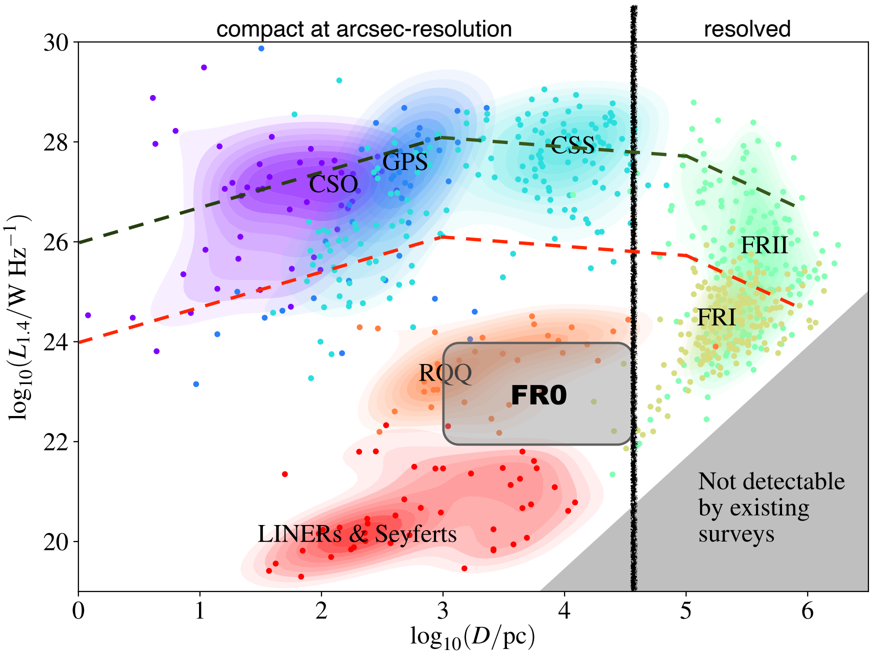

Fig. 1 Radio power/linear-size plot (P-D diagram) for different types of RL and RQ AGN, adapted from plots presented by An and Baan (2012); Jarvis et al. (2019); Hardcastle and Croston (2020). Points show individual objects and coloured contours represent a smoothed estimator of source density. The different categories of source shown are: CSO, GPS, CSS, FR I, FR II, RQ quasars, Seyferts and LINERS, and FR 0s (see Sect. 1 and 2 for the definition of the classes). Red and dark-green dashed lines represents the classical evolutionary tracks of FR Is and FR IIs (e.g., An and Baan 2012). The shaded bottom-right corner shows the effect of surface-brightness limitations by existing radio surveys. The vertical line roughly represents the separation between resolved and unresolved/compact sources based on arcsec angular resolution, generally provided by the VLA array. The black box depicts the VLA detected FR 0s and represents an upper limit on their actual radio physical size.

perpendicular to a relativistic jet, Doppler boosted when seen at small angles to the line of sight. Nevertheless, the advent of modern sensitive and survey-mode telescopes has unveiled new region in the space parameters of RLAGN phenomenology (see e.g., in time domain astronomy, radio/optical/X-ray spectroscopy and polarimetry, jet structure, Padovani 2016; Padovani et al. 2017), which the generic UM struggle to explain in a simple orientation-based model. Although the UM is still generally valid, the most logic way to relieve the tension is the inclusion of the time variable in the UM, i.e. the parameters can evolve across the time. An evolutionary scheme of RLAGN offers a more adaptable method to fine-tune the AGN parameters observed in different states of accretion and ejections (Antonucci, 2012; Netzer, 2015; Tadhunter, 2016a).

The dynamic evolution of the accretion-ejection coupling in RGs is traditionally explained as a progression of the radio power with the linear size of the radio structure (see An and Baan 2012 and references therein). Figure 1 shows the radio power P versus the total extent of the source, D (the so-called “P–D” diagram, Baldwin 1982): different populations of radio-emitting AGN (quiet and loud) span over a very wide range in radio luminosities (nearly ten orders of magnitude) and source sizes (six orders of magnitude) (Hardcastle et al., 2019; Hardcastle and Croston, 2020). In Fig. 1 two representative evolutionary tracks within the P-D diagram are shown and predict CRS to evolve into traditional ∼100-kpc double RGs (FR Is or FR IIs, e.g. Kunert-Bajraszewska et al. 2010; An and Baan 2012; Kunert-Bajraszewska 2016). However, there is a important caveat. All the evolutionary models and our current knowledge on RG populations have been based for long on samples of powerful sources, mostly above 10^{24} W Hz^{-1}, selected from high-flux low-frequency radio surveys such as the Third Cambridge (3C) catalogue (Bennett, 1962). In opposition to the past, recent large-area sensitive survey have revealed that the bulk of the RG population in the local Universe is dominated by sources with radio power below 10^{24} W Hz^{-1} (Best and Heckman, 2012), which include mostly compact FR 0-type RGs. The UM and the evolutionary models are not able to successfully reproduce such abundant population of 'low-luminosity' RLAGN.

A milestone in the comprehension of the the RLAGN phenomenon is the work by Best et al. (2005b), which selected the largest complete sample of low-luminosity RGs ($\lesssim 10^{41}$ erg s^{-1}) by cross-matching Sloan Digital Sky Survey (SDSS, York et al. 2000), National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS, Condon et al. 1998), and the Faint Images of the Radio Sky at Twenty centimeters survey (FIRST, Becker et al. 1995 with flux densities $>$ 5 mJy a 1.4 GHz. This flux-density cut is much below than the selection of, e.g. the 3C catalogue (178 MHz flux density $>$ 9 Jy, Bennett 1962), on which most of our comprehension of the radio-AGN phenomenon is based. The most interesting result from the radio-optical survey is that their radio morphology appears unresolved at the scale of the FIRST radio maps, i.e. 5", which correspond to 10-20 kpc with z<0.3. These compact RGs, named later *FR0s*, which belong to an heterogeneous population of LERG-type red massive ellipticals, represent the bulk of the RG population of the local Universe with a space density $>$ 100 times higher than 3C/RGs.

In this review, we provide an overview of the observational properties and theoretical understanding of this interesting class of compact RGs, FR 0s. We introduce the class of CRS in Sect. 2 to then focus on the FR 0s (Sect. 3), by discussing their selection (radio and host properties). Then we derive the radio luminosity function of local RGs to demonstrate the abundance of FR 0s with respect to the FR I/IIs (Sect. 4). Then we review their multi-band properties from radio (Sect. 5), optical and IR (Sect. 6) to high energy bands (Sect. 7) to picture their typical spectral energy distribution (SED). A discussion of the accretion-ejection coupling (Sect. 8), environmental properties (Sect. 9) and their role of of compact sources in AGN feedback (Sect. 10) lead to drawing static and dynamic scenarios to account for the multi-band properties of FR 0s in relation to the other FR classes (Sect. 11 and 12). A final chapter on future perspective is also included (Sect. 13).

We adopt $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{m_0} = 0.3$, $\Omega_{\Lambda_0} = 0.7$, and 10 kpc as the limiting size for FR 0s intended as unresolved compact RGs.

2 Compact radio sources

In this review we consider CRS, those AGN which appear unresolved at small angular sizes ($\lesssim$ a few arcseconds). CRS can be RQ or RL, and here we will focus on the latter. In RL CRS, the compact component is generally ascribed to the radio core, which is interpreted as non-thermal self-absorbed synchrotron emission from the basis of a relativistic jet, that extracts energy from the spinning BH (Blandford and Znajek, 1977). The connection between the compact core emission and the pc-kpc-Mpc scale extended jet emission, have been discussed in previous reviews (e.g., Condon and Dressel 1978; O'Dell 1978; Kellermann 1980; Kellermann and Pauliny-Toth 1981; O'Dea 1998; Falcke et al. 2004; Lobanov 2006; Tadhunter 2016b; O'Dea and Saikia 2021), which all gather increasing evidence of a large population of CRS in the local Universe.

What does 'compact' mean and what defines the compactness? The angular size of a compact source can vary from milli-arcsecond (mas) to a few arcseconds depending on the frequency, resolution and depth of observations. There is not a specific limit on the physical scale for a compact source. The morphological compactness can be defined as 'unresolved' structure of a radio source, when the deconvolved size is smaller or equal to the radio map beam width and when its visibility function is flat across the entire spatial-frequency plane. Starting with the Rayleigh–Jeans limit for brightness temperature T_b [K] (Condon and Ransom, 2016), the angular dimension θ of a compact source with its peak intensity S_ν [mJy beam^{-1}] at the frequency ν [GHz] is

$$\theta \sim 35 \ S_\nu^{1/2} \ T_b^{-1/2} \ \nu^{-1} \ arcsec. \tag{1}$$

For brightness temperatures above the threshold to discriminate between an AGN and stellar origin (Falcke et al., 2000), $T_b \gg 10^7$ K, for a spectral peak frequency between hundreds of MHz to GHz, the angular size varies between a few mas to a few arcseconds. This corresponds to a linear dimension range of several hundreds of parsec to kpc scale in the nearby Universe ($z<0.3$). However, in literature, a CRS is trivially classified as a morphologically point-like source based on the corresponding angular resolution.

In theory, a conventional definition of a compact source predicts the presence of a characteristic self absorption in the radio spectrum at low frequencies (below GHz regime). A varying opacity throughout the source entails a spectral characterisation: a flat, inverted or undulating spectrum over a wide range of frequencies due to the superposition of several radio-emitting partially opaque sources. Both the generally flat-spectrum and the compactness of the source can lead to the interpretation of an unresolved radio-emitting nucleus.

A (flat-spectrum) compact radio core is observed across all type of galaxies and AGN. Even normal spiral, star forming galaxies, RQAGN and late-type galaxies (LTG) in general reveal a compact nucleus, whose radio origin is thermal and non-thermal emission from several physical processes (Condon, 1992; Panessa et al., 2019). A prior selection of the optical hosts, ETGs rather than LTGs, can help to exclude RQAGN from genuine RL CRS samples.

In fact, the presence of a arcsec-scale compact radio emission at the centre of ETGs has been affirmed since ’70s as main results of shallow VLA radio surveys (e.g. Rogstad and Ekers 1969; Heeschen 1970; Ekers and Ekers 1973; Kellermann and Pauliny-Toth 1981; Sadler 1984; Fanti et al. 1986, 1987; Wrobel and Heeschen 1991; Slee et al. 1994; Giroletti et al. 2005; Capetti et al. 2009; Nyland et al. 2016; Hardcastle et al. 2019; Grossová et al. 2022; Wójtowicz et al. 2022). More massive galaxies and earlier in type appear to be more probably connected to the presence of a RLAGN (e.g., Smith et al. 1986; Best et al. 2005a; Floyd et al. 2010; Kim et al. 2017; Zheng et al. 2020), able to launch from the weakest to the most powerful jets in the Universe (large range of luminosities, morphologies, duty cycles and speeds, e.g. Heckman and Best 2014; Morganti 2017; Morganti et al. 2021; Saikia 2022).

Hosted in ETGs, RL CRS have been classified based on radio spectral and morphological properties. Other than Blazars which appear intrinsically small because of projection effects and affected by relativistic beaming (one-sidedness, superluminal motions, and high brightness temperatures), misaligned CRS (Readhead et al., 1994; O’Dea, 1998; Orienti, 2016; O’Dea and Saikia, 2021) have been largely studied at high powers ($L_{1.4\,\mathrm{GHz}} > 10^{25}$ W Hz^{-1}) and are characterised by a convex synchrotron radio spectrum: the peak position around 100 MHz in the case of compact-steep spectrum (CSS) sources, and at about 1 GHz in the case of GHz-peaked spectrum (GPS) sources, or even up to a few GHz in the sub-population of high frequency peakers (HFP) (Fanti et al., 1985; Spencer et al., 1989; Stanghellini et al., 1998; Snellen et al., 1998; Dallacasa et al., 2000; Kunert et al., 2002; Orienti et al., 2007; Hancock et al., 2010) (Fig. 1). Morphologically, lobes and hot spots are typically resolved with very-long baseline interferometry (VLBI) observations and a weak component hosting the core is occasionally present. Depending on their size, CSS/GPS may be termed as compact symmetric objects (CSO) if they are smaller than 1 kpc, or medium-sized symmetric objects (MSO) if they extend up to 10 - 15 kpc (Conway, 2002; Fanti et al., 2001). The existence of a relation between the rest-frame peak frequency and the projected linear size (e.g. O’Dea and Baum 1997) indicates that the mechanism responsible for the curvature of the spectrum is the youth: these sources are small because they are still in an early stage of their evolution, and will develop into FR I/II sources (e.g., Phillips and Mutel 1982; Fanti et al. 1990; Snellen et al. 2000; An and Baan 2012). The alternative scenarios point to a dense medium which might limit and frustrate the jet growth (van Breugel et al., 1984; Carvalho, 1994, 1998; Ghisellini et al., 2004; Giroletti et al., 2005), or to a short or recurrent activity due to occasional BH accretion (Readhead et al., 1994; Gugliucci et al., 2005; Kunert-Bajraszewska et al., 2010, 2011).

In conclusion, the CRS category can embrace a large population of radio-emitting sources: RQAGN, star-forming galaxies, Blazars, young RGs and the FR 0s. In the next section, we will focus on the properties of this ’new’ class of compact RGs, in relation with the large-scale RLAGN population.

3 Low-luminosity CRS: the FR0s

A significant fraction of nearby galaxies shows evidence of weak nuclear activity unrelated to normal stellar processes. Recent high-resolution, multiwavelength observations indicate that this activity derives from BH accretion with a wide range of accretion rates and is associated with CRS (e.g., Nagar et al. 2005; Ho 2008). In fact, moving to lower luminosities generally corresponds to selecting AGN with smaller and weaker jet (compact) structures and flatter radio spectra (e.g., Nagar et al. 2005; Sadler et al. 2014; Baldi and Capetti 2010; Gürkan et al. 2018; Sabater et al. 2019; Hardcastle et al. 2019), but with an increasing contribution from spurious RQAGN (Mezcua and Prieto, 2014; Baldi et al., 2021b). Current radio surveys of the local Universe have unearthed a large population of low-luminosity AGN (LLAGN, with bolometric luminosities $\lesssim 10^{40}$ erg s^{-1}), which were not explored in the past. Best and Heckman (2012), up-dating the sample of Best et al. (2005b), select 18,286 RGs (the SDSS/NVSS sample, hereafter), with low powers ($L_{1.4\,\rm GHz} < 10^{24}$ W Hz^{-1}) at low redshifts (z<0.3), whose the majority (∼80%) are LLAGN and radio compact (5"), with linear sizes $\lesssim$ 10-20 kpc.

The role of LLAGN and their compact jet emission in galaxy-BH coevolution (Ho, 2008; Kormendy and Ho, 2013) is crucial for several aspects:

i) since LLAGN outnumber the quasar population by a few order of magnitudes at z<0.3 (Nagar et al., 2005; Best et al., 2005a; Saikia et al., 2018), they provide the snapshot of the ordinary relation between an accreting BH and its host. The absence of an outshing AGN at the galaxy centre allows to better study the co-evolutionary link between the host and the central BH;

ii) since LLAGN reside in less massive galaxies, the identification of LLAGN would help to constrain the occupation fraction of active BH in galaxies at low stellar masses $>10^{9-10}$ M$_\odot$ (Greene, 2012; Gallo and Sesana, 2019), and the BH mass density function at M$_{\rm BH}$ $<10^8$ M$_\odot$. These quantities are fundamental to calibrate the prescriptions for BH-galaxy growth of semi-analytical and numerical models (e.g., Shankar 2009; Barausse et al. 2017);

iii) due to lack of sensitive surveys in the past, the role of LLAGN in galaxy evolution has been always downgraded with respect to powerful quasars, which by definition can offer a larger energetic budget to the host. Yet, recently the advent of deep radio surveys is reversing our view on AGN activity: LLAGN are always switched on at some level at low radio powers (L$_{150\,\rm MHz}$ $\gtrsim 10^{21}$ W Hz^{-1}, Sabater et al. 2019) and have galactic-scale jets, that can have a tremendous impact on their hosts by continuously injecting energy into the host, a crucial aspect for the jet-mode (or radio-mode) feedback (Fabian, 2012).

While in the optical band the role of LLAGN in BH-galaxy co-evolution and their BH accretion properties have been largely studied (Ho, 2008; Fanidakis et al., 2011), their connection with the radio band has recently started to be explored. The past and current optical-radio studies of radio-emitting LLAGN collect observational evidence that three states of accretion-ejection exist: RQ Seyferts and RQ and RL LINERs (Low-Ionization Nuclear Emission line Regions, Hine and Longair 1979; Heckman 1980; Kewley et al. 2006), in opposition two the distinct accretion-ejection states at higher luminosities, LERGs and HERGs. LINERs have lower accretion rates ($\dot{m}$), are usually more radio-loud and reside in earlier type galaxies than Seyferts (Ho, 2008). In fact, LINERs tend to host compact cores (Cohen et al., 1969; Falcke et al., 2000; Filho et al., 2002b; Maoz, 2007), more radio luminous as the BH mass (or galaxy mass) increases (e.g. Laor 2000; Best et al. 2005b; Mauch and Sadler 2007). RQ LINERs and Seyferts exhibit sub-relativistic and not collimated jet (Baldi et al., 2021b). Conversely, RL LINERs have been generally interpreted as the scaled-down version of powerful RLAGN in terms of accretion and jet luminosities (Chiaberge et al., 2005; Balmaverde and Capetti, 2006a). The nuclei of RL LINERs can be described with a model of synchrotron self-absorbed base of a low-power (mildly) relativistic jet coupled with an underluminous RIAF disc (typically an ADAF, Narayan and Yi 1994b), analogous to FR I/LERG disc-jet coupling (e.g. Balmaverde and Capetti 2006b; Hardcastle et al. 2009). The low-power CRS population selected from the SDSS/NVSS sample (Best and Heckman, 2012) in the same luminosity range ($\lesssim 10^{41}$ erg s^{-1}) of classical 3C/FR Is include an heterogeneous population of mostly LINER/LERGs[3] with a broad distribution of BH mass and host properties.

Baldi et al. (2010) analysed in details the photometric and spectroscopic properties of the SDSS/NVSS sample to select the bona-fide RLAGN population (see Sect. 3.1). They found that the vast majority of the SDSS/NVSS sample ($\sim$ 80%) are compact LERGs and shows a peculiar property: a dramatic deficit of radio luminosities up to a factor $\sim$1000 with respect to classical 3C/FR Is, when matched in bolometric AGN luminosity. This remarkable result that local Universe is dominated by low-luminosity CRS lacking of substantial extended emission, expresses the need to include them in the taxonomy of RGs. Ghisellini (2011) for the first time introduced in the literature the name *FR 0* to characterise a population of weak CRS hosted in ellipticals, named Core Galaxies[4] (CoreG), which exhibit radio core and AGN bolometric luminosities similar to weakest 3C/FR Is (M87), but with an extended radio emission hundreds of times weaker (Baldi and Capetti, 2009). CoreG host genuine 'miniature' RGs with LINER-like nuclei, which extend the luminosity correlations reported for 3C/FR Is by a factor of $\sim$1000 toward lower luminosities (Balmaverde and Capetti, 2006a; Kharb et al., 2012): this has been interpreted as a sign of a common central engine (RIAF disc) (Balmaverde and Capetti, 2006a; Kharb et al., 2012). CoreG are characterised by kpc-scale jets and a deficit of total radio emission in analogy to the SDSS/NVSS sample, but at lower radio luminosities.

A closer look at the FR 0s at sub-arcsec/mas scale revealed that the majority still appears radio compact, with a flat spectrum in the GHz band (Baldi et al., 2015, 2019a; Cheng and An, 2018; Cheng et al., 2021). However, a small fraction of those exhibits kpc-scale jets, suggesting that FR 0s can actually

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[3] LERG and RL LINER are equivalent classes at low luminosities.

[4] The Core Galaxy nomenclature comes from the (core-type) optical flat surface brightness profile in innermost region of an ETG (e.g. Faber et al. 1997).

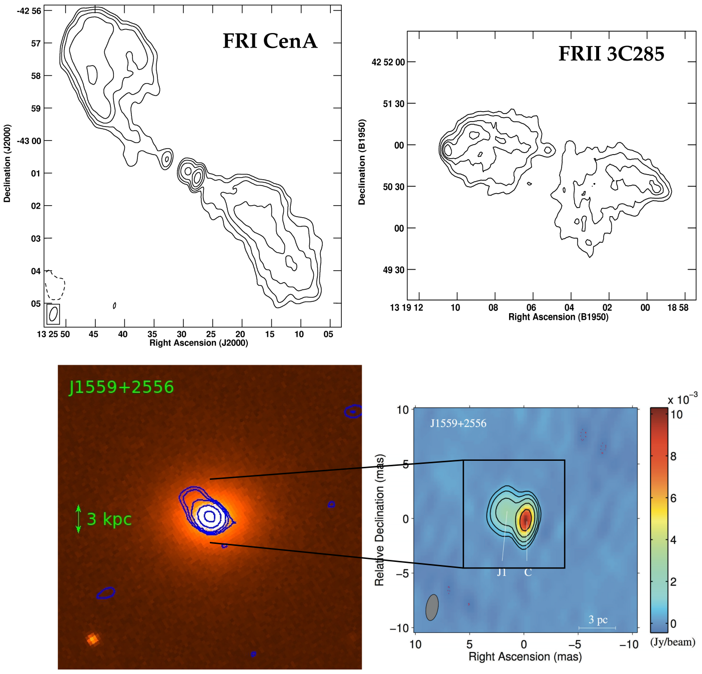

Fig. 2 Multi-band composite panel of RGs. On the top two examples of typical radio morphologies of a FR I (Centaurus A, Burns et al. 1983 at 1.4 GHz) and a FR II (3C 285, Alexander and Leahy 1987 at 1.4 GHz). On the bottom, we show an example of FR 0. The left panel displays the r-band SDSS image of the ETG which hosts the FR 0 with the blue VLA 4.5-GHz radio contours (Baldi et al., 2019a) (3 kpc scale set by the green arrow). The right panel represents the high-resolution zoom on the radio core (on the scale of 3 pc) provided by the VLBI image from Cheng and An (2018). Adapted from Baldi et al. (2019c).

produce collimated structures. The lack of substantially extended radio emission at kpc scale and the spectral flatness for the majority of these CRS have led to the affirmation of the FR 0 nomenclature as an unique class of genuine compact RGs different from the other RLAGN classes.

In conclusion, in the last decade, different parallel studies have brought to light a revolutionary result, i.e. classical 3C FR I/ IIs do not represent the ordinary picture of the RLAGN phenomenon in the local Universe, but FR 0-like LLAGN represent the bulk of the local RG population (Fig. 2). The paucity of sources with weak extended radio structures in high flux limited samples (such as in the 3C sample) is due to a selection bias, since the inclusion of such objects is highly disfavored. In fact, in support to this interpretation, Baldi and Capetti (2009) showed that the lower flux threshold of B2 sample (250 mJy at 408 MHz, Fanti et al. 1978) drastically reduces the selection bias and allows the inclusion of a larger fraction of core-dominated[5] galaxies, consistent with being FR 0s.

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[5] The ratio of core to total extended emission is called the core-dominance parameter (generally at 5 GHz). Core-dominated galaxies have typically a core dominance $\gtrsim 1/3$.

3.1 Selection of FR 0s

Disentangling bona-fide FR 0s from the radio compact impostors (Blazars, young RGs, RQAGN, compact star-forming galaxies) represents a multi-band selection process. This can be harder at low luminosities (mJy-level at $z<0.3$). For example, Best et al. (2005b) used several optical photometric and spectroscopic diagnostics and radio properties to select RLAGN in the SDSS/NVSS sample, however a small fraction ($\sim$10%) of a possible RQAGN contribution is still present after the selection. Because aligned and young RGs can be removed from the sample only on the base of a spectral and temporal radio study which are often not available, the simplest method to select bona-fide FR 0 candidates is based on shallow optical-radio (largely available) selection process which consists of a few steps to maximise the probabilities that the radio emission is associated with a compact RL active nucleus. Accordingly, Baldi et al. (2018) have compiled a catalogue of 104 FR 0 sources (namely, FR0CAT) from the SDSS/NVSS sample, by adopting the following criteria:

- nearby (redshift $z \lesssim 0.05$) galaxies to spatially resolve the radio source.
- compact: the sources are unresolved in the NVSS maps at 45” resolution. More stringently, the source must appear unresolved at FIRST resolution, 5”. The FR 0 candidates consist of unresolved sources for which the deconvolved size is smaller than 4”. At $z = 0.05$ this corresponds to $\sim$5 kpc, that is, to a radius of 2.5 kpc.
- FIRST 1.4-GHz flux density $>$ 5 mJy to increase the possibility of an accurate size and flux measurement. This value corresponds to $\sim$10 times the reference surface brightness, 0.45 mJy beam^{-1}, which is approximately three times the typical rms of the FIRST images.
- LERGs. Selecting LINERs allows to exclude AGN with high-Eddington ratios (generally Seyferts/HERGs) and are more probably associated with RLAGN phenomena (Heckman and Best, 2014; Panessa et al., 2019).

Follow-up observations at higher angular resolution than that of FIRST maps are needed to confirm the compactness of the FR0CAT sources.

The resulting FR0CAT sample turns out to be a population of RGs with a core dominance of a factor $\sim$30 higher than typical 3C/FR Is (Baldi and Capetti, 2009; Baldi et al., 2019a; Whittam et al., 2020), where instead the core typically contributes to 1% to the total radio emission (Morganti et al., 1997). Their 1.4-GHz radio luminosities are in the range 10^{38}-10^{40} erg s^{-1}. These radio selection turned to include mostly luminous ($-21 \gtrsim M_r \gtrsim -23$) red ETGs with BH masses $10^{7.5} \lesssim \mathrm{M_{BH}} \lesssim 10^{9}\ \mathrm{M_{\odot}}$. However, a small fraction of the selected FR 0s departs from this general behavior: galaxies with optical photometric and spectroscopic characteristics (see Sect. 3.2), typical of blue star-forming spirals and RQAGN.

As control samples with respect to the FR0CAT, other catalogues of low-luminosity FR Is and FR II have been selected from the SDSS/NVSS sample, a factor $\sim$10-100 weaker than 3C/RGs. Capetti et al. (2017a) selected 219 low-luminosity FR Is, named FRICAT, with core-brightened radio morphology,

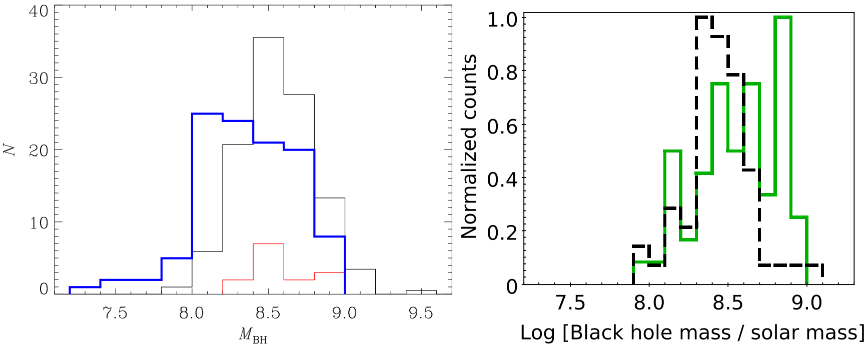

Fig. 3 Left panel: BH mass distribution (in $M_\odot$) of FR 0s (FR0CAT, blue line) with respect to FR Is (FRICAT, radio size > 30 kpc, black line) and small FR Is (sFRICAT, 10 < radio size < 30 kpc, red line) from Baldi et al. (2018). Right panel: compact (black) and extended RGs (green) from Miraghaei and Best (2017), when matched in radio core luminosities.

redshift ≤ 0.15, and extending (at the sensitivity of the FIRST images) to a radius (r) larger than 30 kpc from the optical center of the host. The authors also selected an additional sample (sFRICAT) of 14 smaller (10 < r < 30 kpc) FR Is, limiting to z < 0.05. The distribution of radio luminosity at 1.4 GHz of the FRICAT covers the range 10^{39}-$10^{41.3}$ erg s^{-1} and the sources are all LERGs. The hosts of the FRICAT sources are all luminous (-21 $\gtrsim Mr \gtrsim$ -24), red ETGs with BH masses in the range, $10^8 \lesssim M_{\rm BH} \lesssim 10^{9.5} M_\odot$, slightly larger than FR0CAT BH masses (Fig. 3). Similarly, Capetti et al. (2017b) selected 122 low-luminosity FR IIs, named FRIICAT, with redshift ≤ 0.15, an edge-brightened radio morphology, and those with at least one of the radio emission peaks located at radius r > 30 kpc from the optical galaxy center. The radio luminosity at 1.4 GHz of the FRIICAT sources covers the range $10^{39.5}$ -$10^{42.5}$ erg s^{-1}. The FRIICAT catalog mostly include LERGs (90%), which are luminous (-20 $\gtrsim Mr \gtrsim$ -24), red ETGs with BH masses in the range $10^8 \lesssim M_{\rm BH} \lesssim 10^9$ $M_\odot$.

Other FR 0 samples were selected at lower and higher radio frequencies than the FIRST 1.4 GHz band (see Sect. 5 for details), which instead include more spurious sources than the FR0CAT. At low radio frequencies (hundreds of MHz) which is expected to be dominated by optically-thin emission, the vast majority (~70%) of sources in wide-area survey with LOFAR (Hardcastle et al., 2019; Sabater et al., 2019; Mingo et al., 2019; Capetti et al., 2020a) and GMRT Survey (Capetti et al., 2019), and in deep well-studied field (e.g. ELAIS-N1 and BOOTES, Sirothia et al. 2009; Ishwara-Chandra et al. 2020) appear compact with an angular resolution of a few arcsec and have α between 0 and 0.85, with the flat-spectrum sources more abundant than the steep-spectrum companions.

At higher radio frequencies (tens of GHz) which is expected to be dominated by the optically-thick emission, FR 0s have been selected by Sadler et al. (2014) from the AT20G-6dfGS sample and by Whittam et al. (2016) from the Cambridge 10C survey (mostly z<3) based on their radio morphological compactness (a few arcsec). Both the samples selected 70–80% of CRS, which include FR0-like LERGs and a large fraction of possible GPS/CSS sources.

3.2 Host properties

The different radio-frequency selections of the FR 0s lead to a heterogeneous distribution of their host properties (e.g. galaxy type, color, mass, $\mathrm{M_{BH}}$): selecting red massive ETGs represents the most secure criterion of identifying hosts of a FR 0. In fact, a prior host selection trough several diagnostics can reduce the probability of inclusions of radio-compact impostors. The concentration index $\mathrm{C_r}$ is defined as the ratio of the galaxy radii including 90% and 50% of the light in the r band, respectively. ETG have higher values of concentration index than LTG, i.e. $\mathrm{C_r} > 2.6$ (Strateva et al., 2001). The Dn(4000) spectroscopic index is defined as the ratio between the flux density measured on two sides of the Ca II break (∼4000Å) (Balogh et al., 1999) and high values, Dn(4000) > 1.7, are generally associated with red galaxies (Best et al., 2005a; Capetti and Raiteri, 2015). Optical and infrared color can also separate red ellipticals from blue spirals. The combination of these diagnostics with the FR0CAT criteria listed in Sect. 3.1 allows to identify the radio-compact red massive ETGs which have the highest probabilities to host a RLAGN.

The vast majority of the FR0CAT, FRICAT and FRIICAT hosts are indistinguishable: red massive ETGs, based on the values of the C_r, spectroscopic Dn(4000) indices and broad-band color. Their redness is confirmed by the photometric $u - r$ color, measured over the whole galaxy. The WISE infrared colors further support the general passive nature of the FRCAT hosts (Fig. 4, W1-W2 < 0.2, Wright et al. 2010). Nonetheless, a few galaxies of the FR0CAT extend to redder colors than those from the FRICAT and there is a notable lack of blue host galaxies ($u - r > 2.5$) with respect to the general population of ETGs (Schawinski et al., 2009). In addition, the mass (and BH mass) of FR0CAT sources is on average smaller than those of FRICAT galaxies by a factor ∼1.4 (Fig. 3).

At high frequencies, Sadler et al. (2014) did not opt for a host selection and, in fact, found that the host galaxies of FR 0s display heterogeneous properties with wide range in WISE colours, (33% in LTGs with some ongoing SF, see Fig 4). This implies that the selected FR 0 candidates, which make up the majority of the AT20G-6dFGS sample, probably consists of a mixed bag of genuine FR 0s, young RGs and RQAGN. In fact, the bluer color of the selected FR 0s are generally attributed to galaxies with a recent SF burst or to young RGs in gas-rich environments.

Since the core luminosity has been argued to be a better gauge of jet power than total radio luminosity[6], Miraghaei and Best (2017) matched a sample of CRS and extended RGs on the basis of the core radio luminosities. In terms

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[6] The radio core power is a measure of instantaneous power, rather than the total radio power, that is an averaged value over time and is also influenced by environment

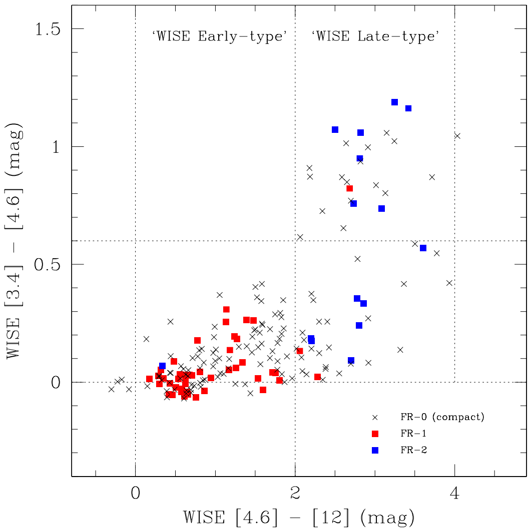

Fig. 4 WISE colour-colour plot (W2-W3 vs. W1-W2) for the host galaxies of FR I (red squares), FR II (blue squares) and compact (FR 0, black crosses) radio sources in the 20 GHz AT20G-6dFGS sample from Sadler et al. (2014). The horizontal line at a $3.4 - 4.6\mu$m colour of 0.6 mag divides the AGN and normal galaxy populations. Objects where radiation from an AGN dominates the galaxy spectrum in the mid-infrared are expected to lie above this line, and objects where starlight dominates should lie below the line. The vertical line W2-W3 >2 identifies LTGs from ETGs. Taken from Sadler (2016).

of host properties, they found that CRS and extended RGs differ only in the BH mass (Fig. 3), similar to the result from the FR0CAT (Baldi et al., 2018).

Instead of a morphological selection on the radio compactness, a simple luminosity cut at low powers in mJy-level radio surveys, roughly allows to select mostly massive ETGs which harbour compact LLAGN, $<10^{23}$ W Hz^{-1} (Best et al., 2005b; Sabater et al., 2019; Hardcastle et al., 2019). Therefore, the selection in radio luminosity/morphology or in host properties often brings to a similar result: low-power CRS in evolved galaxies, although a host selection largely ensures the exclusions of radio-compact impostors.

4 Radio luminosity function

We calculate the radio luminosity functions of the FRCAT sources as object density per unit logarithmic luminosity interval within the maximum volume V$_{max}$ in which the objects would be observed (Schmidt, 1968; Condon, 1989):

$$\Phi\,(\log L_{\rm NVSS}) = \frac{4\pi}{\sigma} \sum_{i=1}^{N(\log L_*)} \frac{1}{V_{max(i)}}, \tag{2}$$

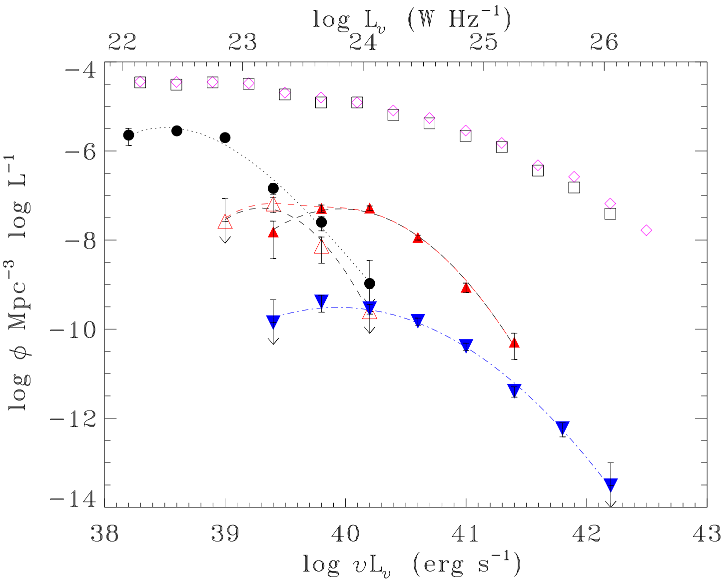

Fig. 5 The local NVSS luminosity function at 1.4 GHz for RLAGN (pink diamonds) and LERGs (empty squares) from the SDSS/NVSS sample (Best and Heckman, 2012). The lower x-axis is expressed in erg s^{-1} and the upper one in W Hz^{-1}. The other points represent the radio luminosity functions for FR 0s (filled circles), small FR Is (empty red up-warded triangles), FR Is (filled red triangles) and FR IIs (blue filled down-warded triangles) from the FR0CAT (Baldi et al., 2018), sFRICAT/FRICAT (Capetti et al., 2017a) and FRIICAT (Capetti et al., 2017b). The dot, dashed and dot-dashed lines are rough fits of the data-points, respectively, for FR 0s, FR Is, and FR IIs, to better visualize the luminosity functions.

where σ is the area of the sky surveyed, $N\,(\log L_*)$ is the number of objects in a given NVSS luminosity bin L_*, and $V_{max(i)}$ is given by the limiting magnitudes/fluxes in both the optical and radio properties of the sample, namely a radio cutoff of 5 mJy and SDSS optical cutoff of r < 18, as well as any imposed redshift limit for the analysis (z < 0.05 for FR0CAT and sFRICAT and z < 0.15 for FRICAT and FRIICAT). The sky area of the overlapping region between the SDSS DR7 spectroscopic survey and the FIRST/NVSS radio survey is $\sigma = 2.17$ steradians. We place detected sources in bins of equal radio luminosities and estimate the uncertainties as in Condon (1989). We use Poisson statistics to estimate uncertainties in luminosity bins with small numbers of sources (N<7). If N=1, we set 1σ upper limit on the luminosity function in that bin. The 1.4-GHz NVSS luminosities functions are derived for the FR 0s, FR Is and FR IIs from the FRCAT in Figure 5 and tabulated in Table 2.

Figure 5 shows that, as expected, FR 0s dominate the radio source population at relatively low radio luminosities $\lesssim 10^{23.5}$ W Hz^{-1}, while the FR Is and FR IIs dominate at the highest luminosities. Quantitatively, FR 0s represent the bulk of the RLAGN population of the local Universe (z<0.05) with a space density ~4.5 times higher than that of FR Is and ~100 than that of FR IIs. In relation to the luminosity function of ETGs, compact sources, consistent

Table 2 The local NVSS radio luminosity functions at 1.4 GHz for FR0CAT, sFRICAT, FRICAT and FRIICAT (LERG) sources. The first column shows the range of 1.4 GHz radio luminosities (erg s^{-1}) considered in each bin. The N columns show the total number of radio sources and $\log_{10}\rho$ their space density (number per $\log_{10}L$ per Mpc^3, see Figure 5).

$\log L_{1.4\mathrm{GHz}}$	FR0CAT		sFRICAT		FRICAT		FRIICAT	
erg s^{-1}	N	$\log_{10}\rho$	N	$\log_{10}\rho$	N	$\log_{10}\rho$	N	$\log_{10}\rho$
38.0-38.4	6	$-5.64^{+0.15}_{-0.23}$	0	–	0	–	0	–
38.4-38.8	27	$-5.55^{+0.08}_{-0.10}$	0	–	0	–	0	–
38.8-39.2	48	$-5.70^{+0.06}_{-0.07}$	1	$<-7.58^{+0.51}$	0	–	0	–
39.2-39.6	14	$-6.84^{+0.10}_{-0.14}$	8	$-7.19^{+0.13}_{-0.20}$	3	$-7.82^{+0.24}_{-0.59}$	1	$<-9.86^{+0.51}$
39.6-40.0	8	$-7.60^{+0.13}_{-0.19}$	4	$-8.13^{+0.20}_{-0.39}$	32	$-7.29^{+0.07}_{-0.09}$	7	$-9.39^{+0.15}_{-0.23}$
40.0-40.4	1	$<-9.97^{+0.51}$	1	$<-9.60^{+0.51}$	91	$-7.28^{+0.05}_{-0.05}$	19	$-9.54^{+0.10}_{-0.12}$
40.4-40.8	0	–	0	–	70	$-7.94^{+0.05}_{-0.06}$	36	$-9.82^{+0.07}_{-0.09}$
40.8-41.2	0	–	0	–	19	$-9.06^{+0.09}_{-0.12}$	34	$-10.39^{+0.07}_{-0.09}$
41.2-41.6	0	–	0	–	4	$-10.29^{+0.20}_{-0.39}$	16	$-11.40^{+0.10}_{-0.13}$
41.6-42.0	0	–	0	–	0	–	9	$-12.23^{+0.13}_{-0.19}$
42.0-42.4	0	–	0	–	0	–	1	$<-13.52^{+0.51}$

with a FR 0 morphology, are found in more than 60% of the giant (K-band magnitude $\leq$ -25) ETGs detected by LOFAR with 150-MHz luminosity $\geq 10^{21}$ W Hz^{-1} (Capetti et al., 2022).

5 Radio properties

In this section, we focus on the radio properties of FR 0s and CRS in general. Here we provide an overview of the radio observations from different telescopes at different frequencies (from 150 MHz to several GHz) and resolutions (from arcsec to milli-arcsec) to probe the physical mechanism acting at different linear scales along the putative jet. Most studies of CRSs which are reported in the next sub-sections, are related to low-z sources (unless explicited) and typically LERGs.

5.1 Low resolution

5.1.1 GHz-band: sub/arcsec-scale with VLA

For the large availability of shallow radio data in the band ∼1-5 GHz, the VLA has been the first telescope used to select and characterise the properties of FR 0s. In fact, for the large sky coverage, moderately high resolution and sensitivity, FIRST and NVSS 1.4-GHz surveys have been largely exploited to select CRS and RGs in general in the local Universe, but other than these data the radio information was extremely limited. Later, follow-up VLA observations of 25 FR 0s at 1.4, 4.5, and 7.5 GHz revealed that two third still appear compact at the angular resolution of 0.3” (a few hundreds of parsec) and with a flat radio spectrum in the GHz band (Baldi et al., 2015, 2019a).

Only a third of the sample exhibits twin or one-sided jets extended on a scale of ∼2-14 kpc (see Fig. 2 as an example). The apparent radio compactness of most of FR 0s at kpc scales could be caused by the fact that jet emission is below the surface brightness limit of most large-scale radio surveys. In fact, Shabala et al. (2017) demonstrated that VLBI-scale compact AGN could have lobes and plumes too faint to be detected by most surveys with the VLA and LOFAR. The absence of substantial extended jet emission, whether due to detection limit or intrinsic inability, represents the characteristic feature of the FR 0 class and their uniqueness from the other classes of RGs.

Wide-area GHz-band surveys also revealed a large fraction of low-power CRS, e.g., ∼93% in the VLA-COSMOS Large Project at 3 GHz (Bondi et al., 2018; Vardoulaki et al., 2021). These FR 0s candidates are associated with less massive hosts $\sim 10^{10.8}$ $M_\odot$, with lower radio powers 10^{19} W Hz^{-1} and at higher redshifts (median z ∼ 1.0) than the FR0CAT sources. In the Very Large Array Sky Survey (VLASS; Lacy et al. 2020) at 3 GHz, Nyland et al. (2020) selected ∼2000 compact RGs, but the redshift information is not well characterised for the entire sample. The selected CRS in these surveys consists of a heterogeneous population of AGN with red and blue colors, consistent with genuine FR 0s, star-forming galaxies, RQAGN and Blazars. Furthermore, Kozieł-Wierzbowska et al. (2020) found that ∼90% of the optical SDSS galaxies at z<0.5 with a FIRST counterpart appear compact with $L_{1.4\mathrm{GHz}} \sim 10^{21}$ - 10^{26} W Hz^{-1}, hosted typically by ellipticals, a similar result to the work by Baldi and Capetti (2010).

Other GHz-band studies on core-dominated LINERs with moderate radio-loudness hosted in ETGs (e.g. Nagar et al. 2000; Filho et al. 2000, 2002b; Verdoes Kleijn et al. 2002a; Filho et al. 2004; Kharb et al. 2012; Singh et al. 2015b; Dullo et al. 2018; Zajaček et al. 2019; Singh et al. 2019) strengthen the result that nearby elliptical galaxies tend to power RL LLAGN with galactic-scale jet structures, in analogy to FR 0 galaxies.

5.1.2 High frequency: ATCA, AMI and mm-band

Interferometric observations at $\nu \gtrsim$ 5 GHz have the advantage of isolating better the compact optically-thick flat-spectrum core. In fact, at high frequencies the Australia Telescope Compact Array (ATCA) played an important role in the early studies of FR 0s. Sadler et al. (2014) have cross-matched the Australia Telescope 20 GHz (AT20G) Survey with the optical spectroscopic 6dF Galaxy Survey (6dFGS; Jones et al. 2009) to produce a volume-limited sample of 202 high-frequency CRS associated with local galaxies (at a median z ∼ 0.06) with 20-GHz flux density limit of 40 mJy. The angular resolution 10–15" corresponds to a projected linear size of 10–15 kpc. Chhetri et al. (2013) used data from the longest (6 km) ATCA baseline to determine how much of the radio emission seen by the AT20G survey arose in very compact components. They showed that generally almost all their 20 GHz radio emission comes from a central source $\lesssim$ 0.2" and almost half of the AT20G sources has flat radio spectra at 1–20 GHz. The selected FR 0s represent the dominant population (∼70–75%) of the AT20G–6dFGS catalogue at radio powers between $\sim 10^{22}$ and 10^{26} W Hz^{-1} in the local Universe. In addition, the high-frequency selected FR 0s consist of a heterogeneous population in terms of both their optical spectra (75% LERGs, 25% HERGs) and host galaxy type (67% ETGs, 33% LTGs). Further studies of these 20-GHz CRS confirmed that the flat-spectrum AT20G objects sources tend to preserve a similar spectral shape in polarisation and are hosted in bluer galaxies than standard ETGs (Chhetri et al., 2012, 2020; Massardi et al., 2011).

Whittam et al. (2016) and Whittam et al. (2020) selected a complete sample of 96 faint (> 0.5 mJy) RGs from the Tenth Cambridge (10C) survey at 15.7 GHz including LERGs and HERGs, mostly, within z∼3. Sixty-five sources are unresolved in the 610-MHz GMRT radio observations, placing an upper limit on their angular size of ∼2 ”. The majority of these sources have flat spectra and are core dominated. The selected FR 0 population is the most abundant in the subset of sources with 15.7-GHz flux densities <1 mJy, extending the results of Sadler et al. (2014) at higher redshifts, z ∼ 1.

Baldi et al. (in preparation) observed 25 FR0CAT sources at 15 GHz with the Arcminute Microkelvin Imager (AMI) telescope with an angular resolution of ∼30”, previously observed with VLA by Baldi et al. (2015) and Baldi et al. (2019a). The sources appear all unresolved and extend the spectral flatness of FR0CAT objects at higher frequencies.

Mikhailov and Sotnikova (2021b,a) conducted quasi-simultaneous radio observations of 34 FR 0s up to 22.3 GHz with the single-dish radio telescope RATAN-600 operating in transit mode with resolution varying from 11 to 80”. Quasi-simultaneous spectra in the range 2 - 8.2 GHz are generally flat ($\alpha < 0.5$), but with a larger spread in the spectral index at higher frequencies. The key result is that some FR 0s demonstrate a variability level of up to 25% on a time scale of 1 year.

In the mm-band, Doi et al. (2011) conducted continuum observations for a sample of nearby ETGs and LLAGN and found compact nuclear emission (on a scale 3-7”), showing flat or inverted spectra consistent with the scenario of small jets powered by RIAF discs. In conclusion, high-frequency observations of RL CRSs confirm their flat-spectrum shape for majority of FR 0 candidates.

5.1.3 Low frequency: GMRT and LOFAR

Low-frequency observations (< 1 GHz) has the advantage of probing the synchrotron-aged plasma and the optically-thin emission from extended diffuse jet, crucial to test the duty cycles of FR 0s. Using the data release of the TIFR (Tata Institute of Fundamental Research) GMRT Sky Survey (TGSS), Capetti et al. (2019) studied the low-frequency properties of 43 FR 0 galaxies (FR0CAT, with 150-MHz flux densities > 17.5 mJy) at 150 MHz. No extended emission has been detected around the detected FR 0s, corresponding to a luminosity limit of $\lesssim 4 \times 10^{23}$ W Hz^{-1} over an area of 100 kpc × 100 kpc. The majority of the FR 0s have a flat or inverted SED (150 MHz - 1.4 GHz, $\alpha < 0.5$): this spectral behavior confirms the general paucity of optically thin extended emission within the TGSS beam. By focusing on a sub-sample of FR 0s with 1.4-GHz flux densities > 50 mJy and including 5-GHz data from the Green Bank 6-cm survey (Gregory et al., 1996), the authors found that $\sim$75% of them have a slightly convex radio spectrum, with a smaller curvature than powerful GPS sources. The typical FR 0s radio spectrum is better described by a gradual steepening toward high frequencies, rather than a transition from an optically-thick to an optically-thin regime as seen in young RGs.

Dedicated deep radio surveys on well-studied fields, such as ELIAS-N1, have also detected large numbers of compact RGs: GMRT observations at 610 MHz (Ishwara-Chandra et al., 2020) and 325 MHz (Sirothia et al., 2009) found CRS with a median spectral index of $\sim$0.85 between 610 and 1400 MHz (Ishwara-Chandra et al., 2020). The flat-spectrum sources, which are expected to be core-dominated, represent the FR 0 candidates.

The vast majority, $\sim$70%, of the radio sources in the LOFAR Two-metre Sky Survey (LoTSS, Shimwell et al. 2017, 2019; Hardcastle et al. 2019) appear compact at 150 MHz with 6” resolution, consistent with a FR 0 morphology. Capetti et al. (2020a) explored in details the LOFAR properties of the FR0CAT sources. Most of the objects still appear point-like structures with sizes of $\lesssim$ 3-6 kpc. However, $\sim$18% of the FR 0s present resolved emission of low surface brightness, usually with a jetted morphology extending between 15 and 50 kpc. No extended emission is detected around the rest of FR 0s, with a typical luminosity limit of $\sim 5 \times 10^{22}$ W Hz^{-1} over an area of 100 kpc × 100 kpc. The spectral slopes of FR 0s between 150 MHz and 1.4 GHz span a broad range ($-0.7 \lesssim \alpha \lesssim 0.8$) with a median value of $\alpha \sim 0.1$; only 20% of them have a steep spectrum ($\alpha \gtrsim 0.5$), which is an indication of the presence of diffuse emission confined within the spatial resolution limit. The fraction of FR 0s showing evidence for the presence of jets, by including both spectral and morphological information, is $\sim$40%. In conclusion, the GMRT and LOFAR study of the FR 0s corroborates the result on the absence of extended emission in most of the sources, even at MHz regime, where optically-thin jet emission is expected to dominate over the core component, as seen in classical RLAGN.

5.2 High resolution

The VLBI technique enables to access to the pc-scale radio emission, a crucial region to study the jet properties of FR 0s. Cheng and An (2018) and Cheng et al. (2021) studied a sample of FR 0s with world-wide VLBI, the American Very Long Baseline Array (VLBA) and European VLBI Network (EVN) and found resolved jets of a few pc for $\sim$80% of the sample (Cheng and An, 2018; Cheng et al., 2021) (see Fig. 6 as example). The VLBI multi-epoch data and the symmetry of the radio structures indicates that the jet bulk speeds are mildly relativistic (between $0.08c$ and $0.51c$) with low bulk Lorentz factors (between 1.7 and 6) and large viewing angles. However, these VLBI-based studies focused on particularly bright FR 0s (flux densities > 50 mJy, a factor 10 higher than the typical FR0CAT flux selection threshold, Baldi et al.

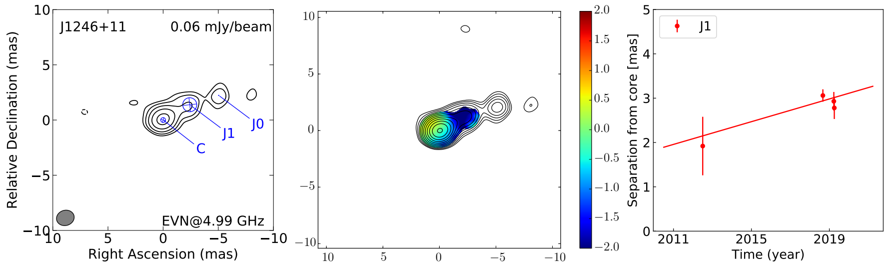

Fig. 6 EVN image at 5 GHz, spectral index map and jet proper motions of one FR 0 from Cheng et al. (2021) from left to right panel. The grey-colored ellipse in the bottom-left corner of each panel denotes the restoring beam. The spectral index maps (spectral index colour coded in the left palette) are obtained by using the EVN 5 and 8 GHz data. The proper motions of jet components are determined by the linear fit to the component positions as a function of time. Adapted from Cheng et al. (2021).

2018) with radio power 10^{23} –10^{24} W Hz^{-1}. Recent VLBI studies also target less luminous FR 0s. Giovannini et al. (2023) studied pc-scale emission of 18 FR0CAT objects observed with the VLBA at 1.5 and 5 GHz and/or with the EVN at 1.7 GHz with flux densities a factor several lower than those of the FR 0s studied by Cheng and An (2018) and Cheng et al. (2021). All sources have been detected but one with radio core power down to 10^{21} W Hz^{-1}. Four sources remain unresolved at pc scale, while jets have been detected in all other sources. High-resolution observations carried out with the eMERLIN UK-wide array for a sample of 5 FR 0s at 5 GHz, reaching a resolution of ∼40 mas show sub-mJy core components (Baldi et al., 2021a). The pc-scale core emission contributes, on average, to 3-6% of the total radio emission measured at kpc scale from NVSS maps, although an increasing core contribution for flat/inverted-spectrum sources is evident. VLBI studies of FR 0s clearly demonstrate the jet-to-counter-jet flux ratios of FR 0s is significantly smaller that those of 3C/FR Is (Baldi et al., 2021a; Giovannini et al., 2023), supporting the picture that jet bulk velocities in the FR 0s are lower (see Sect 8 for further discussion on this issue).

Apart from the cases (∼30%) where the VLBI core emission is higher than previous low-resolution data, possibly due to source variability and/or an inverted/peculiar radio spectrum, mas-scale radio emission is typically up to half of arcsec-scale core emission unresolved with VLA (Cheng and An, 2018; Cheng et al., 2021; Baldi et al., 2021a; Giovannini et al., 2023). This suggests that a large fraction of emission is missed by moving from pc to kpc scale emission. Baldi et al. (2021a) combined, for the first time, the visibility datasets of the eMERLIN and VLA in the same band for five low-power FR 0s (Baldi et al., 2015) in order to probe the intermediate scales of the jet length. This procedure turned out to be successful in detecting pc-scale jets for 4 objects, which were missing in the two original datasets (see Fig. 7 for an example) because unresolved in VLA maps and resolved out in the eMERLIN maps. We can thus conclude that FR 0s, although apparently lacking extended emissions, are effectively able to emanate pc-scale jets, whose both the small size and the

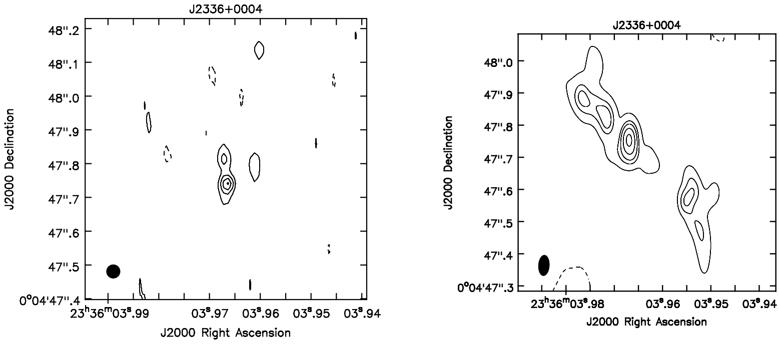

Fig. 7 The 5-GHz map of the one FR 0 (J2336+0004) observed with the eMERLIN array (40 mas) and its 4.9-GHz map (∼60 mas), obtained by combining eMERLIN and VLA visibilities. The filled area, shown at the bottom-left corner of the images, represents the restoring beam of the maps. Adapted from Baldi et al. (2021a).

low brightness make them hard to isolate and detect. The combination of long and short baselines represents a powerful tool to study the jet properties of the FR 0 population.

Other VLBI studies on nearby low-power LINERs (e.g. Falcke et al. 2000; Filho et al. 2002a; Nagar et al. 2002a) confirmed that such type of optical nuclei are typically associated with pc-scale core-dominated radio structures, again in analogy with FR 0s.

5.3 Radio SED

To reconstruct the typical broad-band radio SED of a FR 0, we collect the multi-frequency radio data from MHz to GHz for the FR0CAT objects, available from low and high frequency surveys and single dish observations. Figure 8 depicts the mean radio SED (black solid line) from 150 MHz to 22 GHz with 1σ dispersion (considering only detections). The main result is the overall flat spectral index ($-0.011 < \alpha < 0.025$), which confirms the general tendency of FR 0 population of being characterised by lack of optically-thin component throughout the frequencies. The mean FR0 radio SED is flatter than the typical one derived for classical RLAGN, ∼-0.6 – -0.7 (Elvis et al., 1994), even selecting the low-z sample of RLAGN (Shang et al., 2011). Non-thermal self-absorbed synchrotron emission from the basis of a core-dominated jet is most probably responsible to justify the observed spectral flatness.

At higher resolution, the (GHz-band) radio SED of the pc-scale cores is as flat as the those derived from low-resolution radio observations (Fig. 6, Cheng and An 2018; Cheng et al. 2021). The jet components resolved with VLBI appear to have steeper spectra than those of cores, ∼-1 – -2. This result confirms the small jet contribution to the total emission in FR 0s and, indeed,

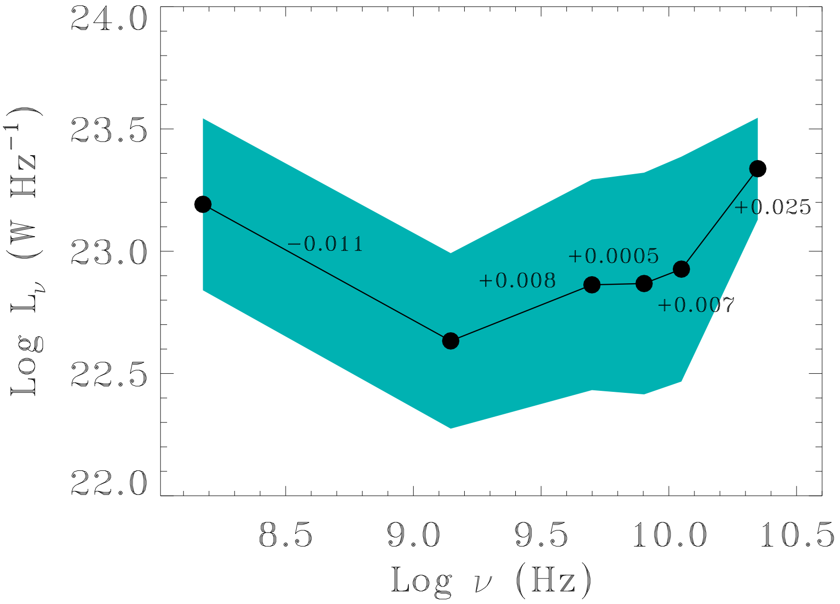

Fig. 8 The mean radio spectra (L$_\nu$ vs ν) of FR 0s from the FR0CAT (Baldi et al., 2018) from 150 MHz to 22.3 GHz. The data are taken: 150 MHz from Capetti et al. (2019, 2020a); 1.4 GHz from FIRST, 4.5-5 GHz from VLA (Baldi et al., 2019a) and Green Bank 6-cm survey (GB6, Gregory et al. 1996); 7.5-8.2 GHz from VLA (Baldi et al., 2019a) and RATAN-600 telescope (Mikhailov and Sotnikova, 2021b); 11.2 and 22.3 GHz from RATAN-600 telescope (Mikhailov and Sotnikova, 2021b). The color filled area represents the 1 σ distribution of the population. The numbers show the spectral indices in the 5 frequency segments (L$_\nu \sim \nu^\alpha$) and are all consistent with a flat spectrum.

sub-kpc scale jets can emerge from radio maps with hybrid angular resolution (e.g., combining short and long baselines) and deep VLBI observations.

6 Optical and Infrared properties

In the optical band, the continuum and spectral information of genuine FR 0s are mostly limited to the SDSS data. For the FR0CAT host galaxies, the optical absolute magnitude distribution covers the range -21 $\lesssim$ M$_\mathrm{r}$ $\lesssim$ -23, corresponding to masses $\sim$10$^{10-11}$ M$_\odot$, consistent with massive ETGs, as also inferred from the infrared colors. Instead, from the nuclear point of view, a study of the optical and IR accretion-related emission of FR 0s, in analogy to what has been done with Hubble Space Telescope for nearby 3C/FR Is (Chiaberge et al., 1999a; Baldi et al., 2010), is still missing. The lack of a proper optical nuclear power estimate leads to the assumption of the optical galaxy emission as upper limit on the optical AGN. Considering 5 mJy as radio flux cut from the FR0CAT sample, the radio loudness of FR0CAT sources is at least > 11.

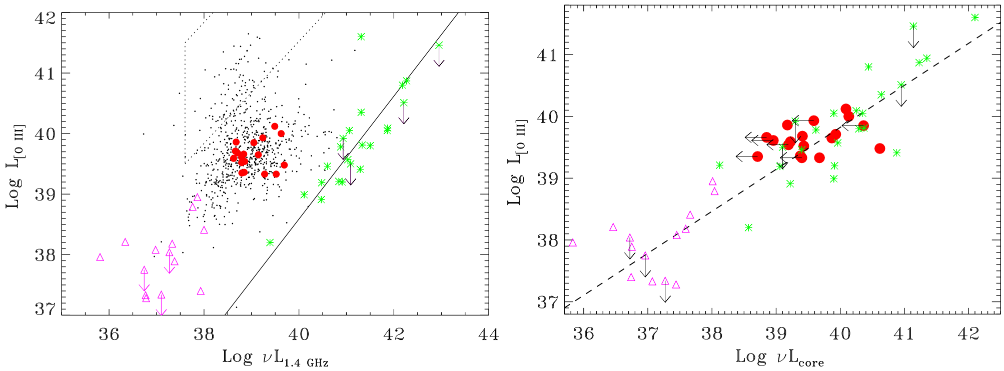

Fig. 9 Left panel: NVSS vs. [O III] line luminosity (erg s^{-1}). The small points correspond to the SDSS/NVSS sample selected by Best and Heckman (2012). The solid line represents the correlation between line and radio luminosity derived for the 3C/FR I sample (green stars) (Baldi et al., 2019a). The dotted lines include the region where RQAGN (Seyferts) are found. The filled circles are FR 0s studied with the VLA by Baldi et al. (2019a) and the empty pink triangles are the CoreG. Right panel: VLA radio core vs [O III] line luminosity (erg s^{-1}) for 3C/FR Is, FR 0s and CoreG and the dashed line represents their common radio-optical luminosity correlation.

An optical-band quantity which is widely used to characterise the AGN emission is the [O III]λ5007 emission line, that is produced by a continuum radiation from the accretion disc or jet which photoionises and heats the ambient gas. Since it is easily observed and largely available from SDSS spectra, its luminosity is usually used as proxy of the bolometric AGN power (Heckman et al., 2004) (see Sect. 8 for details and caveats). While the line luminosities of FR 0s do not correlate with the total radio luminosities in analogy to CoreG, but in opposition to classical RLAGN (left panel, Fig. 9), do with the radio core luminosities, once the sub-arcsec core emission is resolved. In fact, FR 0s lie on the radio-line correlation (see Sect. 8 for a better discussion), valid for FR Is and CoreG (Baldi et al., 2015, 2019a) (right panel, Fig. 9). This result indicates that, since [O III] line is mostly isotropic, the radio compactness of FR 0s is not due to geometric effects and, thus, excludes an aligned orientation to the line of sight. Similarly, Miraghaei and Best (2017) found that compact RGs have $L_{[O\ III]}$ distribution similar to that of extended RGs, 10^{39}-10^{40} erg s^{-1}, when matched in radio core luminosities.

The high detection rates of optical and IR nuclei and the lack of evidence of a thermal emission at IR wavelengths have been interpreted as the absence of a dusty torus in 3C/FR Is and generally for LERGs (e.g Chiaberge et al. 1999b; Leipski et al. 2009; Baldi and Capetti 2010; van der Wolk et al. 2010; Antonucci 2012; Dicken et al. 2014; Tadhunter 2016a). This scenario has been also applied to LINER-like LLAGN in general (FR 0s included), which find similar optical and IR characteristics of FR Is (e.g. Ho 2008; Müller-Sánchez et al. 2013), consistent with a luminosity-dependent model of a torus that disappears at very low accretion rates (Elitzur and Shlosman, 2006; Balmaverde and Capetti, 2015; González-Martín et al., 2015).

7 High-energy properties

The study of high-energy (HE, >0.1 keV) properties of jetted AGN can help investigating the accretion and ejection mechanisms in action. The current and upcoming generations of HE detectors are revolutionising our picture of how the central engines at the center of the RLAGN are able to launch plasma at relativistic speeds and extend their spectra to very-high energies (up to TeV, Rani 2019; Rulten 2022). In addition, the detection of HE emission and neutrinos associated with low-luminosity, misaligned AGN and BL Lacs (e.g., Abdo et al. 2010; IceCube Collaboration et al. 2018, 2022; Torresi 2020) have opened a new window on the physics of particle accelerations and jets even in AGN with less extreme conditions than that expected in powerful Blazars.

FR 0s, ∼4.5 times more numerous than FR Is in the local Universe (z<0.05), represent potentially interesting targets at high and very-high energies (from X-ray to TeV) and could contribute non-negligibly to the extragalactic HE background (Stecker et al., 2019). Here we discuss the HE properties (from keV to TeV) of FR 0s, in analogy with the review from Baldi et al. (2019c).

7.1 X-ray

The X-ray emission represents an optimal proxy to study the accretion properties of active BHs, because the keV band can probe the HE photons produced by the corona and disc. Torresi et al. (2018) performed the first systematic study in the X-ray (2-10 keV) band of a sample of 19 nearby FR 0s selected from Best and Heckman (2012), having available X-ray data in the public archives of the *XMM-Newton, Chandra* and *Swift* satellites. Their FIRST 1.4-GHz flux densities (>30 mJy) are higher than the FR0*CAT* sources. Torresi et al. (2018) found that the X-ray spectra of these FR 0s are generally well represented by a power-law $\mathit{\Gamma} \sim 1.9$ absorbed by Galactic column density and do not require an additional intrinsic absorber, suggesting the absence of a dusty torus, similarly to 3C/FR Is (e.g. Donato et al. 2004; Balmaverde et al. 2006), confirming the results from optical and IR studies. In some cases, the addition of a thermal component is required by the data: this soft X-ray emission could be related to the extended intergalactic medium or to the hot corona typical of ETGs (Fabbiano et al., 1992). The X-ray luminosities of FR 0s, $\mathrm{L_X}$, range between 10^{40} and 10^{43} erg s^{-1}, similar to those of 3C/FR Is (Balmaverde et al., 2006; Hardcastle and Worrall, 2000).

When the X-ray luminosity is compared to the radio core one, a statistically significant correlation is established (Fig. 10), valid for FR Is and FR 0s. This result corroborates the common interpretation that the X-ray emission in low-power RGs, FR 0s, FR Is and LERGs in general, has a non-thermal origin from the jet (e.g. Balmaverde and Capetti 2006b; Hardcastle and Worrall 2000; Hardcastle et al. 2009). The X-ray luminosities of FR 0s also supports the idea that the central engine of FR 0s is powered by a sub-Eddington RIAF-type accretion disc, $\dot{L_E} \sim 10^{-3}$-10^{-5}, similar to 3C/FR Is and different from powerful

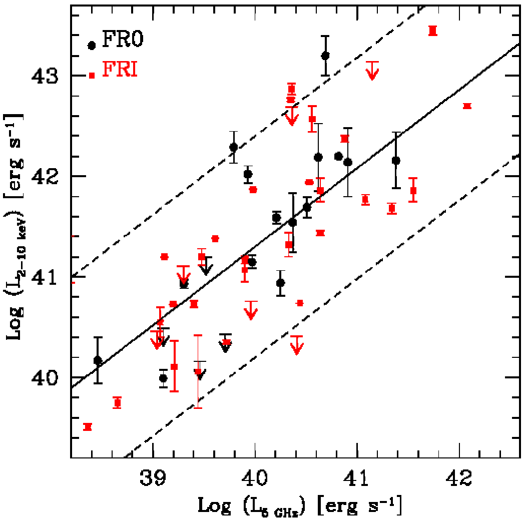

Fig. 10 X-ray (2-10 keV) luminosity versus 5-GHz radio core luminosity for FR 0s (black circles) from SDSS/NVSS sample and 3C/FR Is (red squares). Arrows indicate upper limits. The black solid line is the linear regression for the overall sample of FR 0s and FR Is, excluding the upper limits. The black dashed lines represent the 1σ uncertainties on the slope. Adapted from Torresi et al. (2018).

3C/FR IIs (HERGs) (Baum et al., 1995; Evans et al., 2006; Hardcastle et al., 2009). Since the study from Torresi et al. (2018) is slightly biased towards high-luminous FR 0s, a dedicated study of the accretion properties with deep Chandra data would be required for a statistical confirmation.

7.2 Gamma-ray

Gamma rays (> 100 keV) are generally produced under extreme relativistic conditions and offer an unique view of the physical mechanisms in jet launching and propagation (Blandford et al., 2019; Hada, 2019). In such a band, Blazars are known to be the most luminous class of γ-ray emitters and have been thoroughly studied (Abdollahi et al., 2022). Conversely, the HE properties of low-luminosity and misaligned AGN are generally less explored than the luminous counterparts because of their lower flux densities (Abdo et al., 2010; Angioni et al., 2017; Rieger and Levinson, 2018; de Menezes et al., 2020). In fact, there are only a few cases of γ-ray detection of FR 0s in literature.

Grandi et al. (2016) claimed the first Fermi γ-ray detection of a FR 0, Tol 1326-379, with a GeV luminosity of 2×10^{42} erg s^{-1}, similar to FR Is. Its radio-GeV SED is double-peaked (Maraschi et al., 1992), similar to other jet-dominated RLAGN (Fig. 11, see the SEDs of M87, Abdo et al. 2009, and Centaurus A, H. E. S. S. Collaboration et al. 2020), where non-thermal synchrotron and inverse-Compton emission dominates in any band over the disc and host emission. While the GeV luminosity reconciles with the detection of

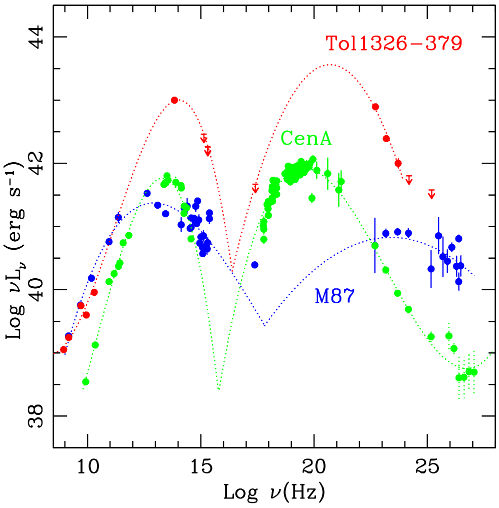

Fig. 11 Multi-band SED (from radio to γ-ray) of the Fermi-detected FR 0, Tol 1326-379 (red symbols) compared to those of two nearby prototype FR Is, HE emitters: Centaurus A (green) and M 87 (blue). The dotted lines are polynomial functions connecting the datapoints and do not represent model fits to data. Adapted from Grandi et al. (2016).

local FR Is, the prominent Compton peak, brighter than the synchrotron one, makes this source similar to flat-spectrum radio quasars, while the steep γ-ray spectrum makes conversely more similar to low-luminosity BL Lacs. Nevertheless, the best scenario which can reproduce the whole SED is a misaligned RG which emits synchrotron and synchrotron self-Compton radiation with a total energy flux of the order of few 10^{44} erg s^{-1} (Grandi et al., 2016). Later, Paliya (2021) reports the γ-ray identification of other three FR 0s from the FR0CAT above 1 GeV using more than a decade of the Fermi Large Area Telescope (LAT) observations. By stacking present large datasets, other FR 0 candidates and compact core-dominated RGs have been recently claimed to be detected (Best and Bazo, 2019; de Menezes et al., 2020). In addition, based on the sensitivities of upcoming MeV–TeV telescopes, a significant population of low luminosity-RGs emitting at HE will be unearthed in the next future (Baldi et al., 2019c; Balmaverde et al., 2020). In fact, it has been estimated that nearby core-dominated RGs (FR0 s and CoreG) can account for ∼4%-18% of the unresolved γ-ray background below 50 GeV observed by the LAT instrument on-board *Fermi* (Stecker et al., 2019; Harvey et al., 2020). Unfortunately, no evident FR 0s have been listed among the non-blazar AGN list in the recently released Fourth LAT AGN Catalog (4LAC, Abdollahi et al. 2020; The Fermi-LAT collaboration et al. 2022) and the γ-ray identification of Tol 1326-379 has been also questioned (Fu et al., 2022).

In addition, Tavecchio et al. (2018) proposed that FR 0s can accelerate HE protons in the jet and be powerful enough to sustain the neutrino production detectable by the IceCube experiment, above several tens of TeV (Jacobsen et al., 2015). Merten et al. (2022) argued that FR0 jets can generate ultra-high-energy cosmic rays through stochastic shear acceleration. In opposition, Mbarek and Caprioli (2021) argued that the lower bulk Lorentz factors of FR0 jets than those of FR I/IIs could disfavour their HE emission in general.

8 Accretion and ejection

Current magneto-hydrodynamic simulations have produced a wide range of accretion discs coupled with jets (e.g., Meier et al. 2001; Ohsuga et al. 2009; Yuan and Narayan 2014). In low accretion regime (where $\dot{L}_{\rm E}$ is typically less than 2% of the Eddington limit, Heckman and Best 2014), ADAF discs are akin to launch jets (Narayan and Yi, 1995). An ADAF system can evolve under standard and normal evolution (SANE, e.g. Narayan et al. 2012) and magnetically arrested disc (MAD, e.g. Bisnovatyi-Kogan and Ruzmaikin 1974; Narayan et al. 2003; Tchekhovskoy et al. 2011) configurations: in the former the disc is significantly not threaded with poloidal magnetic flux, while in the latter the magnetic flux threading the BH horizon becomes so large that the magnetic pressure of the jet can temporarily stop the flow of matter into the BH. Current interest in MAD accretion is driven by the discovery that it leads to low and powerful relativistic jets. In fact, For M87, only strongly magnetized (MAD) disc models remain the most favourable solutions to reproduce the EHT results (e.g. Event Horizon Telescope Collaboration et al. 2021). This result strengthens the common interpretation that low-power RGs (generally FR Is, such as M 87) are probably powered by ADAF (MAD-type?) discs with low $\dot{m}$ and low radiative efficiencies, which channel a small fraction of the disc plasma into the relativistic jet (e.g., Nagar et al. 2000; Falcke et al. 2000; Ho 2002; Hardcastle and Worrall 2000; Balmaverde and Capetti 2006a; Zanni et al. 2007; Ho 2008; Balmaverde et al. 2008; Hardcastle et al. 2009). To study the accretion and ejection characteristics of low-power RGs, it has been widely used broad-band empirical relations to gauge the disc and jet energetics.

For the accretion-related argument, we must rely on various proxies for the bolometric AGN luminosity based on the radiation that is not fully obscured by the torus and does escape or is reprocessed. For its large availability, the radiative bolometric luminosity or accretion power can be estimated from the optical [O III] emission line, $\rm L_{Bol} = 3500\, L_{[O\ III]}$ (for LLAGN, Heckman et al. 2004), as the AGN emission excites the gas clouds in the narrow line region, which re-emit [O III] line almost isotropically. This quantity is a good, but not optimal, proxy since internal obscuration and stellar contamination can affect the measurement. $\rm L_{[O\ III]}$ represents an upper limit on the accretion power for jet-dominated AGN, LERGs, where jet shocks can cause [O III] emission, instead of the underlumious RIAF disc (Capetti et al., 2005).

The AGN jets are observable through their synchrotron emission. The mechanical (kinetic) power of the jets, $L_{\rm Mech}$ has been estimated by using different assumptions. Monochromatic radio luminosity represents only a small fraction of the energy carried by the jets, about 2 orders of magnitude smaller than total $L_{\rm mech}$ (Scheuer, 1974). However, recalibrating this relationship with

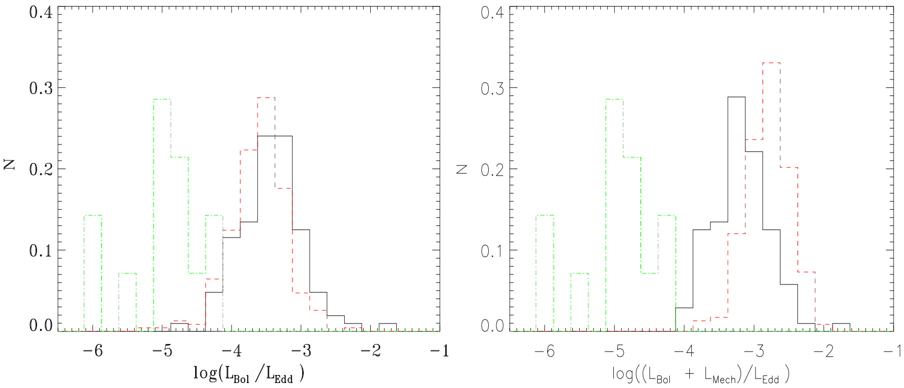

Fig. 12 Histograms of BH accretion rates estimated as Eddington ratio, $\mathrm{L_{Bol}/L_{Edd}}$ (left panel), and as total accretion rate, $\mathrm{(L_{Bol} + L_{Mech})/L_{Edd}}$ (right panel) for FR0CAT objects (black solid line), FRICAT objects (red dashed line) and CoreG (green dot-dashed line).

physical constraints (e.g. synchrotron spectral ageing, radiative loss, content of particles and magnetic fields) has yielded to

$$L_{\mathrm{mech}} = 7 \times 10^{36} f (L_{1.4\,\mathrm{GHz}}/10^{25}\,W\,Hz^{-1})^{0.68}\,W \qquad (3)$$

estimated by Heckman and Best (2014). This relation was obtained by studying the jet mechanical energy as pV work done by the jet to inflate cavities found in hot X-ray emitting halos (Rafferty et al., 2006; Bîrzan et al., 2008; Cavagnolo et al., 2010). The jet energy can also be estimated from synchrotron emission using the minimum energy condition in the radio lobes in an equipartition regime (i.e. the internal energy is almost equally distributed between magnetic field and relativistic particles) (Willott et al., 1999; O'Dea et al., 2009; Daly et al., 2012). The f factor includes all the uncertainties on the physical state of the lobes, such as for example the particle composition, SED, volume filling factor, possible deviation from the equipartition and adiabatic condition, turbulence, additional heating from shocks. Heckman and Best (2014) adopted $f = 4$ based on the best best-fit linear relation of the data. We note that these empirical assumptions, set on samples of FR Is and FR IIs, may not be entirely applicable for FR 0s (Grandi et al., 2021). However we choose to use this value to be consistent with previous works on low-power RGs (Heckman and Best, 2014).

Left panel of Figure 12 depicts the Eddington ratio ($\mathrm{L_{Bol}/L_{Edd}}$) distributions for FR0CAT, FRICAT and CoreG galaxies. FR 0s and FR Is have similar rates, $10^{-5} - 10^{-2}$. A Kolmogorov–Smirnov (KS) statistic test confirms that two distributions are not drawn from different population with a probability P=0.0059. Conversely, CoreG have significantly lower accretion rates $<10^{-4}$.

Since a large amount of the falling gas is launched into the jet without feeding the BH (Zanni et al., 2007), another method to estimate the total accretion is by adding the jet kinetic power to the radiative power as follows $L_{\dot{E},\mathrm{tot}} = \mathrm{(L_{Bol} + L_{Mech})/L_{Edd}}$. The right panel of Fig. 12 shows the distribution of this

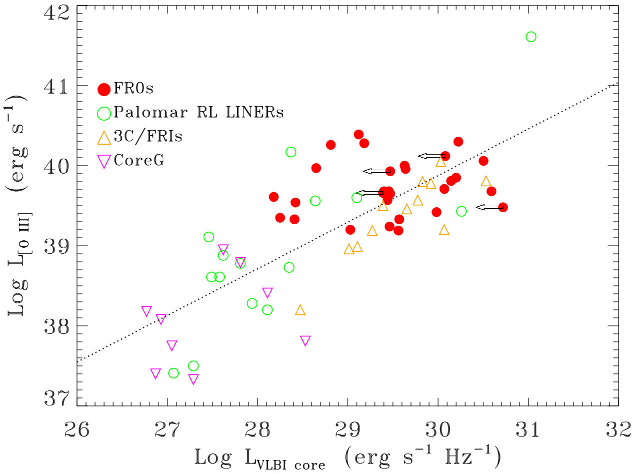

Fig. 13 Parsec-scale core radio power (erg s^{-1} Hz^{-1}) vs. [O III] line luminosity (erg s^{-1}) for different samples of LINER-type RLAGN hosted in ETGs with core-brightened morphologies (see the legend): FR 0s (red filled dots) from Cheng and An (2018); Cheng et al. (2021); Baldi et al. (2021a); Giovannini et al. (2023), RL LINERs from the Palomar sample from Ho et al. (1995) (green empty dots), 3C/FR Is (upwards orange triangles), Core Galaxies (downward pink triangles). The dotted line indicates the best linear correlation.

total accretion rate estimator for the different groups of sources. The CoreG generally have lower total accretion rates than the FR 0s and FR Is. However, there is a considerable overlap between the populations of FR 0s and FR Is, $L_{\dot{E},\mathrm{tot}} \sim 10^{-4} - 10^{-2}$. A KS test confirms that the cumulative distribution function of FR0s is significantly different from that of FR Is ($P = 5.01843 \times 10^{-17}$). These results confirm the X-ray results from Torresi et al. (2018) that FR 0 BHs are fed at low rates, consistent with a jet-mode AGN and RIAF-type accretion states (Heckman and Best, 2014). CoreG, being low-power FR 0s, have also lower accretion rates than FR0CAT objects.

Broad-band proxies for accretion and kinetic jet powers are expected to broadly correlate in RLAGN, with two parallel relations valid for the two accretion states (e.g. Rawlings and Saunders 1991; Willott et al. 1999; Buttiglione et al. 2010). For AGN-dominated RLAGN (HERGs), the correlation between radio and optical (continuum) or X-ray emission probably results from a combination of thermal and non-thermal emission from disc and jet (e.g., Chiaberge et al. 2002; Hardcastle and Worrall 2000; Baldi et al. 2019b). For jet-dominated RLAGN (LERGs), the correlation between two luminosity proxies is best explained as the result of a single emission process in the two bands[7], i.e. non-thermal synchrotron emission from the relativistic jet (e.g. ,Chiaberge et al. 1999b; Balmaverde et al. 2006; Mingo et al. 2014), launched by a RIAF disc as supported by multiple theoretical and analytical studies (e.g. Meier 2001; Begelman 2012; McKinney et al. 2012). This result has been also found

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[7] The caveat is that the optical and X-ray emission represents only an upper limit on the actual accretion power for LERGs.

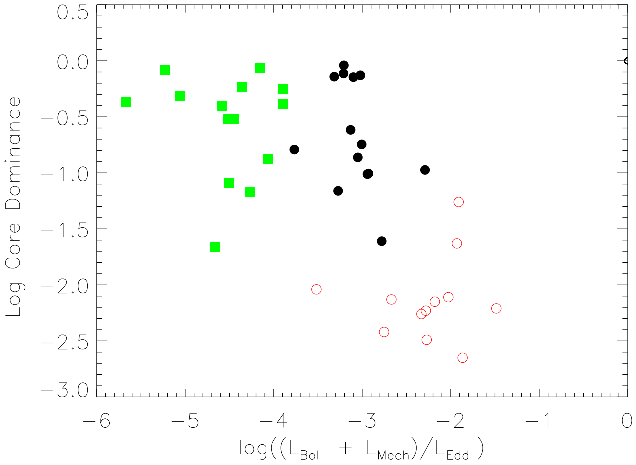

Fig. 14 The core dominance measured as ratio between VLA core and NVSS flux densities for FR 0CAT sources (black filled dots), FRICAT sources (red circles) and CoreG (green squares) as function of total accretion rate $(\mathrm{L_{Bol}} + \mathrm{L_{Mech}})/\mathrm{L_{Edd}}$. We exclude sources with core dominance >1 because probably affected by variability or systematic errors.

valid for low-luminosity AGN, where compact jet dominates the broad-band continuum emission (e.g. Nagar et al. 2002b; Ho 2008; Fernández-Ontiveros et al. 2022). Balmaverde et al. (2008) found that for 3C/FR Is and CoreG the accretion power correlates linearly with the jet power, with an efficiency of conversion from rest mass into jet power of ∼0.012. An [O III]-radio correlation found for FR Is, FR 0s, CoreG, and RL low-power LINERs (e.g. Verdoes Kleijn et al. 2002b; Nagar et al. 2005; Balmaverde and Capetti 2006a; Baldi et al. 2015, 2019a, 2021b) suggests a similar ionising central source, where a scaled-down accretion rate for the core-dominated sources explains a likewise scaled-down jet power with respect to the more powerful 3C/FR Is (Balmaverde et al., 2008). By focusing on parsec-scale radio emission, an analogous [O III]-radio correlation has been reported by Baldi et al. (2021a) over ∼4 orders of magnitudes (Fig. 13) for RGs with comparable properties, e.g. hosted in massive ETGs and characterised by a LINER spectrum (FR I, FR 0s, CoreG, RL LLAGN). By also including the new VLBI data for FR 0s from Giovannini et al. (2023), we fit the data points present in this sequence with a linear (in a log - log plot) relation. We find a correlation in the form $L_{\mathrm{[O\ III]}} \propto L_{\mathrm{VLBI\ core}}^{0.58\pm0.06}$ with a Pearson correlation coefficient of 0.767 which indicates that the two quantities do not correlate with a probability of $8{\times}5\ 10^{-14}$. This statistically-robust relation corroborates the idea that the model of RIAF disc with core-brightened jets of FR Is is also applicable to FR 0s and LINER-like RLAGN in general. The large scatter of the correlation, ∼0.28 dex, could be caused by Doppler boosting, nuclear variability and non-flat spectral index (1.4-8 GHz). However, there is not a clear evidence of Doppler-boosted sources at higher radio luminosities than the linear correlation, such as one-sided jets or highly variable sources.

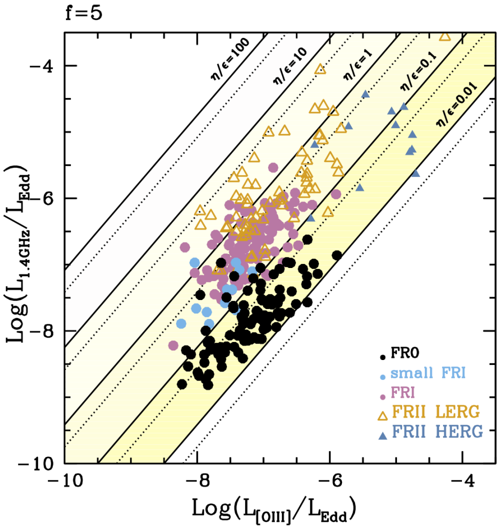

Fig. 15 $L_{1.4\,\mathrm{GHz}}/L_{\mathrm{Edd}}$ versus $L_{[\mathrm{O\ III}]}/L_{\mathrm{Edd}}$ of FRCAT sources (FR 0, FR Is and FR IIs) compared to the predicted values of kinetic jet power estimated by Equation 3 assuming $f = 5$. Each line in the plots corresponds to a different value of η/ϵ. Since a change of the BH mass can have a minor impact on the predicted η/ϵ curves, we plot (solid and dotted) lines corresponds to $M_{\mathrm{BH}} = 10^{7.5}$ $\mathrm{M}_{\odot}$ and $M_{\mathrm{BH}} = 10^{9.5}$. Taken from Grandi et al. (2021).

The accretion-ejection coupling can also be explored by comparing the core dominance, a proxy of the jet brightness structure (i.e. how much the core shines over the extended jet emission), with the total accretion rate, $\dot{L}_{\mathrm{E,tot}}$. Figure 14 presents the distribution of these two quantities for FR0CAT, FRICAT and CoreG galaxies (excluding the few sources with core dominance >1 possibly due to variability or systematic errors). Although the core dominance naturally saturates at 1 as the source becomes weaker (and radio spectrum flatter), a general tendency of the RGs to increases their core dominance as the accretion rate increases, is evident. This results suggest that the capability of a RG to develop kpc-scale structures is related to accretion properties: more core brightened structures are associated with lower-$\dot{m}$ sources.

The jet efficiency, i.e. the fraction of the kinetic jet power produced with respect to the AGN accretion power, offers a good diagnostic to investigate the nature of the nuclei of RGs. The $\mathrm{L}_{\mathrm{Mech}}/\mathrm{L}_{\mathrm{Bol}} \sim \eta/\epsilon$ ratio (η and ϵ are the fraction of gravitational energy converted into jet power and thermal radiation, respectively) directly measures the ability of the system to channel gravitational energy into the jet rather than to dissipate it in thermal radiation. Figure 15 depicts η/ϵ for FR0CAT, FRICAT and FRIICAT objects (Grandi et al., 2021). Neglecting the f and M_{BH} effect on the jet efficiency, whereas HERGs favour a thermal dissipation of the gravitational power, different LERG types, powered by similar inefficient accretion flows, launch jets with different luminosities and different jet efficiencies: FR 0s appear less efficient in extracting energy into the jets than FR Is.

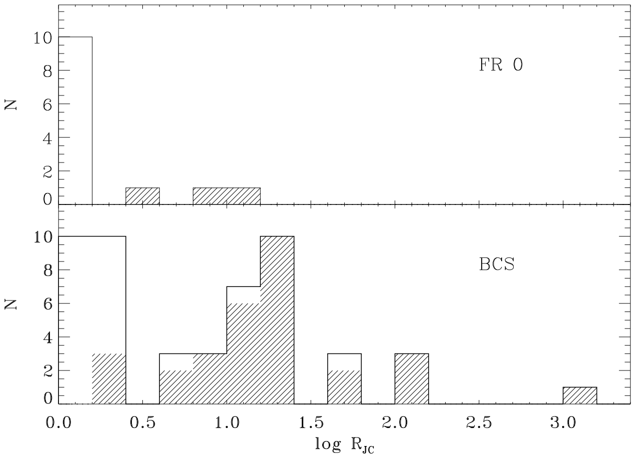

Fig. 16 Distributions of the logarithm of the R_{JC}, the jet-to-counter-jet flux ratio for the FR 0 (top panel) from Giovannini et al. (2023) and FR I/FR II RGs from the Bologna Complete Sample (BCS, bottom panel, from Liuzzo et al. 2009). The dashed histograms correspond to lower limit on the jet sidedness. Taken from Giovannini et al. (2023).

Near the jet launching site, at parsec scale, a comparison between FR 0s and classical 3C/FR Is can help us understanding the reason why FR 0s do not develop large structures. 3C/FR Is generally exhibit core-brightened radio morphologies at parsec scale (Fanti et al., 1987; Venturi et al., 1995; Giovannini et al., 2005) and FR 0s show occasionally similar morphologies when resolved. However, the degree of jet asymmetry and the ratio between one-sided and two-sided jets appear different between the two classes. In FR Is, the effect of Doppler boosting on the jet sidedness, i.e. the jet-to-counter-jet flux ratio, decreases from VLBI to VLA observations and is typically larger than 3 at parsec scale (Bridle, 1984; Parma et al., 1987; Giovannini et al., 1990; Venturi et al., 1995; Xu et al., 2000; Giovannini et al., 2001). On the basis of the presence of a link between jet speed and asymmetry, this result is interpreted as a change of the FR I jet bulk speed from relativistic, $\Gamma > 3$, to sub-relativistic speeds on kpc scales by decelerating, possibly due to entrainment of external material (Bicknell, 1984, 1995; Bowman et al., 1996; Laing and Bridle, 2014; Perucho et al., 2014). For FR 0s the jet sidedness is less prominent: only one third of FR 0s has jet sidedness larger than 2 at parsec scale (Fig. 16). This is a clear observational evidence that the jet bulk speed of FR 0s is significantly smaller than that of FR Is. Following the procedure discussed by Bassi et al. (2018), we can roughly estimate the bulk Lorentz Γ factor of the jet, but with a strong assumption on the unknown orientation: the Γ_{bulk} for the angle of the jet to the line of sight θ_m that maximizes $\beta = v/c$. With these assumptions, considering the range of jet sidedness observed < 10, Γ_{bulk} for FR 0s is typically <2.5. This result concurs with the low jet proper motions studied by Cheng and An (2018) and Cheng et al. (2021). In conclusion, although FR 0 and FR Is share comparable accretion properties, the jets of the former appear less efficient and slower, mildly relativistic at parsec scales with a bulk velocity of the order of $0.5c$. However, a proper systematic analysis on larger samples of FR 0s is needed to draw a final conclusion on their accretion-ejection state.

9 Environment

The kpc- and Mpc-scale environmental properties (e.g. clustering, ICM, location within the cluster/group, relative galaxy velocity) can regulate the accretion and ejection states of an active BH: e.g. bright cluster galaxies at the centre of dense environments typically host a RG and have different merger histories and fueling properties than galaxies at the cluster outskirts moving away from the centre (e.g. Lin et al. 2010; Vattakunnel et al. 2010; Shlosman 2013; Kormendy and Ho 2013; Conselice 2014). The understanding of the relationship between RLAGN activity and their environment is essential for a comprehension of BH-host evolution, AGN triggering and life cycles, and for calibrating feedback processes in cosmological models. However, the role of the environment in shaping RLAGN is still not clear (e.g. Best 2004; Ineson et al. 2013, 2015; Ching et al. 2017; Macconi et al. 2020). The FR I/II dichotomy is believed to depend on jet interaction with the environment (e.g. Laing et al. 1994; Kaiser et al. 1997), or due to galaxy properties (Ledlow and Owen, 1996), apart from mechanisms associated with jet production itself (e.g. Meier 2001).

At small scales, the similarity between the host types of FR 0s and FR Is suggests that the galactic gas conditions between the two classes are rather comparable. Precisely, the smaller optical host masses of the FR 0s than those of FR Is argues against the idea of a dense galaxy-scale environment which could cause the jet deceleration and disruption through the interaction with ISM (Kaiser and Best, 2007). No evidence of a denser hot-gas halo with respect to that of FR Is hosts, which typically permeates the atmosphere of elliptical galaxies, can be inferred from the sparse X-ray studies of FR 0s.

The large-scale environment is typically invoked to explain the deceleration and confinement of FR I jets with respect to FR IIs, since FR Is typically reside in denser environment (denser coronae and richer groups/cluster, e.g. Prestage and Peacock 1988; Hill and Lilly 1991; Zirbel 1997; Gendre et al. 2013; Laing and Bridle 2014; Massaro et al. 2019, 2020b). Several studies on the Mpc-scale environment of CRSs have confirmed that they inhabit dense environment, but the presence of environmental differences with respect to FR Is have been questioned. Torresi et al. (2018) found that at least 50% of the FR0s live in a dense X-ray environment, which reflects massive dark matter halos in which these objects are embedded. Vardoulaki et al. (2021), studying the VLA-COSMOS Large Project, found that FR I/IIs and compact AGN are found in all types and density environments (group or cluster, filaments, field), regardless of their radio structures. Miraghaei and Best (2017) only found a marginal trend of CRSs in denser environments. In this direction, Capetti et al. (2020b) found that FR0CAT sources do indeed live in rich environment but with lower density by a factor of 2 on average, than FR Is, and that about two thirds of FR 0s are located in groups containing <15 members. A similar result was found by Prestage and Peacock (1988) who argued that CRSs lie in regions of lower galactic density than extended sources. In addition, Massaro et al. (2020a) argued that nearby BL Lacs share similar clustering properties with FR 0s, suggesting a common parental population. In conclusion, there is growing evidence of an environmental difference (at least at large scales) between FR 0s and FR Is (and extended RGs in general), which would imply a different cosmological evolution between the two classes.

10 Feedback

AGN feedback comes in two flavours: quasar and radio (or maintenance) mode (e.g. see Croton et al. 2006; Best 2007; Fabian 2012; Bower et al. 2012; Heckman and Best 2014; Harrison 2017). While the former mode is associated with powerful radiatively dominated AGN, i.e. quasars (and HERGs), associated with high Eddington ratios ($\dot{L}_E >$ 0.01-0.02), the radio mode is attributed to BHs with low accretion rates ($\dot{L}_E <$ 0.01, mainly LERGs). The latter release most of their energy in the form of jets, preventing strong cooling flows in galaxy clusters (e.g. Fabian et al. 2003), and regulating the level of SF in their host galaxies (e.g. Best et al. 2006). It is only with the advent of deep multi-band radio surveys, with its combination of high sensitivity to both compact and extended emission (Shimwell et al., 2017) that we are now able to systematically study the effects of feedback from CRSs, whose galactic-scale physical size suggests an interaction with a substantial portion of the host ISM (e.g. Bicknell et al. 2018). In opposition, powerful quasars, which are rare and shorter-lived, have jets that rapidly "drill" through the ISM, depositing most of the energy in the intergalactic medium. Observational evidence continues to mount that lower-power ($L_{1.4\mathrm{GHz}} \lesssim 10^{24}$ W Hz^{-1}) jetted AGN may have a significant impact on their hosts through jet-ISM interactions on sub-galactic (∼1 - 10 kpc) scales, where the jets heat, expel, or shock the ambient ISM, thereby altering the SF efficiency (e.g., Nyland et al. 2013; Jarvis et al. 2019, 2021; Webster et al. 2021b,a; Grandi et al. 2021; Venturi et al. 2021). State-of-the-art simulations (e.g. Sutherland and Bicknell 2007; Wagner and Bicknell 2011; Mukherjee et al. 2016, 2018; Bicknell et al. 2018; Rossi et al. 2020) provide further support to this scenario, demonstrating that lower-power jets are susceptible to disruption and entrainment, which increases the volume and timescale of the feedback, as well as the amount of energy transferred to the ISM (> 5-10% of bolometric power).

FR 0s, showing galaxy-scale jetted emission, could play a critical role in the radio-mode feedback. In fact, they are the best candidates to offer continuous energy injection into the ISM, although at low regimes, but fully inserted in the host and with most of the energy deposited in the ISM. Nevertheless, the role of FR0s and the jetted population of LLAGN in general in the context of feedback remains poorly explored (e.g., Kharb and Silpa 2023).

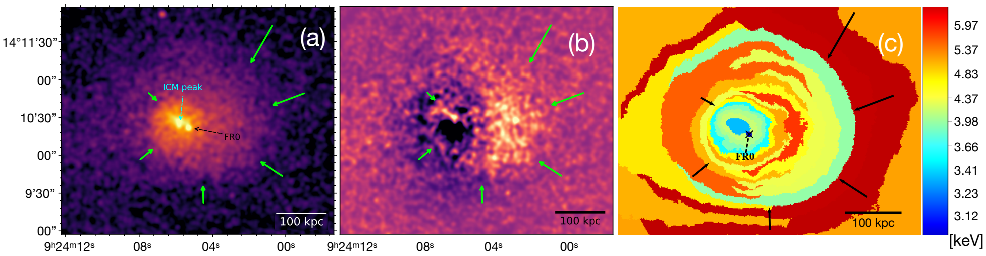

Fig. 17 Panel a: Chandra image (0.5-2 keV) of the cluster A795; the ICM peak and the position of the FR 0 are indicated. Panel b: ICM brightness profile model subtracted to the Chandra image over the same region of panel a. Panel c: Temperature map of A795. In each panel, the arrows highlight the ICM spiral geometry. Taken from Ubertosi et al. (2021b).

Vardoulaki et al. (2021) showed a comparable radio-mode quenching of SF in the hosts of CRSs and of FR I/IIs. In fact, while compact RGs can be also found in less massive hosts ($10^{9.5}$–$10^{11.5}$ $M_{\odot}$) than FR I/IIs, the former also have low specific SF rates and large time from the last burst of SF derived from SED fitting (Delvecchio et al., 2017) similar to those of the latter. CRS hosts lie in cooler X-ray groups than extended RGs with average inter-galactic medium temperatures of ∼1 keV. Additionally, the older the episode of SF, the cooler the X-ray group in which CRS lie, suggesting a SF shutdown by kinetic feedback.

A dense cold- or hot-phase in the ISM can increase the chances to detect signatures of an acting radio-mode feedback. Best et al. (2000) showed that compact radio sources smaller than 90 kpc have emission line nebulae with lower ionization, higher luminosity, and broader line widths than in larger radio sources, consistent with shocks driven by the radio jets or outflows, typically observed in dust-shrouded young RGs . Low-luminosity jet can also carry enough power to shock and remove the cold/hot gas (e.g. Morganti et al. 2019, 2022; Murthy et al. 2022), as demonstrated by some cases with observed disturbed gas kinematics, absorption features and LINER-like line emission in compact sources (e.g. Holt et al. 2008; Glowacki et al. 2017; Baldi et al. 2019b; Tadhunter et al. 2021). The detection of X-ray cavities in low-power RLAGN ($<10^{23}$ W Hz^{-1}) demonstrate the ability of their jets to inflate bubbles in the hot-gas atmosphere (Bîrzan et al., 2004; Allen et al., 2006). Nevertheless, ordinary FR 0s are not expected to drive strong outflows in dense ISM.

The first dedicated study which has observationally addressed the radio-mode feedback for FR 0s is by Ubertosi et al. (2021a), who found two putative X-ray cavities and two prominent cold fronts possibly associated with jet activity of a FR 0 (with a bolometric luminosity of the order of 10^{40} erg s^{-1}), associated with a brightest cluster galaxy (cluster Abell 795) (Fig. 17). The estimated cavity power and the cooling luminosity of the ICM follow the well-known scaling relations (e.g. McNamara and Nulsen 2007, 2012), providing a strong evidence for the self-regulated feedback in this source. Being fuelled by the inflow of a cold spiraling-shape ICM, the central AGN inflate radio cocoons that excavate X-ray depressions and drive shocks in the ICM which sloshes and heats gas, establishing a feedback loop. However, a systematic study of the feedback for a large sample of FR 0s is still missing, mainly because of the great difficulty to detect low-brightness X-ray cavities related to small jets.

To roughly estimate the impact of FR 0 jets on galaxies, assuming that the X-ray atmosphere is regulated by the jet activity, we compare the internal energy within the radio jets with the energy of the hot X-ray emitting gas in the host, similar to the analysis performed by Webster et al. (2021b) for galaxy-scale jets. First, to calculate the jet energetics, we assume that the radio emission comes from a cylindrical region of 5" long with a radius of 0.3" (radio observation based, Baldi et al. 2019a). By using a python code (pysynch[8], Hardcastle et al. 1998) we derive the minimum energy density and the minimum total energy, which is of the order of $\sim 5 \times 10^{48} - 10^{50}$ J, by considering radio flux density between 5 and 500 mJy, consistent with FR0CAT sources. Second, to estimate energy within the hot ISM, several assumptions are needed. Since the small jets of FR 0s should have a larger impact on the bulge, we estimate the bulge mass from the BH mass distribution of FR0CAT, $10^{7.5}$-10^{9} $\mathrm{M}_{\odot}$, using the McConnell and Ma (2013) scaling relation for ETGs. Then we fix the hot gas mass ratio to 5% (e.g., Dai et al. 2010; Trinchieri et al. 2012). Then assuming an average particle mass of 0.62 $\mathrm{m}_{\mathrm{proton}}$ and typical gas temperature of 0.5 keV (Goulding et al., 2016), we are able to estimate the internal energy of the hot phase in the bulge, which is of the order of $\sim 10^{50} - 3\times 10^{51}$ J. Finally, the total jet energy of FR 0s turns out to be ∼3–5% of the total binding energy of the bulge. However, bear in mind that minimum jet energy estimates represent only a lower limit, since the jets must also displace the ISM and produce shocks and its enthalpy for a relativistic gas undergoing adiabatic expansion could be $> 4pV$ (Bîrzan et al., 2004; Croston et al., 2007; Hardcastle and Krause, 2013). In addition, the internal estimated jet energy could be lower than the kinetic jet energy, which can be calculated by using the method by Willott et al. (1999) by using the 151-MHz luminosity. In fact, by considering the LOFAR luminosity of the FR0CAT, 10^{38}-10^{40} erg s^{-1}, the jet output is of the order 1×10^{43} - 4×10^{44} erg s^{-1}. This evaluation also considers the uncertainties on the factor f (<20, Hardcastle et al. 2007 for FR Is), which includes the effect from the jet structure and its environment (Willott et al., 1999). Assuming a lifetime of the jet activity of 10^{7} yr, the kinetic jet energy would range $\sim 3 \times 10^{50}$ - 6×10^{51} J. These can be considered as upper limit of the jet energetics. In this case, the ISM energy would balance jet energetics. We conclude that the FR0 jets are potentially capable of affecting the ISM properties, at least in the bulge.

Current hydrodynamical simulations (Horizon-AGN, Dubois et al. 2014a; Illustris, Vogelsberger et al. 2014; EAGLE, Schaye et al. 2015, MUFASA, Davé et al. 2016) implement quasar- and radio-mode feedback with a typical efficiency of 5-10%, assuming that the energy deposited back into the ISM, scales directly with accretion rate. The ratio $(\mathrm{L}_{\mathrm{Mech}})/(\mathrm{L}_{\mathrm{Bol}}+\mathrm{L}_{\mathrm{Mech}})$ provides a mea-

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[8] https://github.com/mhardcastle/pysynch

sure of the fraction of the total accreted energy released back into the ISM in mechanical form in radio jets. We measured this ratio for FR 0 and FR Is from FRCAT and found that all deposit more than 10% (on average 30% for FR 0s) of their accreted energy back into the ISM in mechanical form. This calculation confirms the result from Whittam et al. (2018) that LERGs in general have higher feedback efficiencies and thus thought to be more responsible for the maintenance mode of mechanical feedback than HERGs, which are, as powerful FR IIs, generally deposit their energy at larger distances in the ICM.

11 Comparison with FR II LERGs

Deep optical-radio surveys have unearthed a large population of low-luminosity FR II LERGs (Capetti et al., 2017b; Jimenez-Gallardo et al., 2019; Webster et al., 2021b), which show kpc-scale edge-brightened radio morphologies, smaller (>30 kpc) and less luminous ($\sim 10^{41}$ erg s^{-1}) than the Mpc-scale powerful 3C/FR II LERGs. Their nuclear properties (luminosity, accretion rates) can still be reproduced by a RIAF disc, consistent with the general jet-mode LERG population (Heckman and Best, 2014). Macconi et al. (2020) suggested that FR II LERGs are characterised by intermediate properties between FR Is and FR II HERGs, since they populate an intermediate region of a correlation between accretion rates and environmental richness. Tadhunter (2016a) argued that FRII LERGs represent a phase of an evolution of a RG, when the accretion has recently switched off or leveled down from a FR II HERG high state, after exhausting the cold gas. Torresi et al. (2022) suggested that a focus on the properties of the warm ionized gas and cold molecular gas in RGs (e.g., Ocaña Flaquer et al. 2010; Ruffa et al. 2019) can complement our comprehension on the puzzling nature of FR II LERGs.

The connection between FR 0 and FR II LERGs is established by their common affinity with FR Is, since they all share a LERG optical spectrum and generally interpreted to be jet-dominated RGs powered by a RIAF disc. In fact, Baldi et al. (2018) envisaged that FR 0s, FR Is and FR II LERGs belong to a single continuous population, with similar BH mass, galaxy and accretion properties, regardless of their different jet morphologies. Differences related to intrinsic intimate BH properties (spin and magnetic field at its horizon, and marginally different BH mass) shape the whole LERG population (Miraghaei and Best, 2017; Grandi et al., 2021): when these parameters are maximized, highly relativistic jets are launched and form fully-fledged FR I/FR II LERGs, while FR 0s would originate from less extreme values of these parameters.

12 Models for FR 0s

Here we will discuss two possible scenarios to account for the multi-band results on FR 0s where the jet and nuclear properties of FR 0s 1) are intrinsically different from other FR classes and do not evolve; 2) evolve within a context of RLAGN population where FR 0 represents a particular phase of this evolution.

12.1 Static scenarios

In a non-evolutionary scenario, where the intrinsic properties of the FR 0 class remain unchanged across their lifetime, we will revise the main features which can determine the accretion and ejection in FR 0s in relation to FR Is.

Magneto-hydrodynamic simulations of jet launching (e.g. McKinney and Gammie 2004; Hawley and Krolik 2006; McKinney 2006; Tchekhovskoy et al. 2011) predict the formation of a light, relativistic outflow powered by the rotational energy of the BH, as described in the work of Blandford and Znajek (1977) (BZ), as well as of a heavier and mildly relativistic outflow powered by the accretion disc, as originally proposed by Blandford and Payne (1982) (BP). LERGs, which are jet-dominated sources, are generally interpreted as BZ powered, while HERGs, which have quasar-type discs, are generally interpreted as powered by BZ and BP for the presence of both relativistic jets and strong disc winds (Heckman and Best, 2014). FR 0s as well as FR Is are expected to launch BZ jets.

For RLAGN jets generated by BZ-type process in RIAF discs (Tchekhovskoy et al., 2011; Liska et al., 2022), the ratio of jet and accretion powers (jet efficiency) is maximum when the BH is both rapidly spinning and has accumulated a substantial amount of large-scale poloidal magnetic flux by accretion (see e.g. Komissarov 2001; Tchekhovskoy et al. 2010). The BZ jet power does not directly depend on the accretion rate, but the outflowing plasma is surely a fraction of the accreting flow. As discussed in Sect. 8, although they can share similar accretion rates, core-dominated RGs and FR 0s show a less jet efficiency than more powerful FR Is. The small fraction of plasma within the disc that is actually channeled into the jet could justify the paucity of matter to accelerate to relativistic speeds in the FR 0 jets.

The BZ jet power depends on $M_{\rm BH}$, the magnitude of the magnetic field B threading the BH and the magnitude of its spin $\bar{a}$ (Chen et al., 2021). In newtonian physics, in a ballistic model, the height of the jet is proportional to the ratio between initial speed and the gravity. Since the gravity is proportional the BH mass and the initial jet speed is set by BZ process as the $\sim E_{kin}^{1/2}\bar{a}^2 M_{\rm BH}^2 B^2$, the maximum jet length is $\sim \bar{a}B$. This mathematical approximation suggests that the limited length of FR 0 jets could, in fact, depend on spin and magnetic field.

$\mathbf{M}_{\rm BH}$, the mass of the central compact object is often used as an indicator of BH activity as AGN are preferentially associated with massive systems (e.g., Chiaberge and Marconi 2011). The jet power roughly establishes the likelihood of the source being radio-jet dominated (Cattaneo and Best, 2009). Kinetic jet power and BH masses are connected in radio active nuclei, as AGN tend to become more radio powerful (i.e. more radio loud) at larger BH masses (e.g. Best et al. 2005a). Furthermore, the $L_{\rm mech}$ - $M_{\rm BH}$ relation mirrors the mass dependence on the accretion rate estimated with the Bondi accretion flow expected from the hot hydrostatic gas halos surrounding the galaxies (e.g. Allen et al. 2006; Balmaverde et al. 2008). The slightly smaller BH masses of

FR 0s can constitute a limit on the jet power, but cannot simply justify the substantial lack of extended jet emission.

Magnetic field B, plays a primary role in the processes of jet formation, acceleration, and collimation (e.g. Blandford and Znajek 1977; Blandford and Payne 1982; Nakamura et al. 2001; Lovelace et al. 2002). Its azimuthal and poloidal components, originated by rotation of accretion disc and BH, are required to form and then hold the jet and extract angular momentum from the disc surface by torque. The magnetic field integrated on BH horizon sets the jet power. The magnetic flux paradigm by Sikora and Begelman (2013) suggests that the radio loudness is determined by the depositing magnetic flux close to the BH more efficiently during hot RIAF-type (ADAF) phase which facilitates jet launching. The amount of magnetic flux accumulation and the geometry of the external field can differentiate between powerful and weak RGs. Moderate jet activity as in FR 0s can also be triggered by the dissipation of turbulent fields in accretion disc coronae (Balbus and Hawley, 1991; Brandenburg et al., 1995). For example, VLBI-observations of the radio-intermediate quasar III-Zw 2 showed that the low magnetic filed has possibly determined its failure to develop a powerful jet (Chamani et al., 2021). A difference in the large-scale magnetic field appears to exist between LERGs and HERGs (O'Sullivan et al., 2015). In addition, Grandi et al. (2021) highlighted that a small-scale different magnetic strength in RGs can result into the separation between FR 0s and other FR classes. In conclusion, low intensity of the magnetic field structure of FR 0s appears to be a plausible scenario to describe their limited jet capabilities, although there is not still clear evidence.

BH spin $\bar{a}$, is the primary ingredient in separating the formation of different jets: the spin paradigm for AGN (Sikora et al., 2007; Garofalo et al., 2010) is a phenomenological scale-invariant framework based on BH-disc parameters for understanding BH feeding, feedback and jet launching mechanisms across the BH mass scale. This model, also named gap paradigm, involves the physics of energy extraction from BH via the BZ effect, the extraction of accretion disc rotational energy via BP jets and disc winds (Pringle, 1981; Kuncic and Bicknell, 2004, 2007). The total outflow power (BZ, BP, disc wind) is based on the size of the gap region between the BH event horizon and the disc. The BH spin still mediates launching the jet and determines the upper bound on the radio loudness (Sikora et al., 2007). Retrograde and prograde BH spin configuration with the accreting material rotating opposite or parallel to the direction of the BH can determine the gap region and so jet power: high retrograde BH spin for greater jet power and low spinning prograde BHs for weak jets (Garofalo, 2009). The latter scenario would fit with the FR 0 class.

Recently, in the framework of BZ jet model, it has been found that the measured poloidal jet magnetic field $\phi_{\rm jet}$ threading a BH (Narayan et al., 2003; Tchekhovskoy et al., 2011; McKinney et al., 2012; Yuan and Narayan, 2014) correlate over seven orders of magnitudes with the disc luminosity for a sample of aligned and misaligned RLAGN, in the form $\phi_{\rm jet} \sim L_{\rm Bol}^{1/2} M_{\rm BH}$ (Zamaninasab et al., 2014), as predicted by a MAD model. This relation suggests that the magnetic field twisted by the rotation of the BHs which power the BZ jets dominate the plasma dynamics of the MAD disc, prevents the gas infall, and slow down the rotation by removing angular momentum into collimated relativistic outflow. Although we cannot directly measure field strength at the BH horizon $\phi_{\rm BH}$, this quantity is the same as $\phi_{\rm jet}$ by the flux freezing approximation for BZ jets. Assuming that $\phi_{\rm jet}$ is set by the BZ mechanism, $\phi_{\rm jet} \sim L_{\rm jet}^{1/2} \bar{a}^{-1} M_{\rm BH}^{-1}$, and the empirical relation from Zamaninasab et al. (2014), we can derive a rough estimate of the BH spin as $\bar{a} \sim L_{\rm Mech}^{1/2} M_{\rm BH}^{-2} L_{\rm Bol}^{-1/2}$ by deriving accretion and jet power, respectively, from [O III] and radio luminosities (Eq. 3). This approximate calculation performed for the FR0CAT and FRICAT leads that FR 0s have on average a smaller BH spin of those of FR Is by a factor 0.97–0.35. A similar result is obtained if the BH spin is estimated by using the empirical correlation with jet power (Narayan and McClintock, 2012).

The smaller BH spin of FR 0s would reflect to a lower bulk Lorentz factor Γ than those of FR Is, as suggested by Baldi et al. (2015, 2019a). The maximisation of the BH parameters (M$_{\rm BH}$, B, $\bar{a}$) would lead to high-Γ jets with a FR I/II morphology. This is in line with theoretical works which suggest a link between BH spin and jet speeds (e.g. Thorne et al. 1986; Meier 1999; Maraschi et al. 2012; Chai et al. 2012). While an initial disc-jet magnetization is needed, high spins are possibly required to launch the most relativistic jets, but observational evidence for the connection between BH spin and the jet is controversial and RQAGN with high spins have been observed (Reynolds, 2014), breaking the one-to-one correspondence between high BH spins and presence of jets. However, the lower BH spin of FR 0s would certainly contribute to the lower jet bulk speeds, observed as lower jet sidedness than FR Is.

To reconcile the common pc-scale L$_{\rm core}$-L$_{\rm Bol}$ luminosity correlations valid for FR 0s and FR Is, the lower jet sidedness of FR 0s, their lack of kpc-scale emission, their putative γ-ray emission, the invoked (static, but valid also for a dynamic scenario) jet model for FR 0s comes from the well-known "two-flow model" (Sol et al., 1989): an outer layer with a mildly relativistic velocity ($v \sim 0.5c$) surrounds an inner electron-positron spine, which moves at much higher relativistic speeds (bulk Lorentz factor ~ 10). The existence of two flows at different velocities provided a good agreement with both theoretical and observational constraints of RGs in general (Ghisellini et al., 2005). This model can provide a simple way to solve the discrepancy between the required high Lorentz factors to produce the observed γ-ray emission and the slower observed motion in jets at pc scales (Cheng and An, 2018; Chen et al., 2021). Based on this model, the inner beam of FR 0s is slower than that of FR Is, which could decelerate on kpc scale to sub-relativistic speeds for entrainment of external material, similarly to FR I jets (Bicknell, 1984, 1995; Bowman et al., 1996; Laing and Bridle, 2014; Perucho et al., 2014). As suggested by the similar Mpc-scale environment, the unification of the FR 0s and weak BL Lacs in a single class of RGs characterised by a fainter slower spine than that of FR Is, finds supports from recent results which identify a large number of BL Lacs showing 'non classical' Blazar-like properties and analogies with FR 0s (e.g. Liuzzo et al. 2013; Massaro et al. 2017; D'Ammando et al. 2018).

Another parameter which can plays a role in two-model flow jets for FR 0s is the prominence of one of two components over the other. In fact, the picture of FR I jets as decelerating flows with transverse velocity gradients and with an intrinsic emissivity (prominence) differences between the spine and the sheath (a slow-moving boundary layer being more prominent than faster material near the centre, Komissarov 1990) founds observational support in resolved jet structures of individual sources (e.g., 3C 84, Giovannini et al. 2018). In FR 0s, the large loss of radio emission from pc-scale structure with respect to the arcsec-scale cores indicates that the jet emissivity does not remain constant and the sheath emission dominates over the spine emission, which cannot be seen, even if boosted. In addition, an intrinsic spine weakness and a brighter slower shear could account for the possible loss of jet stability for galaxy medium entertainment. On kpc scale the spine dies out, dragging the layer to disruption. Another advantage of a sheath-dominated jet is the formation of relativistic shocks between the jet layer of the two flows moving at different speeds, which can accelerate particles along the shock front and produce γ-ray emission by Inverse Compton. This would justify the γ-ray detection of FR 0 candidates (Baldi et al., 2019c).

Another parameter which takes part in shaping the jet structure is the composition, which is one of the major uncertainties in AGN physics. In powerful RGs, protons (or huge Poynting flux with a very low particle content) are needed in the spine to support the jet kinetic energy (De Young, 2006). Conversely, pure leptonic pair (electrons/positrons) jet are excluded, because the jet would be slowed down by Compton interactions. Croston et al. (2018) suggested that FR Is are likely dominated by hadrons (mostly protons) and FR IIs are dominated by leptons, FR 0 jets could be lighter than FR I/II jets, with a smaller hadronic component. This scenario would reduce the necessity for very high bulk Γ factors for FR 0 jets and consequently would probably favour their jet instability by crossing the host galaxy.

12.2 Dynamic scenarios

The inclusion of a temporal variation of the accretion-ejection parameters across the RG life span can better reproduce the different observed classes of RLAGN. The tracks in Figure 18 based on parametric modeling presents the expected evolutionary routes of a radio source that begins as a CSO and successfully evolves to FR I or FR IIs under conditions of long-duration AGN activity. If this standard evolutionary scenario is also applicable to the FR 0s and we consider FR 0s as progenitors of FR Is, FR 0s would correspond to the population of the low-power ($P_{1.4\mathrm{GHz}}$ <10^{24} W Hz^{-1}) CSOs in their earliest evolutionary phase. Instead, the VLBI-resolved FR 0s with pc-scale jets may shift horizontally their position in the P–D diagram into the region of MS0s. However, the much larger space density of FR 0s with respect to FR Is clearly clash against the picture of all FR 0s as young FR Is and necessarily, not all CRS may be destined to evolve into double RGs (Fanti et al.,

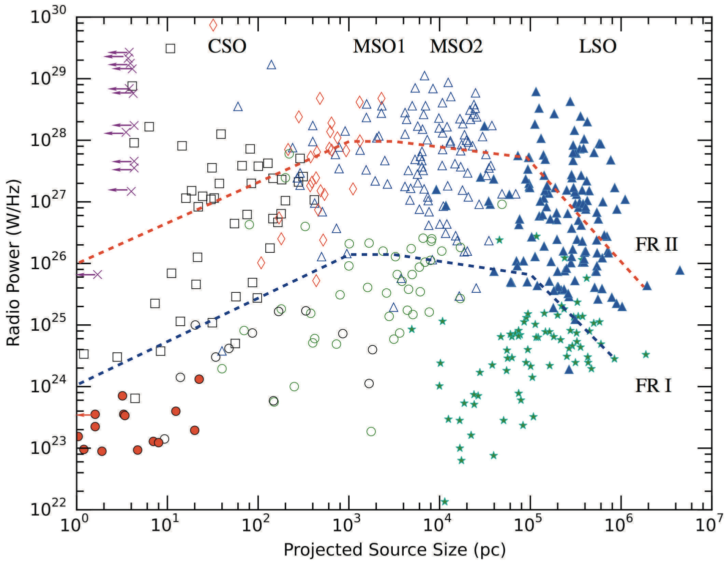

Fig. 18 Radio power vs. source size (P-D diagram) of RGs taken from Cheng and An (2018) and An and Baan (2012). Black squares are CSO, black circles are low-power GPSs, red diamonds are high-power GPSs, purple crosses are HFPs, green circles are low-power CSSs, blue open triangles are high-power CSSs, blue filled triangles are FR IIs, and green filled stars are FR Is. A further morphological sub-classification is also considered that distinguishes among CSO (< 1 kpc), MSO (1-15 kpc), and large symmetric objects (LSO; > 15 kpc, FR I/IIs) (Readhead, 1995). Red and blue dashed lines are illustrative of the evolutionary tracks based on parametric modeling for the high-power and low-power sources, respectively. The pc-scale FR 0s (red filled circles) studied by Cheng and An (2018) are situated in the bottom-left corner, occupied by low-power CSOs and some compact low-power MSOs.

1990, 1995). In fact, a uniform distribution of total lifetimes of RLAGN in the range 0–1000 Myr, estimated from low radio frequencies data, reproduce well the distributions of projected linear sizes of the powerful sources, $10^{25} \lesssim L_{150\,\mathrm{MHz}} \lesssim 10^{27}$ W Hz^{-1}, but diverges from the expectations for the large number of compact/small sources at lower luminosities, even when surface-brightness selection effects are taken into account (Hardcastle et al., 2019). To break this tension, a very different lifetime distribution at low luminosities or the presence of RLAGN populations with different accretion-ejection mechanisms (e.g., FR 0 vs FR I/II) needs to be considered.

A possible scenario to resolve the problem of the large abundance of compact RGs concerns an intermittent AGN activity. Baldi et al. (2018) stated that a radio activity recurrence, with the duration of the active phase covering a wide range of values and with short active periods of a few thousands years strongly favored with respect to longer ones, might account for the large density number of FR 0s. This would explain why radio jets do not develop at large scales (Sadler et al., 2014). An occasional fueling of the central BH can significantly reduce the accretion rate and causes a discontinuous plasma injection in the jet and its possible rapid deceleration and instability within the galaxy. Particular conditions of magnetic field loop, which trap gas and grow magnetic instabilities, could lead to a strangulated BH (Czerny et al., 2009; Yuan and Narayan, 2014; Inayoshi et al., 2020). An 'aborted' jet scenario was invoked by Ghisellini et al. (2004) to account for the jetted RQAGN where the BH fails to eject an extended relativistic particle jet, if the central engine works intermittently. According to this model, a small difference in BH masses, as seen between FR Is and FR 0s, could play a role in aborting the nascent extended jets. Gopal-Krishna et al. (2008) suggested that a dependence of radio jet ejection on BH mass probably could drive a different amount of gas tidally stripped from stars by the central BH, which could cause a blockage of jets truncated in the BH vicinity due to mass loading from the stellar debris. In addition, there is recent evidence that some compact sources, possibly a fraction of the FR 0 population, are turning-off/fading (e.g., Kunert-Bajraszewska et al., 2005, 2006; Giroletti et al., 2005; Orienti et al., 2010) and short-lived due to accretion-related criticality (e.g. Czerny et al. 2009; Kunert-Bajraszewska et al. 2010). However, there is not still observational proof of different nuclear gas distribution between FR 0s and FR Is, which might leads to an intermittent BH feeding or a jet frustration of the former with respect to the long-lasting secular accretion and ejection of the latter (Balmaverde et al., 2006).

A temporal evolution of the BH spin within the gap paradigm predicts FR 0s as a specific phase of a continuous activity in the family of RLAGN (Garofalo et al., 2010). As the gap region reduces in size with BH spin, the BZ/BP jet decreases in power. Instead, continuous mass accretion spins the BH up towards the angular momentum value of the accretion flow. An evolution of the BH spin configuration with the disc angular momentum can reduce or increase the gap region and change the BH spin magnitude. This dynamic process can accommodate the formation of a FR 0 population within two different scenarios: an accretion-driven or a merger-driven one.

In a scenario where the BH spin depends on the accretion history of the system, the gap paradigm has been applied to FR 0s as low, prograde, spinning BHs whose progenitors are powerful FR II quasars (Garofalo and Singh, 2019) (Fig. 19). In gas rich mergers, powerful (FR II) HERGs emerge from a BH accreting in a cold mode, surrounded by a thin REAF disc with a retrograde accretion. Due to the powerful jet feedback, the disc move into a RIAF disc on a timescale of about a few millions years. The continuous accretion across the duty cycles will spin down the BHs, moving the system to lower luminosities with a FR II jet, as the retrograde BH approaches to zero (LERGs). As the BH spin moves to a prograde regime, the BZ-jet power increases as the spin increases. In this low BH spinning regime, jet is weaker than in the FR II stage and teds to level off in a stable state. In this region of BH-jet parameter space, FR 0s find their location, where weak, compact jets are found. As the system keeps on feeding the low-spinning prograde BH, the FR 0 moves to a full-fledged FR I, when the spin is sufficiently higher than 0.2 and the BH must accumulate 30% of its original mass.

The large abundance of FR 0s with respect to the other FR classes can also be interpreted as the result of the limit on the gas availability in nearby

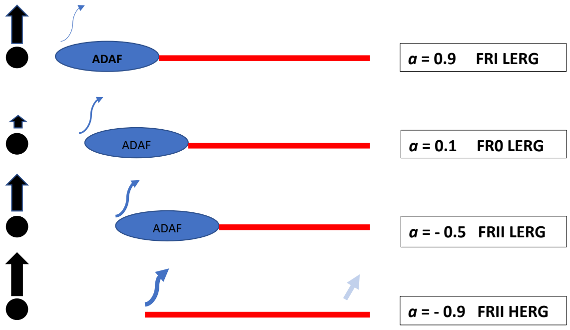

Fig. 19 Focus on the temporal evolution of RGs according to the gap paradigm (Garofalo and Singh, 2019) from high-powered FR II HERGs to FR I LERGs in a accretion-driven scenario. FR 0s represent a stage of this evolution, as prograde low-spinning BHs.

ETGs. The paucity of gas in the FR 0 (small- and large-scale) environments slows down the transition from FR 0s to FR Is because of the low accretion rates. Therefore FR 0s do are not young sources, but they are the result of a prolonged slow accretion of prograde low-spinning massive BHs over timescales of hundreds of millions – billions of years. A sixth of these population succeeds to funnel sufficient fuel to the BH and ultimately turns into a FR I. The poorer Mpc-scale environment of FR 0s and the slightly smaller BH masses (galaxy masses) than those of FR Is are the two main evidences of a different cosmological evolution of FR 0s with respect that of FR Is. Therefore, FR 0s are predicted to grow both in small groups (primarily) and in rich clusters.

In a merger-driven scenario, major mergers are known to be the main mechanism for spinning-up BHs (Martínez-Sansigre and Rawlings, 2011; Bustamante and Springel, 2019). Since such objects is the result of BH-BH coalescence event, galaxies with higher masses are more likely to have undergone more mergers and therefore own high-spinning BHs. The simulations performed by Dubois et al. (2014b) indicate that indeed the most massive BHs ($M_{BH} \gtrsim 10^8$ $M_\odot$), in particular those associated with gas-poor galaxies, acquire most of their mass through BH coalescence. In a poor environment, major merger of galaxies with similar masses are rare, causing a limit on formation of highly-spinning BHs. Although large-scale environment seems to generate a sort of difference in the BH spin distribution, the nature of the connection between environment and BH spin is still under discussion, because opposite results have been also found (e.g.. Smethurst et al. 2019; Beckmann et al. 2022). However, in the standard picture, this merger-driven scenario would agree with the observational result that FR 0s and FR Is live in different environment. Consequently, in this scenario, a positive link between local galaxy density, BH parameters (mass and spin), and accretion rate is set. The poorer neighborhood of FR 0s, on a statistical basis, determines a longer phase of their lower BH spin than those of their companions FR Is, which live in richer environment. FR 0s in clusters of galaxies are likely formed recently and do not have yet accreted a sufficient amount of mass onto their central BH to turn into an FR I. Conversely, rare FR Is in poor groups have likely undergone particular conditions (magnetic field, gas availability, reciprocal galaxy velocity, position in the cluster/group), which have led to an acceleration on their evolution from a FR 0 stage or a different duty cycle. However, the physical process which controls the connection between large-scale environment (Mpc scale) and the BH accretion (Bondi radius, tens and hundred pc) still remains to be understood.

In the nearby Universe ∼70-80% of the RLAGN phase is spent into a compact-jet configuration. Given that ∼30% of the most massive galaxies are active and the activity must be constantly re–triggered so that the galaxy spends over a quarter of its time in an active state (Best et al., 2005a), the FR 0 phase is an important stage of the evolution of an ETG where their galactic-scale jets are continuously operating in maintenance mode. The large excess of CRSs over what would be expected from models in which all sources live to the same age (i.e. constant age models), particularly evident at lower radio luminosities (Shabala et al., 2008; Hardcastle et al., 2019; Shabala et al., 2020) suggest that the actual process of FR 0 evolution is longer than the phase spent as FR I and FR II. Assuming a monotonic jet expansion, the limited size of FR 0s would point to irregular duty cycles, where short active phases occur more often than the longer ones (Baldi et al., 2018, 2019a). However, this would conflict with the LOFAR result that the most massive galaxies are always switched on at some level at $L_{150\,\mathrm{MHz}} \gtrsim 10^{21}$ W Hz^{-1} (Sabater et al., 2019). Therefore, the large uncertainties on the origin and nature of FR 0 jets, the role of environmental and internal conditions on the duration of the compact phase, complicate the estimate of the duty cycle of FR 0s.

13 Conclusions and future perspective

The BH accretion-ejection mechanism provides a major power source in the Universe and is believed to regulate the evolution of galaxies, by injecting energy and momentum. However, the details of how and when this occurs remains uncertain, particularly at low luminosities, where the majority of active BHs are expected. There is compelling evidence, supported by numerical simulations, that low-luminosity RGs channel the bulk of their accretion power into compact and galactic-scale jets (∼1-10 kpc) which may have a significant impact on their hosts, regulating the SF, because they plough energy in the ISM more efficiently than powerful jets. Yet, a poor characterization of the jet physics and the AGN-host connection at low luminosities hampers our comprehension of the accretion-ejection paradigm, feedback and hence the galaxy evolution, specifically at low regimes. The cross-correlation of high-sensitivity radio and optical surveys showed that the vast majority of local RGs (∼80%) appear unresolved on arcsecond scales and shed light on a 'new' class of low-luminosity RGs, *FR 0s*, which lack of kpc-scale extended radio emission. This review about recent results on the multi-band properties of FR 0s collected enough evidence to conclude that FR 0s constitute a unique class of CRSs, which *can* launch small jets with mildly relativistic bulk speed, probably due to small (prograde) BH spins.

To solve the long-lasting question about the large abundance of CRS with respect to what expected by standard RG evolution models, the puzzling nature of FR 0s and their impact on BH-galaxy evolution, an accurate census of the accretion-jet properties is needed with the following characteristics: i) a statistically complete sample to include all galaxy and AGN diversity to explore the role of each physical parameter that controls the accretion-ejection and feedback processes; ii) in the radio band, because long-baseline radio arrays can isolate the low-brightness nuclear emission far better than any other instruments at higher energies; iii) at luminosities as low as possible to probe the very end of luminosity functions, ideally down to SgrA* luminosity ($\sim 10^{15.5}$ W Hz); iv) in the local Universe to enable spatial pc-scale resolution to disentangle the relative AGN-SF contribution and probe small jet structures.

The current and upcoming generation of radio arrays, LOFAR (Best, 2008; Shimwell et al., 2019; Hardcastle and Croston, 2020) and the International LOFAR Telescope (Morabito et al., 2022b,a), ASKAP (Norris et al., 2011; Riggi et al., 2021), MeerKAT (Mauch et al., 2020; Knowles et al., 2022), SKA (Falcke et al., 2004; Kapinska et al., 2015), ngVLA (Nyland et al., 2018a,b), uGMRT (Gupta et al., 2017; Lal et al., 2021), DSA-2000 (Hallinan et al., 2021) and other radio antennae (e.g. ALMA, WSRT), will provide the cornerstone of our understanding of BH activity in the local Universe at low regimes, across a wide range of galaxy types and environments. Because of their sub-arcsecond resolution and μJy-level sensitivity, they will uncover the bulk population of CRSs, opening a new window onto the physical properties of FR 0s. For example, within the full sky coverage of the LOFAR observations, the census of nearby active BHs at 150 GHz will count $\sim$3000 LLAGN with luminosities $< 10^{40}$ erg s^{-1} at z<0.03 (Sabater et al., 2019). The next step will be with the advent of SKA and ngVLA, which will survey vast numbers of nearby galaxies with unprecedented sensitivities at sub-arcsecond resolutions on a large range of radio frequencies (reaching $\sim$1 μJy at $<$ 1GHz over 30 deg^2 will detect $\sim$300000 LLAGN, Prandoni and Seymour 2015; Padovani 2016). A multi-band cross-match with other surveys at higher frequencies (optical, X-ray) will trace a demography of local low-power jetted BHs and their interplay with galaxies, providing firmer constraints on models of accretion-ejection coupling in ordinary AGN (not quasar type) (Prandoni and Seymour, 2014).

Low-frequency radio surveys with SKA precursors (e.g. ASKAP, MWA) and LOFAR are already extremely valuable for studying the putative extended emissions of FR 0s, because it remains crudely true that the observed duty cycle of AGN increases with decreasing frequency: this is because of the longer synchrotron lifetimes of the lower-energy relativistic particles at lower frequencies. Deep sub-arcsecond international LOFAR telescope observations could reveal the true extent of the penetration of FR 0 jet into the galaxy, by discovering synchrotron-aged plasma from past injection events. This would lead to a better characterization of the physical properties, duty cycles and kinetic power of FR 0 jets

Combining hundreds-MHz information with GHz-observations can help characterising the spectral shape of FR 0s to infer the fraction of optically thin, hence extended, emission present in FR 0 jets and eventually isolate the fraction of genuine young radio sources erroneously included in this class. High-resolution radio observations with long baseline arrays (e.g. eMERLIN, EVN, VLBA) are crucial to establish the fraction of jetted FR 0s on pc scale and derive the jet asymmetry and velocity distribution.

With those ideas in mind, the future research on FR 0s will address the following key topics:

- **Pc-scale accretion-ejection.** The origin of the inability of such a large population to grow kpc-scale jets is still a mystery. The separation of the genuine population of FR 0s with respect to other compact impostors (star forming galaxies, RQAGN, young RGs, Blazars) is fundamental to identity the crucial aspects which can diagnose their jet limitations. Accretion and ejection studied with non-radio high-resolution data (e.g. Chandra, JWST, VLT, ELT) can help disentangling the different contribution in CRS population and constraining models of disc and jets.
- **High energy.** Several FR 0 candidates as γ-ray emitters have been detected at the present time. It is important to continue the search for γ-ray emission from CRS and LLAGN in general to study the mechanisms of jet acceleration at low powers.
- **AGN Feedback.** Several studies point to the result that CRS can have a more efficient feedback on galaxy than powerful extended RGs. A single studied case of FR 0 driving turbulence and creating cavities in the X-ray atmosphere of a cluster is not sufficient to derive robust results on the effect of low-power jets of FR 0s in the surrounding medium. Systematic studies with deep Chandra data, combined with VLBI observations will provide a unique data set for advancing our comprehension of the interaction of the FR 0s with their environments.
- **High redshifts.** There is evidence that the local FR 0 population has an important counterpart also at higher redshifts (z>1). A systematic study of the genuine FR 0s at the cosmic noon from deep fields would help understanding the formation and evolution of low-power RLAGN with respect to the other classes of RGs.
- **Numerical Simulations.** High resolution, 3D numerical simulations of low-power jets (total jet power $< 10^{44}$ erg s^{-1}) can help clarifying the formation, propagation and impact of FR 0 jets in the galaxy medium.

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References

Abdo AA, Ackermann M, Ajello M, Atwood WB, Axelsson M, Baldini L, Ballet J, Barbiellini G, Bastieri D, Bechtol K, Bellazzini R, Berenji B, Blandford RD, Bloom ED, Bonamente E, Borgland AW, Bregeon J, Brez A, Brigida M, Bruel P, Burnett TH, Caliandro GA, Cameron RA, Cannon A, Caraveo PA, Casandjian JM, Cavazzuti E, Cecchi C, Çelik Ö, Charles E, Cheung CC, Chiang J, Ciprini S, Claus R, Cohen-Tanugi J, Colafrancesco S, Conrad J, Costamante L, Cutini S, Davis DS, Dermer CD, de Angelis A, de Palma F, Digel SW, Donato D, Silva EdCe, Drell PS, Dubois R, Dumora D, Edmonds Y, Farnier C, Favuzzi C, Fegan SJ, Finke J, Focke WB, Fortin P, Frailis M, Fukazawa Y, Funk S, Fusco P, Gargano F, Gasparrini D, Gehrels N, Georganopoulos M, Germani S, Giebels B, Giglietto N, Giommi P, Giordano F, Giroletti M, Glanzman T, Godfrey G, Grenier IA, Grondin MH, Grove JE, Guillemot L, Guiriec S, Hanabata Y, Harding AK, Hayashida M, Hays E, Horan D, Jóhannesson G, Johnson AS, Johnson RP, Johnson TJ, Johnson WN, Kamae T, Katagiri H, Kataoka J, Kawai N, Kerr M, Knödlseder J, Kocian ML, Kuss M, Lande J, Latronico L, Lemoine-Goumard M, Longo F, Loparco F, Lott B, Lovellette MN, Lubrano P, Madejski GM, Makeev A, Mazziotta MN, McConville W, McEnery JE, Meurer C, Michelson PF, Mitthumsiri W, Mizuno T, Moiseev AA, Monte C, Monzani ME, Morselli A, Moskalenko IV, Murgia S, Nolan PL, Norris JP, Nuss E, Ohsugi T, Omodei N, Orlando E, Ormes JF, Ozaki M, Paneque D, Panetta JH, Parent D, Pelassa V, Pepe M, Pesce-Rollins M, Piron F, Porter TA, Rainò S, Rando R, Razzano M, Reimer A, Reimer O, Reposeur T, Ritz S, Rochester LS, Rodriguez AY, Romani RW, Roth M, Ryde F, Sadrozinski HFW, Sambruna R, Sanchez D, Sander A, Saz Parkinson PM, Scargle JD, Sgrò C, Shaw MS, Smith DA, Smith PD, Spandre G, Spinelli P, Strickman MS, Suson DJ, Tajima H, Takahashi H, Tanaka T, Taylor GB, Thayer JB, Thompson DJ, Tibaldo L, Torres DF, Tosti G, Tramacere A, Uchiyama Y, Usher TL, Vasileiou V, Vilchez N, Waite AP, Wang P, Winer BL, Wood KS, Ylinen T, Ziegler M, Harris DE, Massaro F, Stawarz Ł (2009) Fermi Large Area Telescope Gamma-Ray Detection of the Radio Galaxy M87. ApJ707(1):55–60. https://doi.org/10.1088/0004-637X/707/1/55. arXiv:0910.3565 [astro-ph.HE]

Abdo AA, Ackermann M, Ajello M, Baldini L, Ballet J, Barbiellini G, Bastieri D, Bechtol K, Bellazzini R, Berenji B, Blandford RD, Bloom ED, Bonamente E, Borgland AW, Bouvier A, Brandt TJ, Bregeon J, Brez A, Brigida M, Bruel P, Buehler R, Burnett TH, Buson S, Caliandro GA, Cameron RA, Cannon A, Caraveo PA, Carrigan S, Casandjian JM, Cavazzuti E, Cecchi C, Çelik Ö, Celotti A, Charles E, Chekhtman A, Chen AW, Cheung CC, Chiang J, Ciprini S, Claus R, Cohen-Tanugi J, Colafrancesco S, Conrad J, Davis DS, Dermer CD, de Angelis A, de Palma F, Silva EdCe, Drell PS, Dubois R, Favuzzi C, Fegan SJ, Ferrara EC, Fortin P, Frailis M, Fukazawa Y, Fusco P, Gargano F, Gasparrini D, Gehrels N, Germani S, Giglietto N, Giommi P, Giordano F, Giroletti M, Glanzman T, Godfrey G, Grandi P, Grenier IA, Grove JE, Guillemot L, Guiriec S, Hadasch D, Hayashida M, Hays E, Horan D, Hughes RE, Jackson MS, Jóhannesson G, Johnson AS, Johnson WN, Kamae T, Katagiri H, Kataoka J, Knödlseder J, Kuss M, Lande J, Latronico L, Lee SH, Lemoine-Goumard M, Llena Garde M, Longo F, Loparco F, Lott B, Lovellette MN, Lubrano P, Madejski GM, Makeev A, Malaguti G, Mazziotta MN, McConville W, McEnery JE, Michelson PF, Migliori G, Mitthumsiri W, Mizuno T, Monte C, Monzani ME, Morselli A, Moskalenko IV, Murgia S, Naumann-Godo M, Nestoras I, Nolan PL, Norris JP, Nuss E, Ohsugi T, Okumura A, Omodei N, Orlando E, Ormes JF, Paneque D, Panetta JH, Parent D, Pelassa V, Pepe M, Persic M, Pesce-Rollins M, Piron F, Porter TA, Rainò S, Rando R, Razzano M, Razzaque S, Reimer A, Reimer O, Reyes LC, Roth M, Sadrozinski HFW, Sanchez D, Sander A, Scargle JD, Sgrò C, Siskind EJ, Smith PD, Spandre G, Spinelli P, Stawarz Ł, Stecker FW, Strickman MS, Suson DJ, Takahashi H, Tanaka T, Thayer JB, Thayer JG, Thompson DJ, Tibaldo L, Torres DF, Torresi E, Tosti G, Tramacere A, Uchiyama Y, Usher TL, Vandenbroucke J, Vasileiou V, Vilchez N, Villata M, Vitale V, Waite AP, Wang P, Winer BL, Wood KS, Yang Z, Ylinen T, Ziegler M (2010) Fermi Large Area Telescope Observations of Misaligned Active Galactic Nuclei. ApJ720(1):912–922. https://doi.org/10.1088/0004-637X/720/1/912. arXiv:1007.1624 [astro-ph.HE]

Abdollahi S, Acero F, Ackermann M, Ajello M, Atwood WB, Axelsson M, Baldini L, Ballet J, Barbiellini G, Bastieri D, Becerra Gonzalez J, Bellazzini R, Berretta A, Bissaldi E, Blandford RD, Bloom ED, Bonino R, Bottacini E, Brandt TJ, Bregeon J, Bruel P, Buehler R, Burnett TH, Buson S, Cameron RA, Caputo R, Caraveo PA, Casandjian JM, Castro D, Cavazzuti E, Charles E, Chaty S, Chen S, Cheung CC, Chiaro G, Ciprini S, Cohen-Tanugi J, Cominsky LR, Coronado-Blázquez J, Costantin D, Cuoco A, Cutini S, D'Ammando F, DeKlotz M, de la Torre Luque P, de Palma F, Desai A, Digel SW, Di Lalla N, Di Mauro M, Di Venere L, Domínguez A, Dumora D, Fana Dirirsa F, Fegan SJ, Ferrara EC, Franckowiak A, Fukazawa Y, Funk S, Fusco P, Gargano F, Gasparrini D, Giglietto N, Giommi P, Giordano F, Giroletti M, Glanzman T, Green D, Grenier IA, Griffin S, Grondin MH, Grove JE, Guiriec S, Harding AK, Hayashi K, Hays E, Hewitt JW, Horan D, Jóhannesson G, Johnson TJ, Kamae T, Kerr M, Kocevski D, Kovac'evic' M, Kuss M, Landriu D, Larsson S, Latronico L, Lemoine-Goumard M, Li J, Liodakis I, Longo F, Loparco F, Lott B, Lovellette MN, Lubrano P, Madejski GM, Maldera S, Malyshev D, Manfreda A, Marchesini EJ, Marcotulli L, Martí-Devesa G, Martin P, Massaro F, Mazziotta MN, McEnery JE, Mereu I, Meyer M, Michelson PF, Mirabal N, Mizuno T, Monzani ME, Morselli A, Moskalenko IV, Negro M, Nuss E, Ojha R, Omodei N, Orienti M, Orlando E, Ormes JF, Palatiello M, Paliya VS, Paneque D, Pei Z, Peña-

Herazo H, Perkins JS, Persic M, Pesce-Rollins M, Petrosian V, Petrov L, Piron F, Poon H, Porter TA, Principe G, Rainò S, Rando R, Razzano M, Razzaque S, Reimer A, Reimer O, Remy Q, Reposeur T, Romani RW, Saz Parkinson PM, Schinzel FK, Serini D, Sgrò C, Siskind EJ, Smith DA, Spandre G, Spinelli P, Strong AW, Suson DJ, Tajima H, Takahashi MN, Tak D, Thayer JB, Thompson DJ, Tibaldo L, Torres DF, Torresi E, Valverde J, Van Klaveren B, van Zyl P, Wood K, Yassine M, Zaharijas G (2020) Fermi Large Area Telescope Fourth Source Catalog. ApJS247(1):33. https://doi.org/10.3847/1538-4365/ab6bcb. arXiv:1902.10045 [astro-ph.HE]

Abdollahi S, Acero F, Baldini L, Ballet J, Bastieri D, Bellazzini R, Berenji B, Berretta A, Bissaldi E, Blandford RD, Bloom E, Bonino R, Brill A, Britto RJ, Bruel P, Burnett TH, Buson S, Cameron RA, Caputo R, Caraveo PA, Castro D, Chaty S, Cheung CC, Chiaro G, Cibrario N, Ciprini S, Coronado-Blázquez J, Crnogorcevic M, Cutini S, D'Ammando F, De Gaetano S, Digel SW, Di Lalla N, Dirirsa F, Di Venere L, Domínguez A, Fallah Ramazani V, Fegan SJ, Ferrara EC, Fiori A, Fleischhack H, Franckowiak A, Fukazawa Y, Funk S, Fusco P, Galanti G, Gammaldi V, Gargano F, Garrappa S, Gasparrini D, Giacchino F, Giglietto N, Giordano F, Giroletti M, Glanzman T, Green D, Grenier IA, Grondin MH, Guillemot L, Guiriec S, Gustafsson M, Harding AK, Hays E, Hewitt JW, Horan D, Hou X, Jóhannesson G, Karwin C, Kayanoki T, Kerr M, Kuss M, Landriu D, Larsson S, Latronico L, Lemoine-Goumard M, Li J, Liodakis I, Longo F, Loparco F, Lott B, Lubrano P, Maldera S, Malyshev D, Manfreda A, Martí-Devesa G, Mazziotta MN, Mereu I, Meyer M, Michelson PF, Mirabal N, Mitthumsiri W, Mizuno T, Moiseev AA, Monzani ME, Morselli A, Moskalenko IV, Negro M, Nuss E, Omodei N, Orienti M, Orlando E, Paneque D, Pei Z, Perkins JS, Persic M, Pesce-Rollins M, Petrosian V, Pillera R, Poon H, Porter TA, Principe G, Rainò S, Rando R, Rani B, Razzano M, Razzaque S, Reimer A, Reimer O, Reposeur T, Sánchez-Conde M, Saz Parkinson PM, Scotton L, Serini D, Sgrò C, Siskind EJ, Smith DA, Spandre G, Spinelli P, Sueoka K, Suson DJ, Tajima H, Tak D, Thayer JB, Thompson DJ, Torres DF, Troja E, Valverde J, Wood K, Zaharijas G (2022) Incremental Fermi Large Area Telescope Fourth Source Catalog. ApJS260(2):53. https://doi.org/10.3847/1538-4365/ac6751. arXiv:2201.11184 [astro-ph.HE]

Alexander P, Leahy JP (1987) Ageing and speeds in a representative sample of 21 classical double radio sources. MNRAS 225:1–26

Allen SW, Dunn RJH, Fabian AC, Taylor GB, Reynolds CS (2006) The relation between accretion rate and jet power in X-ray luminous elliptical galaxies. MNRAS 372:21–30. https://doi.org/10.1111/j.1365-2966.2006.10778.x. arXiv:astro-ph/0602549

An T, Baan WA (2012) The Dynamic Evolution of Young Extragalactic Radio Sources. ApJ760(1):77. https://doi.org/10.1088/0004-637X/760/1/77. arXiv:1211.1760 [astro-ph.CO]

Angioni R, Grandi P, Torresi E, Vignali C, Knödlseder J (2017) Radio galaxies with the Cherenkov Telescope Array. Astroparticle Physics 92:42–48. https://doi.org/10.1016/j.astropartphys.2017.02.010. arXiv:1702.05926

[astro-ph.HE]

Antonucci R (1993) Unified models for active galactic nuclei and quasars. ARA&A31:473–521

Antonucci R (2012) A panchromatic review of thermal and nonthermal active galactic nuclei. Astronomical and Astrophysical Transactions 27(4):557–602. arXiv:1210.2716 [astro-ph.CO]

Balbus SA, Hawley JF (1991) A Powerful Local Shear Instability in Weakly Magnetized Disks. I. Linear Analysis. ApJ376:214. https://doi.org/10.1086/170270

Baldi RD, Capetti A (2009) Radio and spectroscopic properties of miniature radio galaxies: revealing the bulk of the radio-loud AGN population. A&A 508:603–614. https://doi.org/10.1051/0004-6361/200913021. arXiv:0910.4261

Baldi RD, Capetti A (2010) Spectro-photometric properties of the bulk of the radio-loud AGN population. A&A519:A48. https://doi.org/10.1051/0004-6361/201014446. arXiv:1005.3223 [astro-ph.CO]

Baldi RD, Chiaberge M, Capetti A, Sparks W, Macchetto FD, O'Dea CP, Axon DJ, Baum SA, Quillen AC (2010) The 1.6 μm Near-infrared Nuclei of 3C Radio Galaxies: Jets, Thermal Emission, or Scattered Light? ApJ725:2426–2443. https://doi.org/10.1088/0004-637X/725/2/2426. arXiv:1010.5277 [astro-ph.CO]

Baldi RD, Capetti A, Giovannini G (2015) Pilot study of the radio-emitting AGN population: the emerging new class of FR 0 radio-galaxies. A&A576:A38. https://doi.org/10.1051/0004-6361/201425426. arXiv:1502.00427

Baldi RD, Capetti A, Massaro F (2018) FR0CAT: a FIRST catalog of FR 0 radio galaxies. A&A609:A1. https://doi.org/10.1051/0004-6361/201731333. arXiv:1709.00015

Baldi RD, Capetti A, Giovannini G (2019a) High-resolution VLA observations of FR0 radio galaxies: the properties and nature of compact radio sources. MNRAS482(2):2294–2304. https://doi.org/10.1093/mnras/sty2703. arXiv:1810.01894 [astro-ph.GA]

Baldi RD, Rodríguez Zaurín J, Chiaberge M, Capetti A, Sparks WB, McHardy IM (2019b) Hubble Space Telescope Emission-line Images of Nearby 3CR Radio Galaxies: Two Photoionization, Accretion, and Feedback Modes. ApJ870(1):53. https://doi.org/10.3847/1538-4357/aaf002. arXiv:1811.04946 [astro-ph.GA]

Baldi RD, Torresi E, Migliori G, Balmaverde B (2019c) The High Energy View of FR0 Radio Galaxies. Galaxies 7(3):76. https://doi.org/10.3390/galaxies7030076. arXiv:1909.04113 [astro-ph.HE]

Baldi RD, Giovannini G, Capetti A (2021a) The eMERLIN and EVN View of FR 0 Radio Galaxies. Galaxies 9(4):106. https://doi.org/10.3390/galaxies9040106. arXiv:2111.09899 [astro-ph.GA]

Baldi RD, Williams DRA, Beswick RJ, McHardy I, Dullo BT, Knapen JH, Zanisi L, Argo MK, Aalto S, Alberdi A, Baan WA, Bendo GJ, Fenech DM, Green DA, Klöckner HR, Körding E, Maccarone TJ, Marcaide JM, Mutie I, Panessa F, Pérez-Torres MA, Romero-Cañizales C, Saikia DJ, Saikia P, Shankar F, Spencer RE, Stevens IR, Uttley P, Brinks E, Corbel S, Martí-Vidal I, Mundell CG, Pahari M, Ward MJ (2021b) LeMMINGs III. The e-MERLIN legacy survey of the Palomar sample: exploring the origin of nuclear radio emission in active and inactive galaxies through the [O III] - radio connection. MNRAS508(2):2019–2038. https://doi.org/10.1093/mnras/stab2613. arXiv:2109.06205 [astro-ph.GA]

Baldwin JE (1982) Evolutionary tracks of extended radio sources. In: Heeschen DS, Wade CM (eds) Extragalactic Radio Sources. vol 97. pp 21–24

Balmaverde B, Capetti A (2006a) The host galaxy/AGN connection in nearby early-type galaxies. Is there a miniature radio-galaxy in every "core" galaxy? A&A447:97–112. https://doi.org/10.1051/0004-6361:20054031

Balmaverde B, Capetti A (2006b) The host galaxy/AGN connection in nearby early-type galaxies. Is there a miniature radio-galaxy in every "core" galaxy? A&A 447:97–112. https://doi.org/10.1051/0004-6361:20054031

Balmaverde B, Capetti A (2015) The naked nuclei of low ionization nuclear emission line regions. A&A581:A76. https://doi.org/10.1051/0004-6361/201526496

Balmaverde B, Capetti A, Grandi P (2006) The Chandra view of the 3C/FR I sample of low luminosity radio-galaxies. A&A451:35–44. https://doi.org/10.1051/0004-6361:20053799. astro-ph/0601175

Balmaverde B, Baldi RD, Capetti A (2008) The accretion mechanism in low-power radio galaxies. A&A 486:119–130. https://doi.org/10.1051/0004-6361:200809810. arXiv:0805.3920

Balmaverde B, Caccianiga A, Della Ceca R, Wolter A, Belfiore A, Ballo L, Berton M, Gioia I, Maccacaro T, Sbarufatti B (2020) Te-REX: a sample of extragalactic TeV-emitting candidates. MNRAS492(3):3728–3741. https://doi.org/10.1093/mnras/stz3532. arXiv:1912.07613 [astro-ph.HE]

Balogh ML, Morris SL, Yee HKC, Carlberg RG, Ellingson E (1999) Differential Galaxy Evolution in Cluster and Field Galaxies at z˜0.3. ApJ527:54–79. https://doi.org/10.1086/308056. arXiv:astro-ph/9906470

Barausse E, Shankar F, Bernardi M, Dubois Y, Sheth RK (2017) Selection bias in dynamically measured supermassive black hole samples: scaling relations and correlations between residuals in semi-analytic galaxy formation models. MNRAS468:4782–4791. https://doi.org/10.1093/mnras/stx799. arXiv:1702.01762

Barthel PD (1989) Is every quasar beamed? ApJ336:606–611

Bassi T, Migliori G, Grandi P, Vignali C, Pérez-Torres MA, Baldi RD, Torresi E, Siemiginowska A, Stanghellini C (2018) Faint γ-ray sources at low redshift: the radio galaxy IC 1531. MNRAS481(4):5236–5246. https://doi.org/10.1093/mnras/sty2622. arXiv:1810.02668 [astro-ph.HE]

Baum SA, Zirbel EL, O'Dea CP (1995) Toward Understanding the Fanaroff-Riley Dichotomy in Radio Source Morphology and Power. ApJ451:88. https://doi.org/10.1086/176202

Becker RH, White RL, Helfand DJ (1995) The FIRST Survey: Faint Images of the Radio Sky at Twenty Centimeters. ApJ450:559–+. https://doi.org/

10.1086/176166

Beckmann RS, Smethurst RJ, Simmons BD, Coil A, Dubois Y, Garland IL, Lintott CJ, Martin G, Peirani S, Pichon C (2022) Supermassive black holes in merger-free galaxies have higher spins which are preferentially aligned with their host galaxy. arXiv e-prints arXiv:2211.13614. arXiv:2211.13614 [astro-ph.GA]

Begelman MC (2012) Radiatively inefficient accretion: breezes, winds and hyperaccretion. MNRAS420:2912–2923. https://doi.org/10.1111/j.1365-2966.2011.20071.x. arXiv:1110.5356 [astro-ph.HE]

Bennett AS (1962) The revised 3C catalogue of radio sources. MmRAS68:163–+

Best PN (2004) The environmental dependence of radio-loud AGN activity and star formation in the 2dFGRS. MNRAS351(1):70–82. https://doi.org/10.1111/j.1365-2966.2004.07752.x. arXiv:astro-ph/0402523 [astro-ph]

Best PN (2007) Feedback from radio-loud AGN. New A Rev.51(1-2):168–173. https://doi.org/10.1016/j.newar.2006.11.014

Best PN, Heckman TM (2012) On the fundamental dichotomy in the local radio-AGN population: accretion, evolution and host galaxy properties. MNRAS421:1569–1582. https://doi.org/10.1111/j.1365-2966.2012.20414.x. arXiv:1201.2397 [astro-ph.CO]

Best PN, Röttgering HJA, Longair MS (2000) Ionization, shocks and evolution of the emission-line gas of distant 3CR radio galaxies. MNRAS311(1):23–36. https://doi.org/10.1046/j.1365-8711.2000.03028.x. arXiv:astro-ph/9908211 [astro-ph]

Best PN, Kauffmann G, Heckman TM, Brinchmann J, Charlot S, Ivezić Ž, White SDM (2005a) The host galaxies of radio-loud active galactic nuclei: mass dependences, gas cooling and active galactic nuclei feedback. MNRAS 362:25–40. https://doi.org/10.1111/j.1365-2966.2005.09192.x. arXiv:astro-ph/0506269

Best PN, Kauffmann G, Heckman TM, Ivezić Ž (2005b) A sample of radio-loud active galactic nuclei in the Sloan Digital Sky Survey. MNRAS 362:9–24. https://doi.org/10.1111/j.1365-2966.2005.09283.x. arXiv:astro-ph/0506268

Best PN, Kaiser CR, Heckman TM, Kauffmann G (2006) AGN-controlled cooling in elliptical galaxies. MNRAS368(1):L67–L71. https://doi.org/10.1111/j.1745-3933.2006.00159.x. arXiv:astro-ph/0602171 [astro-ph]

Best PNea (2008) LOFAR-UK White Paper: A Science case for UK involvement in LOFAR. arXiv e-prints arXiv:0802.1186. arXiv:0802.1186 [astro-ph]

Best S, Bazo J (2019) Gamma-ray counterparts of radio astrophysical sources. J. Cosmology Astropart. Phys.2019(12):004. https://doi.org/10.1088/1475-7516/2019/12/004. arXiv:1906.01664 [astro-ph.GA]

Bicknell GV (1984) A model for the surface brightness of a turbulent low mach number jet. I. Theoretical development and application to 3C 31. ApJ286:68–87. https://doi.org/10.1086/162577

Bicknell GV (1995) Relativistic Jets and the Fanaroff-Riley Classification of Radio Galaxies. ApJS101:29. https://doi.org/10.1086/192232. arXiv:astro-ph/9406064 [astro-ph]

Bicknell GV, Mukherjee D, Wagner AY, Sutherland RS, Nesvadba NPH (2018) Relativistic jet feedback - II. Relationship to gigahertz peak spectrum and compact steep spectrum radio galaxies. MNRAS475(3):3493–3501. https://doi.org/10.1093/mnras/sty070. arXiv:1801.06518 [astro-ph.GA]

Bîrzan L, Rafferty DA, McNamara BR, Wise MW, Nulsen PEJ (2004) A Systematic Study of Radio-induced X-Ray Cavities in Clusters, Groups, and Galaxies. ApJ607:800–809. https://doi.org/10.1086/383519. astro-ph/0402348

Bîrzan L, McNamara BR, Nulsen PEJ, Carilli CL, Wise MW (2008) Radiative Efficiency and Content of Extragalactic Radio Sources: Toward a Universal Scaling Relation between Jet Power and Radio Power. ApJ686(2):859–880. https://doi.org/10.1086/591416. arXiv:0806.1929 [astro-ph]

Bisnovatyi-Kogan GS, Ruzmaikin AA (1974) The Accretion of Matter by a Collapsing Star in the Presence of a Magnetic Field. Ap&SS28(1):45–59. https://doi.org/10.1007/BF00642237

Blandford R, Meier D, Readhead A (2019) Relativistic Jets from Active Galactic Nuclei. ARA&A57:467–509. https://doi.org/10.1146/annurev-astro-081817-051948. arXiv:1812.06025 [astro-ph.HE]

Blandford RD, Payne DG (1982) Hydromagnetic flows from accretion disks and the production of radio jets. MNRAS199:883–903. https://doi.org/10.1093/mnras/199.4.883

Blandford RD, Znajek RL (1977) Electromagnetic extraction of energy from Kerr black holes. MNRAS179:433–456

Bondi M, Zamorani G, Ciliegi P, Smolčić V, Schinnerer E, Delvecchio I, Jiménez-Andrade EF, Liu D, Lang P, Magnelli B, Murphy EJ, Vardoulaki E (2018) Linear radio size evolution of μJy populations. A&A618:L8. https://doi.org/10.1051/0004-6361/201834243. arXiv:1810.04095 [astro-ph.GA]

Bower RG, Benson AJ, Crain RA (2012) What shapes the galaxy mass function? Exploring the roles of supernova-driven winds and active galactic nuclei. MNRAS422(4):2816–2840. https://doi.org/10.1111/j.1365-2966.2012.20516.x. arXiv:1112.2712 [astro-ph.CO]

Bowman M, Leahy JP, Komissarov SS (1996) The deceleration of relativistic jets by entrainment. MNRAS279:899. https://doi.org/10.1093/mnras/279.3.899

Brandenburg A, Nordlund A, Stein RF, Torkelsson U (1995) Dynamo-generated Turbulence and Large-Scale Magnetic Fields in a Keplerian Shear Flow. ApJ446:741. https://doi.org/10.1086/175831

Bridle AH (1984) Sidedness, field configuration, and collimation of extragalactic radio jets. AJ89:979–986. https://doi.org/10.1086/113593

Burns JO, Feigelson ED, Schreier EJ (1983) The inner radio structure of Centaurus A - Clues to the origin of the jet X-ray emission. ApJ273:128–153

Bustamante S, Springel V (2019) Spin evolution and feedback of supermassive black holes in cosmological simulations. MNRAS490(3):4133–4153. https://doi.org/10.1093/mnras/stz2836. arXiv:1902.04651 [astro-ph.GA]

Buttiglione S, Capetti A, Celotti A, Axon DJ, Chiaberge M, Macchetto FD, Sparks WB (2010) An optical spectroscopic survey of the 3CR sample of radio galaxies with z < 0.3 . II. Spectroscopic classes and accretion modes in radio-loud AGN. A&A509:A6. https://doi.org/10.1051/0004-6361/200913290. arXiv:0911.0536

Capetti A, Raiteri CM (2015) Looking for the least luminous BL Lacertae objects. A&A580:A73. https://doi.org/10.1051/0004-6361/201525890. arXiv:1506.08043

Capetti A, Verdoes Kleijn GA, Chiaberge M (2005) The HST view of the nuclear emission line region in low luminosity radio-galaxies. A&A439:935–946. https://doi.org/10.1051/0004-6361:20041609

Capetti A, Kharb P, Axon DJ, Merritt D, Baldi RD (2009) A Very Large Array Radio Survey of Early-Type Galaxies in the Virgo Cluster. AJ138:1990–1997. https://doi.org/10.1088/0004-6256/138/6/1990. arXiv:0910.4102

Capetti A, Massaro F, Baldi RD (2017a) FRICAT: A FIRST catalog of FR I radio galaxies. A&A598:A49. https://doi.org/10.1051/0004-6361/201629287. arXiv:1610.09376 [astro-ph.HE]

Capetti A, Massaro F, Baldi RD (2017b) FRIICAT: A FIRST catalog of FR II radio galaxies. A&A601:A81. https://doi.org/10.1051/0004-6361/201630247. arXiv:1703.03427 [astro-ph.HE]

Capetti A, Baldi RD, Brienza M, Morganti R, Giovannini G (2019) The low-frequency properties of FR 0 radio galaxies. A&A631:A176. https://doi.org/10.1051/0004-6361/201936254. arXiv:1910.06618 [astro-ph.GA]

Capetti A, Brienza M, Baldi RD, Giovannini G, Morganti R, Hardcastle MJ, Rottgering HJA, Brunetti GF, Best PN, Miley G (2020a) The LOFAR view of FR 0 radio galaxies. A&A642:A107. https://doi.org/10.1051/0004-6361/202038671. arXiv:2008.08099 [astro-ph.GA]

Capetti A, Massaro F, Baldi RD (2020b) Large-scale environment of FR 0 radio galaxies. A&A633:A161. https://doi.org/10.1051/0004-6361/201935962. arXiv:2009.03330 [astro-ph.GA]

Capetti A, Brienza M, Balmaverde B, Best PN, Baldi RD, Drabent A, Gürkan G, Rottgering HJA, Tasse C, Webster B (2022) The LOFAR view of giant, early-type galaxies: Radio emission from active nuclei and star formation. A&A660:A93. https://doi.org/10.1051/0004-6361/202142911. arXiv:2202.08593 [astro-ph.GA]

Carvalho JC (1994) The age of GHz-peaked-spectrum radio sources. A&A292:392–394

Carvalho JC (1998) The evolution of GHz-peaked-spectrum radio sources. A&A329:845–852

Cattaneo A, Best PN (2009) On the jet contribution to the active galactic nuclei cosmic energy budget. MNRAS395:518–523. https://doi.org/10.1111/j.1365-2966.2009.14557.x. arXiv:0812.1562

Cavagnolo KW, McNamara BR, Nulsen PEJ, Carilli CL, Jones C, Bîrzan L (2010) A Relationship Between AGN Jet Power and Radio Power. ApJ720(2):1066–1072. https://doi.org/10.1088/0004-637X/720/2/1066. arXiv:1006.5699 [astro-ph.CO]

Chai B, Cao X, Gu M (2012) What Governs the Bulk Velocity of the Jet Components in Active Galactic Nuclei? ApJ759:114. https://doi.org/10.1088/

0004-637X/759/2/114. arXiv:1209.4702 [astro-ph.CO]

Chamani W, Savolainen T, Hada K, Xu MH (2021) Testing the magnetic flux paradigm for AGN radio loudness with a radio-intermediate quasar. A&A652:A14. https://doi.org/10.1051/0004-6361/202140676. arXiv:2106.01089 [astro-ph.HE]

Chen Y, Gu Q, Fan J, Zhou H, Yuan Y, Gu W, Wu Q, Xiong D, Guo X, Ding N, Yu X (2021) The Powers of Relativistic Jets Depend on the Spin of Accreting Supermassive Black Holes. ApJ913(2):93. https://doi.org/10.3847/1538-4357/abf4ff. arXiv:2104.04242 [astro-ph.HE]

Cheng X, An T, Sohn BW, Hong X, Wang A (2021) Parsec-scale properties of eight Fanaroff-Riley type 0 radio galaxies. MNRAS506(2):1609–1622. https://doi.org/10.1093/mnras/stab1388. arXiv:2105.05396 [astro-ph.HE]

Cheng XP, An T (2018) Parsec-scale Radio Structure of 14 Fanaroff-Riley Type 0 Radio Galaxies. ApJ863(2):155. https://doi.org/10.3847/1538-4357/aad22c. arXiv:1807.02505 [astro-ph.HE]

Chhetri R, Ekers RD, Mahony EK, Jones PA, Massardi M, Ricci R, Sadler EM (2012) Spectral properties and the effect on redshift cut-off of compact active galactic nuclei from the AT20G survey. MNRAS422(3):2274–2281. https://doi.org/10.1111/j.1365-2966.2012.20775.x. arXiv:1202.5406 [astro-ph.CO]

Chhetri R, Ekers RD, Jones PA, Ricci R (2013) The AT20G high-angular-resolution catalogue. MNRAS434(2):956–965. https://doi.org/10.1093/mnras/stt975. arXiv:1306.0990 [astro-ph.CO]

Chhetri R, Kimball A, Ekers RD, Mahony EK, Sadler EM, Jarrett T (2020) WISE mid-infrared properties of compact active galactic nuclei selected from the high radio frequency AT20G survey. MNRAS494(1):923–940. https://doi.org/10.1093/mnras/staa513. arXiv:2002.07429 [astro-ph.GA]

Chiaberge M, Marconi A (2011) On the origin of radio loudness in active galactic nuclei and its relationship with the properties of the central supermassive black hole. MNRAS416:917–926. https://doi.org/10.1111/j.1365-2966.2011.19079.x. arXiv:1105.4889 [astro-ph.CO]

Chiaberge M, Capetti A, Celotti A (1999a) The HST view of FR I radio galaxies: evidence for non-thermal nuclear sources. A&A349:77–87

Chiaberge M, Capetti A, Celotti A (1999b) The HST view of FR I radio galaxies: evidence for non-thermal nuclear sources. A&A 349:77–87

Chiaberge M, Capetti A, Celotti A (2002) Understanding the nature of FR II optical nuclei: A new diagnostic plane for radio galaxies. A&A394:791–800

Chiaberge M, Capetti A, Macchetto FD (2005) The Hubble Space Telescope View of LINER Nuclei: Evidence for a Dual Population? ApJ625:716–726. https://doi.org/10.1086/429612

Ching JHY, Croom SM, Sadler EM, Robotham ASG, Brough S, Baldry IK, Bland-Hawthorn J, Colless M, Driver SP, Holwerda BW, Hopkins AM, Jarvis MJ, Johnston HM, Kelvin LS, Liske J, Loveday J, Norberg P, Pracy MB, Steele O, Thomas D, Wang L (2017) Galaxy And Mass Assembly (GAMA): the environments of high- and low-excitation radio galaxies. MNRAS469(4):4584–4599. https://doi.org/10.1093/mnras/stx1173. arXiv:1705.04502 [astro-ph.GA]

Cohen MH, Moffet AT, Shaffer D, Clark BG, Kellermann KI, Jauncey DL, Gulkis S (1969) Compact Radio Source in the Nucleus of M87. ApJ158:L83. https://doi.org/10.1086/180437

Condon JJ (1989) The 1.4 GHz Luminosity Function and Its Evolution. ApJ338:13. https://doi.org/10.1086/167176

Condon JJ (1992) Radio emission from normal galaxies. ARA&A30:575–611. https://doi.org/10.1146/annurev.aa.30.090192.003043

Condon JJ, Dressel LL (1978) Compact radio sources in and near bright galaxies. ApJ221:456–467. https://doi.org/10.1086/156047

Condon JJ, Ransom SM (2016) Essential Radio Astronomy

Condon JJ, Cotton WD, Greisen EW, Yin QF, Perley RA, Taylor GB, Broderick JJ (1998) The NRAO VLA Sky Survey. AJ115:1693–1716. https://doi.org/10.1086/300337

Conselice CJ (2014) The Evolution of Galaxy Structure Over Cosmic Time. ARA&A52:291–337. https://doi.org/10.1146/annurev-astro-081913-040037. arXiv:1403.2783 [astro-ph.GA]

Conway JE (2002) Compact symmetric objects—newborn radio galaxies? New A Rev.46(2-7):263–271. https://doi.org/10.1016/S1387-6473(01)00191-9

Croston JH, Kraft RP, Hardcastle MJ (2007) Shock Heating in the Nearby Radio Galaxy NGC 3801. ApJ660(1):191–199. https://doi.org/10.1086/513500. arXiv:astro-ph/0702094 [astro-ph]

Croston JH, Ineson J, Hardcastle MJ (2018) Particle content, radio-galaxy morphology, and jet power: all radio-loud AGN are not equal. MNRAS476(2):1614–1623. https://doi.org/10.1093/mnras/sty274. arXiv:1801.10172 [astro-ph.GA]

Croton DJ, Springel V, White SDM, De Lucia G, Frenk CS, Gao L, Jenkins A, Kauffmann G, Navarro JF, Yoshida N (2006) The many lives of active galactic nuclei: cooling flows, black holes and the luminosities and colours of galaxies. MNRAS 365:11–28. https://doi.org/10.1111/j.1365-2966.2005.09675.x. astro-ph/0508046

Czerny B, Siemiginowska A, Janiuk A, Nikiel-Wroczyński B, Stawarz Ł (2009) Accretion Disk Model of Short-Timescale Intermittent Activity in Young Radio Sources. ApJ698(1):840–851. https://doi.org/10.1088/0004-637X/698/1/840. arXiv:0903.3940 [astro-ph.CO]

Dai X, Bregman JN, Kochanek CS, Rasia E (2010) On the Baryon Fractions in Clusters and Groups of Galaxies. ApJ719(1):119–125. https://doi.org/10.1088/0004-637X/719/1/119. arXiv:0911.2230 [astro-ph.CO]

Dallacasa D, Stanghellini C, Centonza M, Fanti R (2000) High frequency peakers. I. The bright sample. A&A363:887–900. arXiv:astro-ph/0012428 [astro-ph]

Daly RA, Sprinkle TB, O'Dea CP, Kharb P, Baum SA (2012) The relationship between beam power and radio power for classical double radio sources. MNRAS423(3):2498–2502. https://doi.org/10.1111/j.1365-2966.2012.21060.x. arXiv:1204.1307 [astro-ph.CO]

D'Ammando F, Giroletti M, Rainó S (2018) Exploring the bulk of the BL Lacertae object population. II. Gamma-ray properties. A&A618:A175. https:

//doi.org/10.1051/0004-6361/201833540. arXiv:1809.01173 [astro-ph.HE]

Davé R, Thompson R, Hopkins PF (2016) MUFASA: galaxy formation simulations with meshless hydrodynamics. MNRAS462(3):3265–3284. https://doi.org/10.1093/mnras/stw1862. arXiv:1604.01418 [astro-ph.GA]

Davis F, Kaviraj S, Hardcastle MJ, Martin G, Jackson RA, Kraljic K, Malek K, Peirani S, Smith DJB, Volonteri M, Wang L (2022) Radio AGN in nearby dwarf galaxies: the important role of AGN in dwarf galaxy evolution. MNRAS511(3):4109–4122. https://doi.org/10.1093/mnras/stac068. arXiv:2201.09903 [astro-ph.GA]

de Menezes R, Nemmen R, Finke JD, Almeida I, Rani B (2020) Gamma-ray observations of low-luminosity active galactic nuclei. MNRAS492(3):4120–4130. https://doi.org/10.1093/mnras/staa083. arXiv:2001.03184 [astro-ph.HE]

De Young DS (2006) The Particle Content of Extragalactic Jets. ApJ648(1):200–208. https://doi.org/10.1086/505861. arXiv:astro-ph/0605734 [astro-ph]

Delvecchio I, Smolčić V, Zamorani G, Lagos CDP, Berta S, Delhaize J, Baran N, Alexander DM, Rosario DJ, Gonzalez-Perez V, Ilbert O, Lacey CG, Le Fèvre O, Miettinen O, Aravena M, Bondi M, Carilli C, Ciliegi P, Mooley K, Novak M, Schinnerer E, Capak P, Civano F, Fanidakis N, Herrera Ruiz N, Karim A, Laigle C, Marchesi S, McCracken HJ, Middleberg E, Salvato M, Tasca L (2017) The VLA-COSMOS 3 GHz Large Project: AGN and host-galaxy properties out to z $\lesssim$ 6. A&A602:A3. https://doi.org/10.1051/0004-6361/201629367. arXiv:1703.09720 [astro-ph.GA]

Dicken D, Tadhunter C, Morganti R, Axon D, Robinson A, Magagnoli M, Kharb P, Ramos Almeida C, Mingo B, Hardcastle M, Nesvadba NPH, Singh V, Kouwenhoven MBN, Rose M, Spoon H, Inskip KJ, Holt J (2014) Spitzer Mid-IR Spectroscopy of Powerful 2Jy and 3CRR Radio Galaxies. II. AGN Power Indicators and Unification. ApJ788:98. https://doi.org/10.1088/0004-637X/788/2/98. arXiv:1405.0670

Doi A, Nakanishi K, Nagai H, Kohno K, Kameno S (2011) Millimeter Radio Continuum Emissions as the Activity of Supermassive Black Holes in Nearby Early-type Galaxies and Low-luminosity Active Galactic Nuclei. AJ142(5):167. https://doi.org/10.1088/0004-6256/142/5/167. arXiv:1106.5627 [astro-ph.CO]

Donato D, Sambruna RM, Gliozzi M (2004) Obscuration and Origin of Nuclear X-Ray Emission in FR I Radio Galaxies. ApJ617(2):915–929. https://doi.org/10.1086/425575. arXiv:astro-ph/0408451 [astro-ph]

Dubois Y, Pichon C, Welker C, Le Borgne D, Devriendt J, Laigle C, Codis S, Pogosyan D, Arnouts S, Benabed K, Bertin E, Blaizot J, Bouchet F, Cardoso JF, Colombi S, de Lapparent V, Desjacques V, Gavazzi R, Kassin S, Kimm T, McCracken H, Milliard B, Peirani S, Prunet S, Rouberol S, Silk J, Slyz A, Sousbie T, Teyssier R, Tresse L, Treyer M, Vibert D, Volonteri M (2014a) Dancing in the dark: galactic properties trace spin swings along the cosmic web. MNRAS444(2):1453–1468. https://doi.org/10.1093/mnras/stu1227. arXiv:1402.1165 [astro-ph.CO]

Dubois Y, Volonteri M, Silk J (2014b) Black hole evolution - III. Statistical properties of mass growth and spin evolution using large-scale hydrodynamical cosmological simulations. MNRAS440(2):1590–1606. https://doi.org/10.1093/mnras/stu373. arXiv:1304.4583 [astro-ph.CO]

Dullo BT, Knapen JH, Williams DRA, Beswick RJ, Bendo G, Baldi RD, Argo M, McHardy IM, Muxlow T, Westcott J (2018) The nuclear activity and central structure of the elliptical galaxy NGC 5322. MNRAShttps://doi.org/10.1093/mnras/sty069. arXiv:1801.03660

Ekers RD, Ekers JA (1973) A Survey of Elliptical Galaxies at 6 CM. A&A24:247

Elitzur M, Shlosman I (2006) The AGN-obscuring Torus: The End of the "Doughnut" Paradigm? ApJ648(2):L101–L104. https://doi.org/10.1086/508158. arXiv:astro-ph/0605686 [astro-ph]

Elvis M, Wilkes BJ, McDowell JC, Green RF, Bechtold J, Willner SP, Oey MS, Polomski E, Cutri R (1994) Atlas of quasar energy distributions. ApJS95:1–68

Evans DA, Worrall DM, Hardcastle MJ, Kraft RP, Birkinshaw M (2006) Chandra and XMM-Newton Observations of a Sample of Low-Redshift FR I and FR II Radio Galaxy Nuclei. ApJ642:96–112. https://doi.org/10.1086/500658. astro-ph/0512600

Event Horizon Telescope Collaboration, Akiyama K, Algaba JC, Alberdi A, Alef W, Anantua R, Asada K, Azulay R, Baczko AK, Ball D, Baloković M, Barrett J, Benson BA, Bintley D, Blackburn L, Blundell R, Boland W, Bouman KL, Bower GC, Boyce H, Bremer M, Brinkerink CD, Brissenden R, Britzen S, Broderick AE, Broguiere D, Bronzwaer T, Byun DY, Carlstrom JE, Chael A, Chan Ck, Chatterjee S, Chatterjee K, Chen MT, Chen Y, Chesler PM, Cho I, Christian P, Conway JE, Cordes JM, Crawford TM, Crew GB, Cruz-Osorio A, Cui Y, Davelaar J, De Laurentis M, Deane R, Dempsey J, Desvignes G, Dexter J, Doeleman SS, Eatough RP, Falcke H, Farah J, Fish VL, Fomalont E, Ford HA, Fraga-Encinas R, Friberg P, Fromm CM, Fuentes A, Galison P, Gammie CF, García R, Gelles Z, Gentaz O, Georgiev B, Goddi C, Gold R, Gómez JL, Gómez-Ruiz AI, Gu M, Gurwell M, Hada K, Haggard D, Hecht MH, Hesper R, Himwich E, Ho LC, Ho P, Honma M, Huang CWL, Huang L, Hughes DH, Ikeda S, Inoue M, Issaoun S, James DJ, Jannuzi BT, Janssen M, Jeter B, Jiang W, Jimenez-Rosales A, Johnson MD, Jorstad S, Jung T, Karami M, Karuppusamy R, Kawashima T, Keating GK, Kettenis M, Kim DJ, Kim JY, Kim J, Kim J, Kino M, Koay JY, Kofuji Y, Koch PM, Koyama S, Kramer M, Kramer C, Krichbaum TP, Kuo CY, Lauer TR, Lee SS, Levis A, Li YR, Li Z, Lindqvist M, Lico R, Lindahl G, Liu J, Liu K, Liuzzo E, Lo WP, Lobanov AP, Loinard L, Lonsdale C, Lu RS, MacDonald NR, Mao J, Marchili N, Markoff S, Marrone DP, Marscher AP, Martí-Vidal I, Matsushita S, Matthews LD, Medeiros L, Menten KM, Mizuno I, Mizuno Y, Moran JM, Moriyama K, Moscibrodzka M, Müller C, Musoke G, Mus Mejías A, Michalik D, Nadolski A, Nagai H, Nagar NM, Nakamura M, Narayan R, Narayanan G, Natarajan I, Nathanail A, Neilsen J, Neri R, Ni C, Noutsos A, Nowak MA, Okino H, Olivares

H, Ortiz-León GN, Oyama T, Özel F, Palumbo DCM, Park J, Patel N, Pen UL, Pesce DW, Piétu V, Plambeck R, PopStefanija A, Porth O, Pötzl FM, Prather B, Preciado-López JA, Psaltis D, Pu HY, Ramakrishnan V, Rao R, Rawlings MG, Raymond AW, Rezzolla L, Ricarte A, Ripperda B, Roelofs F, Rogers A, Ros E, Rose M, Roshanineshat A, Rottmann H, Roy AL, Ruszczyk C, Rygl KLJ, Sánchez S, Sánchez-Arguelles D, Sasada M, Savolainen T, Schloerb FP, Schuster KF, Shao L, Shen Z, Small D, Sohn BW, SooHoo J, Sun H, Tazaki F, Tetarenko AJ, Tiede P, Tilanus RPJ, Titus M, Toma K, Torne P, Trent T, Traianou E, Trippe S, van Bemmel I, van Langevelde HJ, van Rossum DR, Wagner J, Ward-Thompson D, Wardle J, Weintroub J, Wex N, Wharton R, Wielgus M, Wong GN, Wu Q, Yoon D, Young A, Young K, Younsi Z, Yuan F, Yuan YF, Zensus JA, Zhao GY, Zhao SS (2021) First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon. ApJ910(1):L13. https://doi.org/10.3847/2041-8213/abe4de. arXiv:2105.01173 [astro-ph.HE]

Fabbiano G, Kim DW, Trinchieri G (1992) An X-ray catalog and atlas of galaxies. ApJS80:531–644. https://doi.org/10.1086/191675

Faber SM, Tremaine S, Ajhar EA, Byun Y, Dressler A, Gebhardt K, Grillmair C, Kormendy J, Lauer TR, Richstone D (1997) The Centers of Early-Type Galaxies with HST. IV. Central Parameter Relations. AJ114:1771–+

Fabian AC (2012) Observational Evidence of Active Galactic Nuclei Feedback. ARA&A50:455–489. https://doi.org/10.1146/annurev-astro-081811-125521. arXiv:1204.4114 [astro-ph.CO]

Fabian AC, Sanders JS, Allen SW, Crawford CS, Iwasawa K, Johnstone RM, Schmidt RW, Taylor GB (2003) A deep Chandra observation of the Perseus cluster: shocks and ripples. MNRAS344:L43–L47. https://doi.org/10.1046/j.1365-8711.2003.06902.x. arXiv:astro-ph/0306036

Falcke H, Nagar NM, Wilson AS, Ulvestad JS (2000) Radio Sources in Low-Luminosity Active Galactic Nuclei. II. Very Long Baseline Interferometry Detections of Compact Radio Cores and Jets in a Sample of LINERs. ApJ542:197–200

Falcke H, Körding E, Nagar NM (2004) Compact radio cores: from the first black holes to the last. New A Rev.48(11-12):1157–1171. https://doi.org/10.1016/j.newar.2004.09.029. arXiv:astro-ph/0409125 [astro-ph]

Fanaroff BL, Riley JM (1974) The morphology of extragalactic radio sources of high and low luminosity. MNRAS167:31P–36P. https://doi.org/10.1093/mnras/167.1.31P

Fanidakis N, Baugh CM, Benson AJ, Bower RG, Cole S, Done C, Frenk CS (2011) Grand unification of AGN activity in the ΛCDM cosmology. MNRAS410(1):53–74. https://doi.org/10.1111/j.1365-2966.2010.17427.x. arXiv:0911.1128 [astro-ph.CO]

Fanti C, Fanti R, Parma P, Schilizzi RT, van Breugel WJM (1985) Compact steep spectrum 3 CR radio sources. VLBI observations at 18 cm. A&A143:292–306

Fanti C, Fanti R, de Ruiter HR, Parma P (1986) VLA observations of low luminosity radio galaxies. III. The A-array observations. A&AS65:145–188

Fanti C, Fanti R, de Ruiter HR, Parma P (1987) VLA observations of low luminosity radio galaxies. IV - The B2 sample revisited. A&AS69:57–76

Fanti C, Fanti R, Dallacasa D, Schilizzi RT, Spencer RE, Stanghellini C (1995) Are compact steep-spectrum sources young? A&A302:317

Fanti C, Pozzi F, Dallacasa D, Fanti R, Gregorini L, Stanghellini C, Vigotti M (2001) Multi-frequency VLA observations of a new sample of CSS/GPS radio sources. A&A369:380–420. https://doi.org/10.1051/0004-6361:20010051

Fanti R, Gioia I, Lari C, Ulrich MH (1978) A new complete sample of radio galaxies. A&AS34:341–362

Fanti R, Fanti C, Schilizzi RT, Spencer RE, Nan Rendong, Parma P, van Breugel WJM, Venturi T (1990) On the nature of compact steep spectrum radio sources. A&A231:333–346

Fernández-Ontiveros JA, López-López X, Prieto A (2022) Compact jets dominate the continuum emission in low-luminosity active galactic nuclei. arXiv e-prints arXiv:2211.09828. arXiv:2211.09828 [astro-ph.HE]

Filho ME, Barthel PD, Ho LC (2000) The Nature of Composite LINER/H II Galaxies as Revealed from High-Resolution VLA Observations. ApJS129:93–110. https://doi.org/10.1086/313412. astro-ph/0002404

Filho ME, Barthel PD, Ho LC (2002a) Light-year scale radio cores in four LINER galaxies. A&A385:425–430. https://doi.org/10.1051/0004-6361:20020138. arXiv:astro-ph/0201505 [astro-ph]

Filho ME, Barthel PD, Ho LC (2002b) The Radio Properties of Composite LINER/H II Galaxies. ApJS142(2):223–238. https://doi.org/10.1086/341786. arXiv:astro-ph/0205196 [astro-ph]

Filho ME, Fraternali F, Markoff S, Nagar NM, Barthel PD, Ho LC, Yuan F (2004) Further clues to the nature of composite LINER/H II galaxies. A&A418:429–443

Floyd DJE, Axon D, Baum S, Capetti A, Chiaberge M, Madrid J, O'Dea CP, Perlman E, Sparks W (2010) Hubble Space Telescope Near-infrared Snapshot Survey of 3CR Radio Source Counterparts. III. Radio Galaxies and Quasars in Context. ApJ713(1):66–81. https://doi.org/10.1088/0004-637X/713/1/66. arXiv:1003.2467 [astro-ph.CO]

Fu WJ, Zhang HM, Zhang J, Liang YF, Yao S, Liang EW (2022) Is TOL 1326-379 a Prototype of γ-Ray Emitting FR0 Radio Galaxy? Research in Astronomy and Astrophysics 22(3):035005. https://doi.org/10.1088/1674-4527/ac4410

Gallo E, Sesana A (2019) Exploring the Local Black Hole Mass Function below 10^6 Solar Masses. ApJ883(1):L18. https://doi.org/10.3847/2041-8213/ab40c6. arXiv:1909.02585 [astro-ph.HE]

Garofalo D (2009) The Spin Dependence of the Blandford-Znajek Effect. ApJ699(1):400–408. https://doi.org/10.1088/0004-637X/699/1/400. arXiv:0904.3486 [astro-ph.HE]

Garofalo D, Singh CB (2019) FR0 Radio Galaxies and Their Place in the Radio Morphology Classification. ApJ871(2):259. https://doi.org/10.3847/1538-4357/aaf056. arXiv:1811.05383 [astro-ph.HE]

Garofalo D, Evans DA, Sambruna RM (2010) The evolution of radio-loud active galactic nuclei as a function of black hole spin. MNRAS406:975–986. https://doi.org/10.1111/j.1365-2966.2010.16797.x. arXiv:1004.1166

Gendre MA, Best PN, Wall JV, Ker LM (2013) The relation between morphology, accretion modes and environmental factors in local radio AGN. MNRAS430:3086–3101. https://doi.org/10.1093/mnras/stt116. arXiv:1301.1526

Ghisellini G (2011) Extragalactic relativistic jets. In: Aharonian FA, Hofmann W, Rieger FM (eds) American Institute of Physics Conference Series. American Institute of Physics Conference Series, vol 1381. pp 180–198. https://doi.org/10.1063/1.3635832. arXiv:1104.0006

Ghisellini G, Haardt F, Matt G (2004) Aborted jets and the X-ray emission of radio-quiet AGNs. A&A413:535–545. https://doi.org/10.1051/0004-6361:20031562. arXiv:astro-ph/0310106 [astro-ph]

Ghisellini G, Tavecchio F, Chiaberge M (2005) Structured jets in TeV BL Lac objects and radiogalaxies. Implications for the observed properties. A&A432(2):401–410. https://doi.org/10.1051/0004-6361:20041404. arXiv:astro-ph/0406093 [astro-ph]

Giovannini G, Feretti L, Comoretto G (1990) VLBI Observations of a Complete Sample of Radio Galaxies. I. Snapshot Data. ApJ358:159. https://doi.org/10.1086/168970

Giovannini G, Cotton WD, Feretti L, Lara L, Venturi T (2001) VLBI Observations of a Complete Sample of Radio Galaxies: 10 Years Later. ApJ552:508–526. https://doi.org/10.1086/320581. arXiv:astro-ph/0101096

Giovannini G, Taylor GB, Feretti L, Cotton WD, Lara L, Venturi T (2005) The Bologna Complete Sample of Nearby Radio Sources. ApJ618:635–648. https://doi.org/10.1086/426106. astro-ph/0409624

Giovannini G, Savolainen T, Orienti M, Nakamura M, Nagai H, Kino M, Giroletti M, Hada K, Bruni G, Kovalev YY, Anderson JM, D'Ammando F, Hodgson J, Honma M, Krichbaum TP, Lee SS, Lico R, Lisakov MM, Lobanov AP, Petrov L, Sohn BW, Sokolovsky KV, Voitsik PA, Zensus JA, Tingay S (2018) A wide and collimated radio jet in 3C84 on the scale of a few hundred gravitational radii. Nature Astronomy 2:472–477. https://doi.org/10.1038/s41550-018-0431-2. arXiv:1804.02198 [astro-ph.GA]

Giovannini G, Baldi RD, Capetti A, Giroletti M, Lico R (2023) Jets in FR 0 radio galaxies. accepted for publication on A&A

Giroletti M, Giovannini G, Taylor GB (2005) Low power compact radio galaxies at high angular resolution. A&A441(1):89–101. https://doi.org/10.1051/0004-6361:20053347. arXiv:astro-ph/0506497 [astro-ph]

Glowacki M, Allison JR, Sadler EM, Moss VA, Curran SJ, Musaeva A, Deng C, Parry R, Sligo MC (2017) H I absorption in nearby compact radio galaxies. MNRAS467(3):2766–2786. https://doi.org/10.1093/mnras/stx214. arXiv:1701.07036 [astro-ph.GA]

González-Martín O, Masegosa J, Márquez I, Rodríguez-Espinosa JM, Acosta-Pulido JA, Ramos Almeida C, Dultzin D, Hernández-García L, Ruschel-Dutra D, Alonso-Herrero A (2015) Nuclear obscuration in LINERs. Clues from Spitzer/IRS spectra on the Compton thickness and the existence of the dusty torus. A&A578:A74. https://doi.org/10.1051/0004-6361/201425254

Gopal-Krishna, Mangalam A, Wiita PJ (2008) Stellar Disruption by Supermassive Black Holes and the Quasar Radio Loudness Dichotomy. ApJ680(1):L13. https://doi.org/10.1086/589739. arXiv:0806.1464 [astro-ph]

Goulding AD, Greene JE, Ma CP, Veale M, Bogdan A, Nyland K, Blakeslee JP, McConnell NJ, Thomas J (2016) The MASSIVE Survey. IV. The X-ray Halos of the Most Massive Early-type Galaxies in the Nearby Universe. ApJ826(2):167. https://doi.org/10.3847/0004-637X/826/2/167. arXiv:1604.01764 [astro-ph.GA]

Grandi P, Capetti A, Baldi RD (2016) Discovery of a Fanaroff-Riley type 0 radio galaxy emitting at γ-ray energies. MNRAS457(1):2–8. https://doi.org/10.1093/mnras/stv2846. arXiv:1512.01242 [astro-ph.GA]

Grandi P, Torresi E, Macconi D, Boccardi B, Capetti A (2021) Jet-Accretion System in the Nearby mJy Radio Galaxies. ApJ911(1):17. https://doi.org/10.3847/1538-4357/abe776. arXiv:2102.08922 [astro-ph.HE]

Greene JE (2012) Low-mass black holes as the remnants of primordial black hole formation. Nature Communications 3:1304. https://doi.org/10.1038/ncomms2314. arXiv:1211.7082 [astro-ph.CO]

Gregory PC, Scott WK, Douglas K, Condon JJ (1996) The GB6 Catalog of Radio Sources. ApJS103:427. https://doi.org/10.1086/192282

Grossová R, Werner N, Massaro F, Lakhchaura K, Plšek T, Gabányi K, Rajpurohit K, Canning REA, Nulsen P, O'Sullivan E, Allen SW, Fabian A (2022) Very Large Array Radio Study of a Sample of Nearby X-Ray and Optically Bright Early-type Galaxies. ApJS258(2):30. https://doi.org/10.3847/1538-4365/ac366c. arXiv:2111.02430 [astro-ph.HE]

Gugliucci NE, Taylor GB, Peck AB, Giroletti M (2005) Dating COINS: Kinematic Ages for Compact Symmetric Objects. ApJ622(1):136–148. https://doi.org/10.1086/427934. arXiv:astro-ph/0412199 [astro-ph]

Gupta Y, Ajithkumar B, Kale HS, Nayak S, Sabhapathy S, Sureshkumar S, Swami RV, Chengalur JN, Ghosh SK, Ishwara-Chandra CH, Joshi BC, Kanekar N, Lal DV, Roy S (2017) The upgraded GMRT: opening new windows on the radio Universe. Current Science 113(4):707–714. https://doi.org/10.18520/cs/v113/i04/707-714

Gürkan G, Hardcastle MJ, Smith DJB, Best PN, Bourne N, Calistro-Rivera G, Heald G, Jarvis MJ, Prandoni I, Röttgering HJA, Sabater J, Shimwell T, Tasse C, Williams WL (2018) LOFAR/H-ATLAS: the low-frequency radio luminosity-star formation rate relation. MNRAS475(3):3010–3028. https://doi.org/10.1093/mnras/sty016. arXiv:1801.02629 [astro-ph.GA]

H E S S Collaboration, Abdalla H, Adam R, Aharonian F, Ait Benkhali F, Angüner EO, Arakawa M, Arcaro C, Armand C, Ashkar H, Backes M, Barbosa Martins V, Barnard M, Becherini Y, Berge D, Bernlöhr K, Blackwell R, Böttcher M, Boisson C, Bolmont J, Bonnefoy S, Bregeon J, Breuhaus M, Brun F, Brun P, Bryan M, Büchele M, Bulik T, Bylund T, Capasso M, Caroff S, Carosi A, Casanova S, Cerruti M, Chand T, Chandra S, Chen A, Colafrancesco S, Curyło M, Davids ID, Deil C, Devin J, deWilt P, Dirson L, Djannati-Ataï A, Dmytriiev A, Donath A, Doroshenko

V, Drury LO, Dyks J, Egberts K, Emery G, Ernenwein JP, Eschbach S, Feijen K, Fegan S, Fiasson A, Fontaine G, Funk S, Füßling M, Gabici S, Gallant YA, Gaté F, Giavitto G, Glawion D, Glicenstein JF, Gottschall D, Grondin MH, Hahn J, Haupt M, Heinzelmann G, Henri G, Hermann G, Hinton JA, Hofmann W, Hoischen C, Holch TL, Holler M, Horns D, Huber D, Iwasaki H, Jamrozy M, Jankowsky D, Jankowsky F, Jardin-Blicq A, Jung-Richardt I, Kastendieck MA, Katarzyński K, Katsuragawa M, Katz U, Khangulyan D, Khélifi B, King J, Klepser S, Kluźniak W, Komin N, Kosack K, Kostunin D, Kraus M, Lamanna G, Lau J, Lemière A, Lemoine-Goumard M, Lenain JP, Leser E, Levy C, Lohse T, Lypova I, Mackey J, Majumdar J, Malyshev D, Marandon V, Marcowith A, Mares A, Mariaud C, Martí-Devesa G, Marx R, Maurin G, Meintjes PJ, Mitchell AMW, Moderski R, Mohamed M, Mohrmann L, Moore C, Moulin E, Muller J, Murach T, Nakashima S, de Naurois M, Ndiyavala H, Niederwanger F, Niemiec J, Oakes L, O'Brien P, Odaka H, Ohm S, de Ona Wilhelmi E, Ostrowski M, Oya I, Panter M, Parsons RD, Perennes C, Petrucci PO, Peyaud B, Piel Q, Pita S, Poireau V, Priyana Noel A, Prokhorov DA, Prokoph H, Pühlhofer G, Punch M, Quirrenbach A, Raab S, Rauth R, Reimer A, Reimer O, Remy Q, Renaud M, Rieger F, Rinchiuso L, Romoli C, Rowell G, Rudak B, Ruiz-Velasco E, Sahakian V, Saito S, Sanchez DA, Santangelo A, Sasaki M, Schlickeiser R, Schüssler F, Schulz A, Schutte HM, Schwanke U, Schwemmer S, Seglar-Arroyo M, Senniappan M, Seyffert AS, Shafi N, Shiningayamwe K, Simoni R, Sinha A, Sol H, Specovius A, Spir-Jacob M, Stawarz Ł, Steenkamp R, Stegmann C, Steppa C, Takahashi T, Tavernier T, Taylor AM, Terrier R, Tiziani D, Tluczykont M, Trichard C, Tsirou M, Tsuji N, Tuffs R, Uchiyama Y, van der Walt DJ, van Eldik C, van Rensburg C, van Soelen B, Vasileiadis G, Veh J, Venter C, Vincent P, Vink J, Voisin F, Völk HJ, Vuillaume T, Wadiasingh Z, Wagner SJ, White R, Wierzcholska A, Yang R, Yoneda H, Zacharias M, Zanin R, Zdziarski AA, Zech A, Ziegler A, Zorn J, ywucka N (2020) Resolving acceleration to very high energies along the jet of Centaurus A. Nature582(7812):356–359. https://doi.org/10.1038/s41586-020-2354-1. arXiv:2007.04823 [astro-ph.HE]

Hada K (2019) Relativistic Jets from AGN Viewed at Highest Angular Resolution. Galaxies 8(1):1. https://doi.org/10.3390/galaxies8010001

Hallinan G, Ravi V, Deep Synoptic Array Team (2021) The DSA-2000: A Radio Survey Camera. In: American Astronomical Society Meeting Abstracts. American Astronomical Society Meeting Abstracts, vol 53. p 316.05

Hancock PJ, Sadler EM, Mahony EK, Ricci R (2010) Observations and properties of candidate high-frequency GPS radio sources in the AT20G survey. MNRAS408(2):1187–1206. https://doi.org/10.1111/j.1365-2966.2010.17199.x. arXiv:1008.1401 [astro-ph.GA]

Hardcastle MJ, Croston JH (2020) Radio galaxies and feedback from AGN jets. New A Rev.88:101539. https://doi.org/10.1016/j.newar.2020.101539. arXiv:2003.06137 [astro-ph.HE]

Hardcastle MJ, Krause MGH (2013) Numerical modelling of the lobes of radio galaxies in cluster environments. MNRAS430(1):174–196. https://doi.org/10.1093/mnras/sts564. arXiv:1301.2531 [astro-ph.CO]

Hardcastle MJ, Worrall DM (2000) Radio, optical and X-ray nuclei in nearby 3CRR radio galaxies. MNRAS 314:359–363

Hardcastle MJ, Birkinshaw M, Worrall DM (1998) Magnetic field strengths in the hotspots of 3C 33 and 111. MNRAS294:615–621. https://doi.org/10.1111/j.1365-8711.1998.01159.x. arXiv:astro-ph/9709228 [astro-ph]

Hardcastle MJ, Evans DA, Croston JH (2007) Hot and cold gas accretion and feedback in radio-loud active galaxies. MNRAS376:1849–1856. https://doi.org/10.1111/j.1365-2966.2007.11572.x. astro-ph/0701857

Hardcastle MJ, Evans DA, Croston JH (2009) The active nuclei of z $<$ 1.0 3CRR radio sources. MNRAS396:1929–1952. https://doi.org/10.1111/j.1365-2966.2009.14887.x. arXiv:0904.1323

Hardcastle MJ, Williams WL, Best PN, Croston JH, Duncan KJ, Röttgering HJA, Sabater J, Shimwell TW, Tasse C, Callingham JR, Cochrane RK, de Gasperin F, Gürkan G, Jarvis MJ, Mahatma V, Miley GK, Mingo B, Mooney S, Morabito LK, O'Sullivan SP, Prandoni I, Shulevski A, Smith DJB (2019) Radio-loud AGN in the first LoTSS data release. The lifetimes and environmental impact of jet-driven sources. A&A622:A12. https://doi.org/10.1051/0004-6361/201833893. arXiv:1811.07943 [astro-ph.GA]

Harrison CM (2017) Impact of supermassive black hole growth on star formation. Nature Astronomy 1:0165. https://doi.org/10.1038/s41550-017-0165. arXiv:1703.06889 [astro-ph.GA]

Harvey M, Rulten CB, Chadwick PM (2020) A search for γ-ray emission from a sample of local Universe low-frequency selected radio galaxies. MNRAS496(1):903–912. https://doi.org/10.1093/mnras/staa1593. arXiv:2006.02831 [astro-ph.HE]

Hawley JF, Krolik JH (2006) Magnetically Driven Jets in the Kerr Metric. ApJ641(1):103–116. https://doi.org/10.1086/500385. arXiv:astro-ph/0512227 [astro-ph]

Heckman TM (1980) An optical and radio survey of the nuclei of bright galaxies. Activity in normal galactic nuclei. A&A500:187–199

Heckman TM, Best PN (2014) The Coevolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe. ARA&A52:589–660. https://doi.org/10.1146/annurev-astro-081913-035722. arXiv:1403.4620

Heckman TM, Kauffmann G, Brinchmann J, Charlot S, Tremonti C, White SDM (2004) Present-Day Growth of Black Holes and Bulges: The Sloan Digital Sky Survey Perspective. ApJ613:109–118

Heeschen DS (1970) Radio Observations of E and SO Galaxies. AJ75:523–529. https://doi.org/10.1086/110987

Hill GJ, Lilly SJ (1991) A Change in the Cluster Environments of Radio Galaxies with Cosmic Epoch. ApJ367:1. https://doi.org/10.1086/169597

Hine RG, Longair MS (1979) Optical spectra of 3CR radio galaxies. MNRAS 188:111–130

Ho LC (2002) On the Relationship between Radio Emission and Black Hole

Mass in Galactic Nuclei. ApJ564:120–132

Ho LC (2008) Nuclear Activity in Nearby Galaxies. ARA&A46:475–539. https://doi.org/10.1146/annurev.astro.45.051806.110546. arXiv:0803.2268

Ho LC, Filippenko AV, Sargent WL (1995) A search for 'dwarf' Seyfert nuclei. 2: an optical spectral atlas of the nuclei of nearby galaxies. ApJS 98:477–593. https://doi.org/10.1086/192170

Holt J, Tadhunter CN, Morganti R (2008) Fast outflows in compact radio sources: evidence for AGN-induced feedback in the early stages of radio source evolution. MNRAS387(2):639–659. https://doi.org/10.1111/j.1365-2966.2008.13089.x. arXiv:0802.1444 [astro-ph]

Hota A, Sirothia SK, Ohyama Y, Konar C, Kim S, Rey SC, Saikia DJ, Croston JH, Matsushita S (2011) Discovery of a spiral-host episodic radio galaxy. MNRAS417(1):L36–L40. https://doi.org/10.1111/j.1745-3933.2011.01115.x. arXiv:1107.4742 [astro-ph.CO]

IceCube Collaboration, Aartsen MG, Ackermann M, Adams J, Aguilar JA, Ahlers M, Ahrens M, Al Samarai I, Altmann D, Andeen K, Anderson T, Ansseau I, Anton G, Argüelles C, Auffenberg J, Axani S, Bagherpour H, Bai X, Barron JP, Barwick SW, Baum V, Bay R, Beatty JJ, Becker Tjus J, Becker KH, BenZvi S, Berley D, Bernardini E, Besson DZ, Binder G, Bindig D, Blaufuss E, Blot S, Bohm C, Börner M, Bos F, Böser S, Botner O, Bourbeau E, Bourbeau J, Bradascio F, Braun J, Brenzke M, Bretz HP, Bron S, Brostean-Kaiser J, Burgman A, Busse RS, Carver T, Cheung E, Chirkin D, Christov A, Clark K, Classen L, Coenders S, Collin GH, Conrad JM, Coppin P, Correa P, Cowen DF, Cross R, Dave P, Day M, de André JPAM, De Clercq C, DeLaunay JJ, Dembinski H, De Ridder S, Desiati P, de Vries KD, de Wasseige G, de With M, DeYoung T, Díaz-Vélez JC, di Lorenzo V, Dujmovic H, Dumm JP, Dunkman M, Dvorak E, Eberhardt B, Ehrhardt T, Eichmann B, Eller P, Evenson PA, Fahey S, Fazely AR, Felde J, Filimonov K, Finley C, Flis S, Franckowiak A, Friedman E, Fritz A, Gaisser TK, Gallagher J, Gerhardt L, Ghorbani K, Glauch T, Glüsenkamp T, Goldschmidt A, Gonzalez JG, Grant D, Griffith Z, Haack C, Hallgren A, Halzen F, Hanson K, Hebecker D, Heereman D, Helbing K, Hellauer R, Hickford S, Hignight J, Hill GC, Hoffman KD, Hoffmann R, Hoinka T, Hokanson-Fasig B, Hoshina K, Huang F, Huber M, Hultqvist K, Hünnefeld M, Hussain R, In S, Iovine N, Ishihara A, Jacobi E, Japaridze GS, Jeong M, Jero K, Jones BJP, Kalaczynski P, Kang W, Kappes A, Kappesser D, Karg T, Karle A, Katz U, Kauer M, Keivani A, Kelley JL, Kheirandish A, Kim J, Kim M, Kintscher T, Kiryluk J, Kittler T, Klein SR, Koirala R, Kolanoski H, Köpke L, Kopper C, Kopper S, Koschinsky JP, Koskinen DJ, Kowalski M, Krings K, Kroll M, Krückl G, Kunwar S, Kurahashi N, Kuwabara T, Kyriacou A, Labare M, Lanfranchi JL, Larson MJ, Lauber F, Leonard K, Lesiak-Bzdak M, Leuermann M, Liu QR, Lozano Mariscal CJ, Lu L, Lünemann J, Luszczak W, Madsen J, Maggi G, Mahn KBM, Mancina S, Maruyama R, Mase K, Maunu R, Meagher K, Medici M, Meier M, Menne T, Merino G, Meures T, Miarecki S, Micallef J, Momenté G, Montaruli T, Moore RW, Morse R, Moulai M, Nahnhauer R, Nakarmi P, Naumann U, Neer G, Niederhausen H, Nowicki SC, Nygren DR, Obertacke Pollmann A, Olivas A, O'Murchadha A, O'Sullivan E, Palczewski T, Pandya H, Pankova DV, Peiffer P, Pepper JA, Pérez de los Heros C, Pieloth D, Pinat E, Plum M, Price PB, Przybylski GT, Raab C, Rädel L, Rameez M, Rauch L, Rawlins K, Rea IC, Reimann R, Relethford B, Relich M, Resconi E, Rhode W, Richman M, Robertson S, Rongen M, Rott C, Ruhe T, Ryckbosch D, Rysewyk D, Safa I, Sälzer T, Sanchez Herrera SE, Sandrock A, Sandroos J, Santander M, Sarkar S, Sarkar S, Satalecka K, Schlunder P, Schmidt T, Schneider A, Schoenen S, Schöneberg S, Schumacher L, Sclafani S, Seckel D, Seunarine S, Soedingrekso J, Soldin D, Song M, Spiczak GM, Spiering C, Stachurska J, Stamatikos M, Stanev T, Stasik A, Stein R, Stettner J, Steuer A, Stezelberger T, Stokstad RG, Stößl A, Strotjohann NL, Stuttard T, Sullivan GW, Sutherland M, Taboada I, Tatar J, Tenholt F, Ter-Antonyan S, Terliuk A, Tilav S, Toale PA, Tobin MN, Toennis C, Toscano S, Tosi D, Tselengidou M, Tung CF, Turcati A, Turley CF, Ty B, Unger E, Usner M, Vandenbroucke J, Van Driessche W, van Eijk D, van Eijndhoven N, Vanheule S, van Santen J, Vogel E, Vraeghe M, Walck C, Wallace A, Wallraff M, Wandler FD, Wandkowsky N, Waza A, Weaver C, Weiss MJ, Wendt C, Werthebach J, Westerhoff S, Whelan BJ, Whitehorn N, Wiebe K, Wiebusch CH, Wille L, Williams DR, Wills L, Wolf M, Wood J, Wood TR, Woschnagg K, Xu DL, Xu XW, Xu Y, Yanez JP, Yodh G, Yoshida S, Yuan T, Fermi-LAT Collaboration, Abdollahi S, Ajello M, Angioni R, Baldini L, Ballet J, Barbiellini G, Bastieri D, Bechtol K, Bellazzini R, Berenji B, Bissaldi E, Blandford RD, Bonino R, Bottacini E, Bregeon J, Bruel P, Buehler R, Burnett TH, Burns E, Buson S, Cameron RA, Caputo R, Caraveo PA, Cavazzuti E, Charles E, Chen S, Cheung CC, Chiang J, Chiaro G, Ciprini S, Cohen-Tanugi J, Conrad J, Costantin D, Cutini S, D'Ammando F, de Palma F, Digel SW, Di Lalla N, Di Mauro M, Di Venere L, Domínguez A, Favuzzi C, Franckowiak A, Fukazawa Y, Funk S, Fusco P, Gargano F, Gasparrini D, Giglietto N, Giomi M, Giommi P, Giordano F, Giroletti M, Glanzman T, Green D, Grenier IA, Grondin MH, Guiriec S, Harding AK, Hayashida M, Hays E, Hewitt JW, Horan D, Jóhannesson G, Kadler M, Kensei S, Kocevski D, Krauss F, Kreter M, Kuss M, La Mura G, Larsson S, Latronico L, Lemoine-Goumard M, Li J, Longo F, Loparco F, Lovellette MN, Lubrano P, Magill JD, Maldera S, Malyshev D, Manfreda A, Mazziotta MN, McEnery JE, Meyer M, Michelson PF, Mizuno T, Monzani ME, Morselli A, Moskalenko IV, Negro M, Nuss E, Ojha R, Omodei N, Orienti M, Orlando E, Palatiello M, Paliya VS, Perkins JS, Persic M, Pesce-Rollins M, Piron F, Porter TA, Principe G, Rainò S, Rando R, Rani B, Razzano M, Razzaque S, Reimer A, Reimer O, Renault-Tinacci N, Ritz S, Rochester LS, Saz Parkinson PM, Sgrò C, Siskind EJ, Spandre G, Spinelli P, Suson DJ, Tajima H, Takahashi M, Tanaka Y, Thayer JB, Thompson DJ, Tibaldo L, Torres DF, Torresi E, Tosti G, Troja E, Valverde J, Vianello G, Vogel M, Wood K, Wood M, Zaharijas G, MAGIC Collaboration, Ahnen ML, Ansoldi S, Antonelli LA, Arcaro C, Baack D, Babić A, Banerjee B, Bangale P, Barres de Almeida U, Barrio JA, Becerra González J, Bednarek W, Bernardini

E, Berti A, Bhattacharyya W, Biland A, Blanch O, Bonnoli G, Carosi A, Carosi R, Ceribella G, Chatterjee A, Colak SM, Colin P, Colombo E, Contreras JL, Cortina J, Covino S, Cumani P, Da Vela P, Dazzi F, De Angelis A, De Lotto B, Delfino M, Delgado J, Di Pierro F, Domínguez A, Dominis Prester D, Dorner D, Doro M, Einecke S, Elsaesser D, Fallah Ramazani V, Fernández-Barral A, Fidalgo D, Foffano L, Pfrang K, Fonseca MV, Font L, Franceschini A, Fruck C, Galindo D, Gallozzi S, García López RJ, Garczarczyk M, Gaug M, Giammaria P, Godinović N, Gora D, Guberman D, Hadasch D, Hahn A, Hassan T, Hayashida M, Herrera J, Hose J, Hrupec D, Inoue S, Ishio K, Konno Y, Kubo H, Kushida J, Lelas D, Lindfors E, Lombardi S, Longo F, López M, Maggio C, Majumdar P, Makariev M, Maneva G, Manganaro M, Mannheim K, Maraschi L, Mariotti M, Martínez M, Masuda S, Mazin D, Minev M, M JM, Mirzoyan R, Moralejo A, Moreno V, Moretti E, Nagayoshi T, Neustroev V, Niedzwiecki A, Nievas Rosillo M, Nigro C, Nilsson K, Ninci D, Nishijima K, Noda K, Nogués L, Paiano S, Palacio J, Paneque D, Paoletti R, Paredes JM, Pedaletti G, Peresano M, Persic M, Prada Moroni PG, Prandini E, Puljak I, Rodriguez Garcia J, Reichardt I, Rhode W, Ribó M, Rico J, Righi C, Rugliancich A, Saito T, Satalecka K, Schweizer T, Sitarek J, Šnidaric ´ I, Sobczynska D, Stamerra A, Strzys M, Surić T, Takahashi M, Tavecchio F, Temnikov P, Terzić T, Teshima M, Torres-Albà N, Treves A, Tsujimoto S, Vanzo G, Vazquez Acosta M, Vovk I, Ward JE, Will M, S, Zaric ´ D, AGILE Team, Lucarelli F, Tavani M, Piano G, Donnarumma I, Pittori C, Verrecchia F, Barbiellini G, Bulgarelli A, Caraveo P, Cattaneo PW, Colafrancesco S, Costa E, Di Cocco G, Ferrari A, Gianotti F, Giuliani A, Lipari P, Mereghetti S, Morselli A, Pacciani L, Paoletti F, Parmiggiani N, Pellizzoni A, Picozza P, Pilia M, Rappoldi A, Trois A, Vercellone S, Vittorini V, ASAS-SN Team, Stanek KZ, Franckowiak A, Kochanek CS, Beacom JF, Thompson TA, Holoien TWS, Dong S, Prieto JL, Shappee BJ, Holmbo S, HAWC Collaboration, Abeysekara AU, Albert A, Alfaro R, Alvarez C, Arceo R, Arteaga-Velázquez JC, Avila Rojas D, Ayala Solares HA, Becerril A, Belmont-Moreno E, Bernal A, Caballero-Mora KS, Capistrán T, Carramiñana A, Casanova S, Castillo M, Cotti U, Cotzomi J, Coutiño de León S, De León C, De la Fuente E, Diaz Hernandez R, Dichiara S, Dingus BL, DuVernois MA, Díaz-Vélez JC, Ellsworth RW, Engel K, Fiorino DW, Fleischhack H, Fraija N, García-González JA, Garfias F, González Muñoz A, González MM, Goodman JA, Hampel-Arias Z, Harding JP, Hernandez S, Hona B, Hueyotl-Zahuantitla F, Hui CM, Hüntemeyer P, Iriarte A, Jardin-Blicq A, Joshi V, Kaufmann S, Kunde GJ, Lara A, Lauer RJ, Lee WH, Lennarz D, León Vargas H, Linnemann JT, Longinotti AL, Luis-Raya G, Luna-García R, Malone K, Marinelli SS, Martinez O, Martinez-Castellanos I, Martínez-Castro J, Martínez-Huerta H, Matthews JA, Miranda-Romagnoli P, Moreno E, Mostafá M, Nayerhoda A, Nellen L, Newbold M, Nisa MU, Noriega-Papaqui R, Pelayo R, Pretz J, Pérez-Pérez EG, Ren Z, Rho CD, Rivière C, Rosa-González D, Rosenberg M, Ruiz-Velasco E, Ruiz-Velasco E, Salesa Greus F, Sandoval A, Schneider M, Schoorlemmer H, Sinnis G, Smith AJ, Springer RW, Surajbali P, Tibolla

O, Tollefson K, Torres I, Villaseñor L, Weisgarber T, Werner F, Yapici T, Gaurang Y, Zepeda A, Zhou H, Álvarez JD, H E S S Collaboration, Abdalla H, Angüner EO, Armand C, Backes M, Becherini Y, Berge D, Böttcher M, Boisson C, Bolmont J, Bonnefoy S, Bordas P, Brun F, Büchele M, Bulik T, Caroff S, Carosi A, Casanova S, Cerruti M, Chakraborty N, Chandra S, Chen A, Colafrancesco S, Davids ID, Deil C, Devin J, Djannati-Ataï A, Egberts K, Emery G, Eschbach S, Fiasson A, Fontaine G, Funk S, Füßling M, Gallant YA, Gaté F, Giavitto G, Glawion D, Glicenstein JF, Gottschall D, Grondin MH, Haupt M, Henri G, Hinton JA, Hoischen C, Holch TL, Huber D, Jamrozy M, Jankowsky D, Jankowsky F, Jouvin L, Jung-Richardt I, Kerszberg D, Khélifi B, King J, Klepser S, Kluz ´niak W, Komin N, Kraus M, Lefaucheur J, Lemière A, Lemoine-Goumard M, Lenain JP, Leser E, Lohse T, López-Coto R, Lorentz M, Lypova I, Marandon V, Guillem Martí-Devesa G, Maurin G, Mitchell AMW, Moderski R, Mohamed M, Mohrmann L, Moulin E, Murach T, de Naurois M, Niederwanger F, Niemiec J, Oakes L, O'Brien P, Ohm S, Ostrowski M, Oya I, Panter M, Parsons RD, Perennes C, Piel Q, Pita S, Poireau V, Priyana Noel A, Prokoph H, Pühlhofer G, Quirrenbach A, Raab S, Rauth R, Renaud M, Rieger F, Rinchiuso L, Romoli C, Rowell G, Rudak B, Sasaki DA, Sanchez M, Schlickeiser R, Schüssler F, Schulz A, Schwanke U, Seglar-Arroyo M, Shafi N, Simoni R, Sol H, Stegmann C, Steppa C, Tavernier T, Taylor AM, Tiziani D, Trichard C, Tsirou M, van Eldik C, van Rensburg C, van Soelen B, Veh J, Vincent P, Voisin F, Wagner SJ, Wagner RM, Wierzcholska A, Zanin R, Zdziarski AA, Zech A, Ziegler A, Zorn J, ywucka N, INTEGRAL Team, Savchenko V, Ferrigno C, Bazzano A, Diehl R, Kuulkers E, Laurent P, Mereghetti S, Natalucci L, Panessa F, Rodi J, Ubertini P, Kanata K, Teams SO, Morokuma T, Ohta K, Tanaka YT, Mori H, Yamanaka M, Kawabata KS, Utsumi Y, Nakaoka T, Kawabata M, Nagashima H, Yoshida M, Matsuoka Y, Itoh R, Kapteyn Team, Keel W, Liverpool Telescope Team, Copperwheat C, Steele I, Swift/NuSTAR Team, Cenko SB, Cowen DF, DeLaunay JJ, Evans PA, Fox DB, Keivani A, Kennea JA, Marshall FE, Osborne JP, Santander M, Tohuvavohu A, Turley CF, VERITAS Collaboration, Abeysekara AU, Archer A, Benbow W, Bird R, Brill A, Brose R, Buchovecky M, Buckley JH, Bugaev V, Christiansen JL, Connolly MP, Cui W, Daniel MK, Errando M, Falcone A, Feng Q, Finley JP, Fortson L, Furniss A, Gueta O, Hütten M, Hervet O, Hughes G, Humensky TB, Johnson CA, Kaaret P, Kar P, Kelley-Hoskins N, Kertzman M, Kieda D, Krause M, Krennrich F, Kumar S, Lang MJ, Lin TTY, Maier G, McArthur S, Moriarty P, Mukherjee R, Nieto D, O'Brien S, Ong RA, Otte AN, Park N, Petrashyk A, Pohl M, Popkow A, Pueschel SE, Quinn J, Ragan K, Reynolds PT, Richards GT, Roache E, Rulten C, Sadeh I, Santander M, Scott SS, Sembroski GH, Shahinyan K, Sushch I, Trépanier S, Tyler J, Vassiliev VV, Wakely SP, Weinstein A, Wells RM, Wilcox P, Wilhelm A, Williams DA, Zitzer B, VLA/B Team, Tetarenko AJ, Kimball AE, Miller-Jones JCA, Sivakoff GR (2018) Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. Science 361(6398):eaat1378. https:

//doi.org/10.1126/science.aat1378. arXiv:1807.08816 [astro-ph.HE]

IceCube Collaboration, Abbasi R, Ackermann M, Adams J, Aguilar JA, Ahlers M, Ahrens M, Alameddine JM, Alispach C, Alves J A A, Amin NM, Andeen K, Anderson T, Anton G, Argüelles C, Ashida Y, Axani S, Bai X, Balagopal AV, Barbano VA, Barwick SW, Bastian B, Basu V, Baur S, Bay R, Beatty JJ, Becker KH, Becker Tjus J, Bellenghi C, Benzvi S, Berley D, Bernardini E, Besson DZ, Binder G, Bindig D, Blaufuss E, Blot S, Boddenberg M, Bontempo F, Borowka J, Böser S, Botner O, Böttcher J, Bourbeau E, Bradascio F, Braun J, Brinson B, Bron S, Brostean-Kaiser J, Browne S, Burgman A, Burley RT, Busse RS, Campana MA, Carnie-Bronca EG, Chen C, Chen Z, Chirkin D, Choi K, Clark BA, Clark K, Classen L, Coleman A, Collin GH, Conrad JM, Coppin P, Correa P, Cowen DF, Cross R, Dappen C, Dave P, de Clercq C, Delaunay JJ, Delgado López D, Dembinski H, Deoskar K, Desai A, Desiati P, de Vries KD, de Wasseige G, de With M, Deyoung T, Diaz A, Díaz-Vélez JC, Dittmer M, Dujmovic H, Dunkman M, Duvernois MA, Dvorak E, Ehrhardt T, Eller P, Engel R, Erpenbeck H, Evans J, Evenson PA, Fan KL, Fazely AR, Fedynitch A, Feigl N, Fiedlschuster S, Fienberg AT, Filimonov K, Finley C, Fischer L, Fox D, Franckowiak A, Friedman E, Fritz A, Fürst P, Gaisser TK, Gallagher J, Ganster E, Garcia A, Garrappa S, Gerhardt L, Ghadimi A, Glaser C, Glauch T, Glüsenkamp T, Goldschmidt A, Gonzalez JG, Goswami S, Grant D, Grégoire T, Griswold S, Günther C, Gutjahr P, Haack C, Hallgren A, Halliday R, Halve L, Halzen F, Hanson MHMK, Hardin J, Harnisch AA, Haungs A, Hebecker D, Helbing K, Henningsen F, Hettinger EC, Hickford S, Hignight J, Hill C, Hill GC, Hoffman KD, Hoffmann R, Hokanson-Fasig B, Hoshina K, Huang F, Huber M, Huber T, Hultqvist K, Hünnefeld M, Hussain R, Hymon K, in S, Iovine N, Ishihara A, Jansson M, Japaridze GS, Jeong M, Jin M, Jones BJP, Kang D, Kang W, Kang X, Kappes A, Kappesser D, Kardum L, Karg T, Karl M, Karle A, Katz U, Kauer M, Kellermann M, Kelley JL, Kheirandish A, Kin K, Kintscher T, Kiryluk J, Klein SR, Koirala R, Kolanoski H, Kontrimas T, Köpke L, Kopper C, Kopper S, Koskinen DJ, Koundal P, Kovacevich M, Kowalski M, Kozynets T, Kun E, Kurahashi N, Lad N, Lagunas Gualda C, Lanfranchi JL, Larson MJ, Lauber F, Lazar JP, Lee JW, Leonard K, Leszczyńska A, Li Y, Lincetto M, Liu QR, Liubarska M, Lohfink E, Lozano Mariscal CJ, Lu L, Lucarelli F, Ludwig A, Luszczak W, Lyu Y, Ma WY, Madsen J, Mahn KBM, Makino Y, Mancina S, Mariş IC, Martinez-Soler I, Maruyama R, Mase K, McElroy T, McNally F, Mead JV, Meagher K, Mechbal S, Medina A, Meier M, Meighen-Berger S, Micallef J, Mockler D, Montaruli T, Moore RW, Morse R, Moulai M, Naab R, Nagai R, Nahnhauer R, Naumann U, Necker J, Nguyen LV, Niederhausen H, Nisa MU, Nowicki SC, Nygren D, Obertack A, Pollmann E, Oehler M, Oeyen B, Olivas A, O'Sullivan E, Pandya H, Pankova DV, Park N, Parker GK, Paudel EN, Paul L, Pérez de Los Heros C, Peters L, Peterson J, Philippen S, Pieper S, Pittermann M, Pizzuto A, Plum M, Popovych Y, Porcelli A, Prado Rodriguez M, Price PB, Pries B, Przybylski GT, Rack-Helleis CRJ, Raissi A, Rameez M, Rawlins K, Rea IC, Rehman A, Reichherzer P, Reimann R, Renzi G, Resconi

E, Reusch S, Rhode W, Richman M, Riedel B, Roberts EJ, Robertson S, Roellinghoff G, Rongen M, Rott C, Ruhe T, Ryckbosch D, Rysewyk Cantu D, Safa I, Saffer J, Sanchez Herrera SE, Sandrock A, Sandroos J, Santander M, Sarkar S, Sarkar S, Satalecka K, Schaufel M, Schieler H, Schindler S, Schmidt T, Schneider A, Schneider J, Schröder FG, Schumacher L, Schwefer G, Sclafani S, Seckel D, Seunarine S, Sharma A, Shefali S, Silva M, Skrzypek B, Smithers B, Snihur R, Soedingrekso J, Soldin D, Spannfellner C, Spiczak GM, Spiering C, Stachurska J, Stamatikos M, Stanev T, Stein R, Stettner J, Steuer A, Stezelberger T, Stokstad R, Stürwald T, Stuttard T, Sullivan GW, Taboada I, Ter-Antonyan S, Tilav S, Tischbein F, Tollefson K, Tönnis C, Toscano S, Tosi D, Trettin A, Tselengidou M, Tung CF, Turcati A, Turcotte R, Turley CF, Twagirayezu JP, Ty B, Unland Elorrieta MA, Valtonen-Mattila N, Vandenbroucke J, van Eijndhoven N, Vannerom D, van Santen J, Verpoest S, Walck C, Watson TB, Weaver C, Weigel P, Weindl A, Weiss MJ, Weldert J, Wendt C, Werthebach J, Weyrauch M, Whitehorn N, Wiebusch CH, Williams DR, Wolf M, Woschnagg K, Wrede G, Wulff J, Xu XW, Yanez JP, Yoshida S, Yu S, Yuan T, Zhangan Z, Zhelnin DP (2022) Evidence for neutrino emission from the nearby active galaxy NGC 1068. Science 378(6619):538–543. https://doi.org/10.1126/science.abg3395. arXiv:2211.09972 [astro-ph.HE]

Inayoshi K, Ichikawa K, Ho LC (2020) Universal Transition Diagram from Dormant to Actively Accreting Supermassive Black Holes. ApJ894(2):141. https://doi.org/10.3847/1538-4357/ab8569. arXiv:2001.11032 [astro-ph.GA]

Ineson J, Croston JH, Hardcastle MJ, Kraft RP, Evans DA, Jarvis M (2013) Radio-loud Active Galactic Nucleus: Is There a Link between Luminosity and Cluster Environment? ApJ770(2):136. https://doi.org/10.1088/0004-637X/770/2/136. arXiv:1305.1050 [astro-ph.CO]

Ineson J, Croston JH, Hardcastle MJ, Kraft RP, Evans DA, Jarvis M (2015) The link between accretion mode and environment in radio-loud active galaxies. MNRAS453(3):2682–2706. https://doi.org/10.1093/mnras/stv1807. arXiv:1508.01033 [astro-ph.GA]

Ishwara-Chandra CH, Taylor AR, Green DA, Stil JM, Vaccari M, Ocran EF (2020) A wide-area GMRT 610-MHz survey of ELAIS N1 field. MNRAS497(4):5383–5394. https://doi.org/10.1093/mnras/staa2341. arXiv:2008.02530

Jackson N, Rawlings S (1997) [O III] 500.7 spectroscopy of 3C galaxies and quasars at redshift z¿1. MNRAS 286:241–256

Jacobsen IB, Wu K, On AYL, Saxton CJ (2015) High-energy neutrino fluxes from AGN populations inferred from X-ray surveys. MNRAS451(4):3649–3663. https://doi.org/10.1093/mnras/stv1196. arXiv:1506.05916 [astro-ph.HE]

Jarvis ME, Harrison CM, Thomson AP, Circosta C, Mainieri V, Alexander DM, Edge AC, Lansbury GB, Molyneux SJ, Mullaney JR (2019) Prevalence of radio jets associated with galactic outflows and feedback from quasars. MNRAS485(2):2710–2730. https://doi.org/10.1093/mnras/stz556.

arXiv:1902.07727 [astro-ph.GA]

Jarvis ME, Harrison CM, Mainieri V, Alexander DM, Arrigoni Battaia F, Calistro Rivera G, Circosta C, Costa T, De Breuck C, Edge AC, Girdhar A, Kakkad D, Kharb P, Lansbury GB, Molyneux SJ, Mukherjee D, Mullaney JR, Farina EP, Silpa S, Thomson AP, Ward SR (2021) The quasar feedback survey: discovering hidden Radio-AGN and their connection to the host galaxy ionized gas. MNRAS503(2):1780–1797. https://doi.org/10.1093/mnras/stab549. arXiv:2103.00014 [astro-ph.GA]

Jimenez-Gallardo A, Massaro F, Capetti A, Prieto MA, Paggi A, Baldi RD, Grossova R, Ostorero L, Siemiginowska A, Viada S (2019) COMP2CAT: hunting compact double radio sources in the local Universe. A&A627:A108. https://doi.org/10.1051/0004-6361/201935104. arXiv:1905.02212 [astro-ph.HE]

Jones DH, Read MA, Saunders W, Colless M, Jarrett T, Parker QA, Fairall AP, Mauch T, Sadler EM, Watson FG, Burton D, Campbell LA, Cass P, Croom SM, Dawe J, Fiegert K, Frankcombe L, Hartley M, Huchra J, James D, Kirby E, Lahav O, Lucey J, Mamon GA, Moore L, Peterson BA, Prior S, Proust D, Russell K, Safouris V, Wakamatsu KI, Westra E, Williams M (2009) The 6dF Galaxy Survey: final redshift release (DR3) and southern large-scale structures. MNRAS399(2):683–698. https://doi.org/10.1111/j.1365-2966.2009.15338.x. arXiv:0903.5451 [astro-ph.CO]

Kaiser CR, Best PN (2007) Luminosity function, sizes and FR dichotomy of radio-loud AGN. MNRAS381(4):1548–1560. https://doi.org/10.1111/j.1365-2966.2007.12350.x. arXiv:0708.3733 [astro-ph]

Kaiser CR, Dennett-Thorpe J, Alexander P (1997) Evolutionary tracks of FRII sources through the P-D diagram. MNRAS292(3):723–732. https://doi.org/10.1093/mnras/292.3.723. arXiv:astro-ph/9710104 [astro-ph]

Kapinska AD, Hardcastle M, Jackson C, An T, Baan W, Jarvis M (2015) Unravelling lifecycles and physics of radio-loud AGN in the SKA Era. In: Advancing Astrophysics with the Square Kilometre Array (AASKA14). p 173. https://doi.org/10.22323/1.215.0173. arXiv:1412.5884 [astro-ph.GA]

Kaviraj S, Shabala SS, Deller AT, Middelberg E (2015) Radio AGN in spiral galaxies. MNRAS454(2):1595–1604. https://doi.org/10.1093/mnras/stv1957. arXiv:1412.5602 [astro-ph.GA]

Kellermann KI (1980) Radio galaxies and quasars. In: Ninth Texas Symposium on Relativistic Astrophysics. vol 336. pp 1–11. https://doi.org/10.1111/j.1749-6632.1980.tb15914.x

Kellermann KI, Pauliny-Toth IIK (1981) Compact radio sources. ARA&A19:373–410. https://doi.org/10.1146/annurev.aa.19.090181.002105

Kellermann KI, Sramek R, Schmidt M, Shaffer DB, Green R (1989a) VLA Observations of Objects in the Palomar Bright Quasar Survey. AJ98:1195. https://doi.org/10.1086/115207

Kellermann KI, Sramek R, Schmidt M, Shaffer DB, Green R (1989b) VLA observations of objects in the Palomar Bright Quasar Survey. AJ98:1195–1207. https://doi.org/10.1086/115207

Kewley LJ, Groves B, Kauffmann G, Heckman T (2006) The host galaxies and classification of active galactic nuclei. MNRAS 372:961–976. https://doi.org/10.1111/j.1365-2966.2006.10859.x. arXiv:astro-ph/0605681

Kharb P, Silpa S (2023) Looking for signatures of agn feedback in radio-quiet agn. Galaxies 11(1). https://doi.org/10.3390/galaxies11010027, URL https://www.mdpi.com/2075-4434/11/1/27

Kharb P, Capetti A, Axon DJ, Chiaberge M, Grandi P, Robinson A, Giovannini G, Balmaverde B, Macchetto D, Montez R (2012) Examining the Radio-loud/Radio-quiet Dichotomy with New Chandra and VLA Observations of 13 UGC Galaxies. AJ143:78. https://doi.org/10.1088/0004-6256/143/4/78. arXiv:1201.4175

Kim M, Ho LC, Peng CY, Barth AJ, Im M (2017) Stellar Photometric Structures of the Host Galaxies of Nearby Type 1 Active Galactic Nuclei. ApJS232(2):21. https://doi.org/10.3847/1538-4365/aa8a75. arXiv:1710.02194 [astro-ph.GA]

Knowles K, Cotton WD, Rudnick L, Camilo F, Goedhart S, Deane R, Ramatsoku M, Bietenholz MF, Brüggen M, Button C, Chen H, Chibueze JO, Clarke TE, de Gasperin F, Ianjamasimanana R, Józsa GIG, Hilton M, Kesebonye KC, Kolokythas K, Kraan-Korteweg RC, Lawrie G, Lochner M, Loubser SI, Marchegiani P, Mhlahlo N, Moodley K, Murphy E, Namumba B, Oozeer N, Parekh V, Pillay DS, Passmoor SS, Ramaila AJT, Ranchod S, Retana-Montenegro E, Sebokolodi L, Sikhosana SP, Smirnov O, Thorat K, Venturi T, Abbott TD, Adam RM, Adams G, Aldera MA, Bauermeister EF, Bennett TGH, Bode WA, Botha DH, Botha AG, Brederode LRS, Buchner S, Burger JP, Cheetham T, de Villiers DIL, Dikgale-Mahlakoana MA, du Toit LJ, Esterhuyse SWP, Fadana G, Fanaroff BL, Fataar S, Foley AR, Fourie DJ, Frank BS, Gamatham RRG, Gatsi TG, Geyer M, Gouws M, Gumede SC, Heywood I, Hlakola MJ, Hokwana A, Hoosen SW, Horn DM, Horrell JMG, Hugo BV, Isaacson AR, Jonas JL, Jordaan JDB, Joubert AF, Julie RPM, Kapp FB, Kasper VA, Kenyon JS, Kotzé PPA, Kotze AG, Kriek N, Kriel H, Krishnan VK, Kusel TW, Legodi LS, Lehmensiek R, Liebenberg D, Lord RT, Lunsky BM, Madisa K, Magnus LG, Main JPL, Makhaba A, Makhathini S, Malan JA, Manley JR, Marais SJ, Maree MDJ, Martens A, Mauch T, McAlpine K, Merry BC, Millenaar RP, Mokone OJ, Monama TE, Mphego MC, New WS, Ngcebetsha B, Ngoasheng KJ, Ockards MT, Otto AJ, Patel AA, Peens-Hough A, Perkins SJ, Ramanujam NM, Ramudzuli ZR, Ratcliffe SM, Renil R, Robyntjies A, Rust AN, Salie S, Sambu N, Schollar CTG, Schwardt LC, Schwartz RL, Serylak M, Siebrits R, Sirothia SK, Slabber M, Sofeya L, Taljaard B, Tasse C, Tiplady AJ, Toruvanda O, Twum SN, van Balla TJ, van der Byl A, van der Merwe C, van Dyk CL, Van Tonder V, Van Wyk R, Venter AJ, Venter M, Welz MG, Williams LP, Xaia B (2022) The MeerKAT Galaxy Cluster Legacy Survey. I. Survey Overview and Highlights. A&A657:A56. https://doi.org/10.1051/0004-6361/202141488. arXiv:2111.05673 [astro-ph.GA]

Komissarov SS (1990) Emission by Relativistic Jets with Boundary Layers. Soviet Astronomy Letters 16:284

Komissarov SS (2001) Direct numerical simulations of the Blandford-Znajek effect. MNRAS326(3):L41–L44. https://doi.org/10.1046/j.1365-8711.2001.04863.x

Kormendy J, Ho LC (2013) Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. ARA&A51:511–653. https://doi.org/10.1146/annurev-astro-082708-101811. arXiv:1304.7762

Kotilainen JK, León-Tavares J, Olguín-Iglesias A, Baes M, Anórve C, Chavushyan V, Carrasco L (2016) Discovery of a Pseudobulge Galaxy Launching Powerful Relativistic Jets. ApJ832(2):157. https://doi.org/10.3847/0004-637X/832/2/157. arXiv:1609.02417 [astro-ph.GA]

Kozieł-Wierzbowska D, Goyal A, ywucka N (2020) Radio Sources Associated with Optical Galaxies and Having Unresolved or Extended Morphologies (ROGUE). I. A Catalog of SDSS Galaxies with FIRST Core Identifications. ApJS247(2):53. https://doi.org/10.3847/1538-4365/ab63d3. arXiv:1912.09959 [astro-ph.GA]

Kratzer RM, Richards GT (2015) Mean and Extreme Radio Properties of Quasars and the Origin of Radio Emission. AJ149(2):61. https://doi.org/10.1088/0004-6256/149/2/61. arXiv:1405.2344 [astro-ph.GA]

Kuncic Z, Bicknell GV (2004) Dynamics and Energetics of Turbulent, Magnetized Disk Accretion around Black Holes: A First-Principles Approach to Disk-Corona-Outflow Coupling. ApJ616(2):669–687. https://doi.org/10.1086/425032. arXiv:astro-ph/0402421 [astro-ph]

Kuncic Z, Bicknell GV (2007) Towards a new standard model for black hole accretion. Ap&SS311(1-3):127–135. https://doi.org/10.1007/s10509-007-9522-8. arXiv:0705.0791 [astro-ph]

Kunert M, Marecki A, Spencer RE, Kus AJ, Niezgoda J (2002) FIRST-based survey of Compact Steep Spectrum sources. I. MERLIN images of arcsecond scale objects. A&A391:47–54. https://doi.org/10.1051/0004-6361:20020532. arXiv:astro-ph/0112511 [astro-ph]

Kunert-Bajraszewska M (2016) Dichotomy in the population of young AGN: Optical, radio, and X-ray properties. Astronomische Nachrichten 337(1-2):27. https://doi.org/10.1002/asna.201512259. arXiv:1510.09061 [astro-ph.GA]

Kunert-Bajraszewska M, Marecki A, Thomasson P, Spencer RE (2005) FIRST-based survey of Compact Steep Spectrum sources. II. MERLIN and VLA observations of medium-sized symmetric objects. A&A440:93–105. https://doi.org/10.1051/0004-6361:20042496. astro-ph/0505435

Kunert-Bajraszewska M, Marecki A, Thomasson P (2006) FIRST-based survey of compact steep spectrum sources. IV. Multifrequency VLBA observations of very compact objects. A&A450:945–958. https://doi.org/10.1051/0004-6361:20054428. astro-ph/0601288

Kunert-Bajraszewska M, Gawroński MP, Labiano A, Siemiginowska A (2010) A survey of low-luminosity compact sources and its implication for the evolution of radio-loud active galactic nuclei - I. Radio data. MNRAS408:2261–2278. https://doi.org/10.1111/j.1365-2966.2010.17271.x. arXiv:1009.5235 [astro-ph.CO]

Kunert-Bajraszewska M, Labiano A, Gawronski MP (2011) Emission line - radio correlation for Low Luminosity Compact sources. Evolution schemes. arXiv e-prints arXiv:1106.5918. https://doi.org/10.48550/arXiv.1106.5918. arXiv:1106.5918 [astro-ph.CO]

Lacy M, Baum SA, Chandler CJ, Chatterjee S, Clarke TE, Deustua S, English J, Farnes J, Gaensler BM, Gugliucci N, Hallinan G, Kent BR, Kimball A, Law CJ, Lazio TJW, Marvil J, Mao SA, Medlin D, Mooley K, Murphy EJ, Myers S, Osten R, Richards GT, Rosolowsky E, Rudnick L, Schinzel F, Sivakoff GR, Sjouwerman LO, Taylor R, White RL, Wrobel J, Andernach H, Beasley AJ, Berger E, Bhatnager S, Birkinshaw M, Bower GC, Brandt WN, Brown S, Burke-Spolaor S, Butler BJ, Comerford J, Demorest PB, Fu H, Giacintucci S, Golap K, Güth T, Hales CA, Hiriart R, Hodge J, Horesh A, Ivezić Ž, Jarvis MJ, Kamble A, Kassim N, Liu X, Loinard L, Lyons DK, Masters J, Mezcua M, Moellenbrock GA, Mroczkowski T, Nyland K, O'Dea CP, O'Sullivan SP, Peters WM, Radford K, Rao U, Robnett J, Salcido J, Shen Y, Sobotka A, Witz S, Vaccari M, van Weeren RJ, Vargas A, Williams PKG, Yoon I (2020) The Karl G. Jansky Very Large Array Sky Survey (VLASS). Science Case and Survey Design. PASP132(1009):035001. https://doi.org/10.1088/1538-3873/ab63eb. arXiv:1907.01981 [astro-ph.IM]

Laing RA, Bridle AH (2014) Systematic properties of decelerating relativistic jets in low-luminosity radio galaxies. MNRAS437:3405–3441. https://doi.org/10.1093/mnras/stt2138. arXiv:1311.1015

Laing RA, Jenkins CR, Wall JV, Unger SW (1994) Spectrophotometry of a Complete Sample of 3CR Radio Sources: Implications for Unified Models. In: Bicknell GV, Dopita MA, Quinn PJ (eds) The Physics of Active Galaxies. Astronomical Society of the Pacific Conference Series, vol 54. p 201

Lal DV, Legodi P, Fanaroff B, Venturi T, Smirnov OM, Bondi M, Thorat K, Bester LH, Józsa GIG, Kleiner D, Loi F, Makhathini S, White SV (2021) Viewing Classical Radio Galaxies with the Upgraded GMRT and MeerKAT—A Progress Report. Galaxies 9(4):87. https://doi.org/10.3390/galaxies9040087

Laor A (2000) On Black Hole Masses and Radio Loudness in Active Galactic Nuclei. ApJ543:L111–L114. https://doi.org/10.1086/317280. astro-ph/0009192

Ledlow MJ, Owen FN (1996) 20 CM VLA Survey of Abell Clusters of Galaxies. VI. Radio/Optical Luminosity Functions. AJ112:9–+

Leipski C, Antonucci R, Ogle P, Whysong D (2009) The Spitzer View of FR I Radio Galaxies: On the Origin of the Nuclear Mid-Infrared Continuum. ApJ701(2):891–914. https://doi.org/10.1088/0004-637X/701/2/891. arXiv:0906.2152 [astro-ph.CO]

Lin YT, Shen Y, Strauss MA, Richards GT, Lunnan R (2010) On the Populations of Radio Galaxies with Extended Morphology at z 0.3. ApJ723:1119–1138. https://doi.org/10.1088/0004-637X/723/2/1119. arXiv:1006.5452

Liska MTP, Musoke G, Tchekhovskoy A, Porth O, Beloborodov AM (2022) Formation of Magnetically Truncated Accretion Disks in 3D Radiation-transport Two-temperature GRMHD Simulations. ApJ935(1):L1. https:

//doi.org/10.3847/2041-8213/ac84db. arXiv:2201.03526 [astro-ph.HE]

Liuzzo E, Giovannini G, Giroletti M, Taylor GB (2009) The Bologna complete sample of nearby radio sources. II. Phase referenced observations of faint nuclear sources. A&A505(2):509–520. https://doi.org/10.1051/0004-6361/200912586. arXiv:0908.4391 [astro-ph.CO]

Liuzzo E, Giroletti M, Giovannini G, Boccardi B, Tamburri S, Taylor GB, Casadio C, Kadler M, Tosti G, Mignano A (2013) Exploring the bulk of the BL Lacertae object population. I. Parsec-scale radio structures. A&A560:A23. https://doi.org/10.1051/0004-6361/201322144. arXiv:1309.2774 [astro-ph.HE]

Lobanov A (2006) Compact radio jets and nuclear regions in active galaxies. In: Baan W, Bachiller R, Booth R, Charlot P, Diamond P, Garrett M, Hong X, Jonas J, Kus A, Mantovani F, Marecki A, Olofsson H, Schlueter W, Tornikoski M, Wang N, Zensus A (eds) Proceedings of the 8th European VLBI Network Symposium. p 3

Lovelace RVE, Li H, Koldoba AV, Ustyugova GV, Romanova MM (2002) Poynting Jets from Accretion Disks. ApJ572(1):445–455. https://doi.org/10.1086/340292. arXiv:astro-ph/0210571 [astro-ph]

Macconi D, Torresi E, Grandi P, Boccardi B, Vignali C (2020) Radio morphology-accretion mode link in Fanaroff-Riley type II low-excitation radio galaxies. MNRAS493(3):4355–4366. https://doi.org/10.1093/mnras/staa560. arXiv:2002.09360 [astro-ph.HE]

Macfarlane C, Best PN, Sabater J, Gürkan G, Jarvis MJ, Röttgering HJA, Baldi RD, Calistro Rivera G, Duncan KJ, Morabito LK, Prandoni I, Retana-Montenegro E (2021) The radio loudness of SDSS quasars from the LOFAR Two-metre Sky Survey: ubiquitous jet activity and constraints on star formation. MNRAS506(4):5888–5907. https://doi.org/10.1093/mnras/stab1998. arXiv:2107.09141 [astro-ph.GA]

Mao MY, Blanchard JM, Owen F, Sjouwerman LO, Singh V, Scaife A, Paragi Z, Norris RP, Momjian E, Johnson G, Browne I (2018) The first VLBI detection of a spiral DRAGN core. MNRAS478(1):L99–L104. https://doi.org/10.1093/mnrasl/sly081. arXiv:1805.03039 [astro-ph.GA]

Maoz D (2007) Low-luminosity active galactic nuclei: are they UV faint and radio loud? MNRAS377(4):1696–1710. https://doi.org/10.1111/j.1365-2966.2007.11735.x. arXiv:astro-ph/0702292 [astro-ph]

Maraschi L, Ghisellini G, Celotti A (1992) A Jet Model for the Gamma-Ray–emitting Blazar 3C 279. ApJ397:L5. https://doi.org/10.1086/186531

Maraschi L, Colpi M, Ghisellini G, Perego A, Tavecchio F (2012) On the role of black hole spin and accretion in powering relativistic jets in AGN. Journal of Physics Conference Series 355(1):012016. https://doi.org/10.1088/1742-6596/355/1/012016

Martínez-Sansigre A, Rawlings S (2011) Evidence for cosmic evolution in the spin of the most massive black holes. MNRAS418(1):L84–L88. https://doi.org/10.1111/j.1745-3933.2011.01148.x. arXiv:1109.0997 [astro-ph.HE]

Massardi M, Ekers RD, Murphy T, Mahony E, Hancock PJ, Chhetri R, de Zotti G, Sadler EM, Burke-Spolaor S, Calabretta M, Edwards PG, Ekers JA, Jackson CA, Kesteven MJ, Newton-McGee K, Phillips C, Ricci R, Roberts P, Sault RJ, Staveley-Smith L, Subrahmanyan R, Walker MA, Wilson WE (2011) The Australia Telescope 20 GHz (AT20G) Survey: analysis of the extragalactic source sample. MNRAS412(1):318–330. https://doi.org/10.1111/j.1365-2966.2010.17917.x. arXiv:1010.5942 [astro-ph.CO]

Massaro F, Marchesini EJ, D'Abrusco R, Masetti N, Andruchow I, Smith HA (2017) Radio-weak BL Lac Objects in the Fermi Era. ApJ834(2):113. https://doi.org/10.3847/1538-4357/834/2/113. arXiv:1701.06067 [astro-ph.HE]

Massaro F, Álvarez-Crespo N, Capetti A, Baldi RD, Pillitteri I, Campana R, Paggi A (2019) Deciphering the Large-scale Environment of Radio Galaxies in the Local Universe: Where Are They Born? Where Do They Grow? Where Do They Die? ApJS240(2):20. https://doi.org/10.3847/1538-4365/aaf1c7. arXiv:1811.11179 [astro-ph.HE]

Massaro F, Capetti A, Paggi A, Baldi RD, Tramacere A, Pillitteri I, Campana R (2020a) Dragon's Lair: On the Large-scale Environment of BL Lac Objects. ApJ900(2):L34. https://doi.org/10.3847/2041-8213/abac56. arXiv:2009.03318 [astro-ph.GA]

Massaro F, Capetti A, Paggi A, Baldi RD, Tramacere A, Pillitteri I, Campana R, Jimenez-Gallardo A, Missaglia V (2020b) Deciphering the Large-scale Environment of Radio Galaxies in the Local Universe. II. A Statistical Analysis of Environmental Properties. ApJS247(2):71. https://doi.org/10.3847/1538-4365/ab799e. arXiv:2004.02969 [astro-ph.HE]

Mauch T, Sadler EM (2007) Radio sources in the 6dFGS: local luminosity functions at 1.4GHz for star-forming galaxies and radio-loud AGN. MNRAS 375:931–950. https://doi.org/10.1111/j.1365-2966.2006.11353.x. arXiv:astro-ph/0612018

Mauch T, Cotton WD, Condon JJ, Matthews AM, Abbott TD, Adam RM, Aldera MA, Asad KMB, Bauermeister EF, Bennett TGH, Bester H, Botha DH, Brederode LRS, Brits ZB, Buchner SJ, Burger JP, Camilo F, Chalmers JM, Cheetham T, de Villiers D, de Villiers MS, Dikgale-Mahlakoana MA, du Toit LJ, Esterhuyse SWP, Fadana G, Fanaroff BL, Fataar S, February S, Frank BS, Gamatham RRG, Geyer M, Goedhart S, Gounden S, Gumede SC, Heywood I, Hlakola MJ, Horrell JMG, Hugo B, Isaacson AR, Józsa GIG, Jonas JL, Julie RPM, Kapp FB, Kasper VA, Kenyon JS, Kotzé PPA, Kriek N, Kriel H, Kusel TW, Lehmensiek R, Loots A, Lord RT, Lunsky BM, Madisa K, Magnus LG, Main JPL, Malan JA, Manley JR, Marais SJ, Martens A, Merry B, Millenaar R, Mnyandu N, Moeng IPT, Mokone OJ, Monama TE, Mphego MC, New WS, Ngcebetsha B, Ngoasheng KJ, Ockards MTO, Oozeer N, Otto AJ, Patel AA, Peens-Hough A, Perkins SJ, Ramaila AJT, Ramudzuli ZR, Renil R, Richter LL, Robyntjies A, Salie S, Schollar CTG, Schwardt LC, Serylak M, Siebrits R, Sirothia SK, Smirnov OM, Sofeya L, Stone G, Taljaard B, Tasse C, Theron IP, Tiplady AJ, Toruvanda O, Twum SN, van Balla TJ, van der Byl A, van der Merwe C, Van Tonder V, Wallace BH, Welz MG, Williams LP, Xaia B (2020) The 1.28 GHz MeerKAT DEEP2 Image. ApJ888(2):61. https://doi.org/10.3847/1538-4357/ab5d2d.

arXiv:1912.06212 [astro-ph.GA]

Mbarek R, Caprioli D (2021) Espresso and Stochastic Acceleration of Ultra-high-energy Cosmic Rays in Relativistic Jets. ApJ921(1):85. https://doi.org/10.3847/1538-4357/ac1da8. arXiv:2105.05262 [astro-ph.HE]

McConnell NJ, Ma CP (2013) Revisiting the Scaling Relations of Black Hole Masses and Host Galaxy Properties. ApJ764(2):184. https://doi.org/10.1088/0004-637X/764/2/184. arXiv:1211.2816 [astro-ph.CO]

McKinney JC (2006) General relativistic magnetohydrodynamic simulations of the jet formation and large-scale propagation from black hole accretion systems. MNRAS368(4):1561–1582. https://doi.org/10.1111/j.1365-2966.2006.10256.x. arXiv:astro-ph/0603045 [astro-ph]

McKinney JC, Gammie CF (2004) A Measurement of the Electromagnetic Luminosity of a Kerr Black Hole. ApJ611(2):977–995. https://doi.org/10.1086/422244. arXiv:astro-ph/0404512 [astro-ph]

McKinney JC, Tchekhovskoy A, Blandford RD (2012) General relativistic magnetohydrodynamic simulations of magnetically choked accretion flows around black holes. MNRAS423(4):3083–3117. https://doi.org/10.1111/j.1365-2966.2012.21074.x. arXiv:1201.4163 [astro-ph.HE]

McNamara BR, Nulsen PEJ (2007) Heating Hot Atmospheres with Active Galactic Nuclei. ARA&A45(1):117–175. https://doi.org/10.1146/annurev.astro.45.051806.110625. arXiv:0709.2152 [astro-ph]

McNamara BR, Nulsen PEJ (2012) Mechanical feedback from active galactic nuclei in galaxies, groups and clusters. New Journal of Physics 14(5):055023. https://doi.org/10.1088/1367-2630/14/5/055023. arXiv:1204.0006 [astro-ph.CO]

Meier DL (1999) A Magnetically Switched, Rotating Black Hole Model for the Production of Extragalactic Radio Jets and the Fanaroff and Riley Class Division. ApJ522(2):753–766. https://doi.org/10.1086/307671. arXiv:astro-ph/9810352 [astro-ph]

Meier DL (2001) The Association of Jet Production with Geometrically Thick Accretion Flows and Black Hole Rotation. ApJ548:L9–L12. https://doi.org/10.1086/318921. astro-ph/0010231

Meier DL, Koide S, Uchida Y (2001) Magnetohydrodynamic Production of Relativistic Jets. Science 291(5501):84–92. https://doi.org/10.1126/science.291.5501.84

Merten L, Boughelilba M, Reimer A, Da Vela P, Vorobiov S, Tavecchio F, Bonnoli G, Lundquist JP, Righi C (2022) FR-0 jetted active galaxies: extending the zoo of candidate sites for UHECR acceleration. In: 37th International Cosmic Ray Conference. 12-23 July 2021. Berlin. p 986. arXiv:2107.13278 [astro-ph.HE]

Mezcua M, Prieto MA (2014) Evidence of Parsec-scale Jets in Low-luminosity Active Galactic Nuclei. ApJ787(1):62. https://doi.org/10.1088/0004-637X/787/1/62. arXiv:1403.6675 [astro-ph.GA]

Mikhailov A, Sotnikova Y (2021a) The relationship between FR0 radio galaxies and gigahertz-peaked spectrum sources. Astronomische Nachrichten 342(1130):1130–1134. https://doi.org/10.1002/asna.20210050.

arXiv:2111.06141 [astro-ph.GA]

Mikhailov AG, Sotnikova YV (2021b) Radio Properties of FR0 Galaxies According to Multifrequency Measurements with RATAN-600. Astronomy Reports 65(4):233–245. https://doi.org/10.1134/S1063772921040028

Miley G (1980) The structure of extended extragalactic radio sources. ARA&A18:165–218. https://doi.org/10.1146/annurev.aa.18.090180.001121

Mingo B, Hardcastle MJ, Croston JH, Dicken D, Evans DA, Morganti R, Tadhunter C (2014) An X-ray survey of the 2 Jy sample - I. Is there an accretion mode dichotomy in radio-loud AGN? MNRAS440(1):269–297. https://doi.org/10.1093/mnras/stu263. arXiv:1402.1770 [astro-ph.GA]

Mingo B, Croston JH, Hardcastle MJ, Best PN, Duncan KJ, Morganti R, Rottgering HJA, Sabater J, Shimwell TW, Williams WL, Brienza M, Gurkan G, Mahatma VH, Morabito LK, Prandoni I, Bondi M, Ineson J, Mooney S (2019) Revisiting the Fanaroff-Riley dichotomy and radio-galaxy morphology with the LOFAR Two-Metre Sky Survey (LoTSS). MNRAS488(2):2701–2721. https://doi.org/10.1093/mnras/stz1901. arXiv:1907.03726 [astro-ph.GA]

Mingo B, Croston JH, Best PN, Duncan KJ, Hardcastle MJ, Kondapally R, Prandoni I, Sabater J, Shimwell TW, Williams WL, Baldi RD, Bonato M, Bondi M, Dabhade P, Gürkan G, Ineson J, Magliocchetti M, Miley G, Pierce JCS, Röttgering HJA (2022) Accretion mode versus radio morphology in the LOFAR Deep Fields. MNRAS511(3):3250–3271. https://doi.org/10.1093/mnras/stac140. arXiv:2201.04433 [astro-ph.GA]

Miraghaei H, Best PN (2017) The nuclear properties and extended morphologies of powerful radio galaxies: the roles of host galaxy and environment. MNRAS466(4):4346–4363. https://doi.org/10.1093/mnras/stx007. arXiv:1701.00919 [astro-ph.GA]

Morabito LK, Jackson NJ, Mooney S, Sweijen F, Badole S, Kukreti P, Venkattu D, Groeneveld C, Kappes A, Bonnassieux E, Drabent A, Iacobelli M, Croston JH, Best PN, Bondi M, Callingham JR, Conway JE, Deller AT, Hardcastle MJ, McKean JP, Miley GK, Moldon J, Röttgering HJA, Tasse C, Shimwell TW, van Weeren RJ, Anderson JM, Asgekar A, Avruch IM, van Bemmel IM, Bentum MJ, Bonafede A, Brouw WN, Butcher HR, Ciardi B, Corstanje A, Coolen A, Damstra S, de Gasperin F, Duscha S, Eislöffel J, Engels D, Falcke H, Garrett MA, Griessmeier J, Gunst AW, van Haarlem MP, Hoeft M, van der Horst AJ, Jütte E, Kadler M, Koopmans LVE, Krankowski A, Mann G, Nelles A, Oonk JBR, Orru E, Paas H, Pandey VN, Pizzo RF, Pandey-Pommier M, Reich W, Rothkaehl H, Ruiter M, Schwarz DJ, Shulevski A, Soida M, Tagger M, Vocks C, Wijers RAMJ, Wijnholds SJ, Wucknitz O, Zarka P, Zucca P (2022a) Sub-arcsecond imaging with the International LOFAR Telescope. I. Foundational calibration strategy and pipeline. A&A658:A1. https://doi.org/10.1051/0004-6361/202140649. arXiv:2108.07283 [astro-ph.IM]

Morabito LK, Sweijen F, Radcliffe JF, Best PN, Kondapally R, Bondi M, Bonato M, Duncan KJ, Prandoni I, Shimwell TW, Williams WL, van Weeren RJ, Conway JE, Rivera GC (2022b) Identifying active galactic nuclei via brightness temperature with sub-arcsecond International LOFAR Telescope observations. MNRAShttps://doi.org/10.1093/mnras/stac2129. arXiv:2207.13096 [astro-ph.GA]

Morganti R (2017) The many routes to AGN feedback. Frontiers in Astronomy and Space Sciences 4:42. https://doi.org/10.3389/fspas.2017.00042. arXiv:1712.05301 [astro-ph.GA]

Morganti R, Oosterloo TA, Reynolds JE, Tadhunter CN, Migenes V (1997) A study of cores in a complete sample of radio sources. MNRAS284(3):541–551. https://doi.org/10.1093/mnras/284.3.541

Morganti R, Schulz R, Nyland K, Paragi Z, Oosterloo T, Mahony E, Murthy S (2019) The parsec-scale structure of jet-driven HI outflows in radio galaxies. arXiv e-prints arXiv:1901.01446. arXiv:1901.01446 [astro-ph.GA]

Morganti R, Jurlin N, Oosterloo T, Brienza M, Orrú E, Kutkin A, Prandoni I, Adams EAK, Dénes H, Hess KM, Shulevski A, van der Hulst T, Ziemke J (2021) Combining LOFAR and Apertif Data for Understanding the Life Cycle of Radio Galaxies. Galaxies 9(4):88. https://doi.org/10.3390/galaxies9040088. arXiv:2111.04776 [astro-ph.GA]

Morganti R, Oosterloo T, Murthy S, Tadhunter C (2022) The impact of young radio jets traced by cold molecular gas. arXiv e-prints arXiv:2201.04157. arXiv:2201.04157 [astro-ph.GA]

Mukherjee D, Bicknell GV, Sutherland R, Wagner A (2016) Relativistic jet feedback in high-redshift galaxies - I. Dynamics. MNRAS461(1):967–983. https://doi.org/10.1093/mnras/stw1368. arXiv:1606.01143 [astro-ph.HE]

Mukherjee D, Bicknell GV, Wagner AY, Sutherland RS, Silk J (2018) Relativistic jet feedback - III. Feedback on gas discs. MNRAS479(4):5544–5566. https://doi.org/10.1093/mnras/sty1776. arXiv:1803.08305 [astro-ph.HE]

Müller-Sánchez F, Prieto MA, Mezcua M, Davies RI, Malkan MA, Elitzur M (2013) The Central Molecular Gas Structure in LINERs with Low-luminosity Active Galactic Nuclei: Evidence for Gradual Disappearance of the Torus. ApJ763(1):L1. https://doi.org/10.1088/2041-8205/763/1/L1. arXiv:1212.1162 [astro-ph.CO]

Murthy S, Morganti R, Wagner AY, Oosterloo T, Guillard P, Mukherjee D, Bicknell G (2022) Cold gas removal from the centre of a galaxy by a low-luminosity jet. Nature Astronomy 6:488–495. https://doi.org/10.1038/s41550-021-01596-6. arXiv:2202.05222 [astro-ph.GA]

Nagar NM, Falcke H, Wilson AS, Ho LC (2000) Radio Sources in Low-Luminosity Active Galactic Nuclei. I. VLA Detections of Compact, Flat-Spectrum Cores. ApJ542:186–196. https://doi.org/10.1086/309524

Nagar NM, Falcke H, Wilson AS, Ho LC (2002a) 'Radio-loud' low luminosity AGN. New A Rev.46(2-7):225–229. https://doi.org/10.1016/S1387-6473(01)00185-3

Nagar NM, Falcke H, Wilson AS, Ulvestad JS (2002b) Radio sources in low-luminosity active galactic nuclei. III. "AGNs" in a distance-limited sample of "LLAGNs". A&A392:53–82. https://doi.org/10.1051/0004-6361:20020874. arXiv:astro-ph/0207176 [astro-ph]

Nagar NM, Falcke H, Wilson AS (2005) Radio sources in low-luminosity active galactic nuclei. IV. Radio luminosity function, importance of jet power, and radio properties of the complete Palomar sample. A&A435:521–543. https://doi.org/10.1051/0004-6361:20042277. arXiv:astro-ph/0502551

Nakamura M, Uchida Y, Hirose S (2001) Production of wiggled structure of AGN radio jets in the sweeping magnetic twist mechanism. New A6(2):61–78. https://doi.org/10.1016/S1384-1076(01)00041-0

Narayan R, McClintock JE (2012) Observational evidence for a correlation between jet power and black hole spin. MNRAS419(1):L69–L73. https://doi.org/10.1111/j.1745-3933.2011.01181.x. arXiv:1112.0569 [astro-ph.HE]

Narayan R, Yi I (1994a) Advection-dominated accretion: A self-similar solution. ApJ428:L13–L16. https://doi.org/10.1086/187381. astro-ph/9403052

Narayan R, Yi I (1994b) Advection-dominated Accretion: A Self-similar Solution. ApJ428:L13. https://doi.org/10.1086/187381. arXiv:astro-ph/9403052 [astro-ph]

Narayan R, Yi I (1995) Advection-dominated accretion: Self-similarity and bipolar outflows. ApJ444:231–243

Narayan R, Igumenshchev IV, Abramowicz MA (2000) Self-similar Accretion Flows with Convection. ApJ539:798–808

Narayan R, Igumenshchev IV, Abramowicz MA (2003) Magnetically Arrested Disk: an Energetically Efficient Accretion Flow. PASJ55:L69–L72. https://doi.org/10.1093/pasj/55.6.L69. arXiv:astro-ph/0305029 [astro-ph]

Narayan R, SÄ dowski A, Penna RF, Kulkarni AK (2012) GRMHD simulations of magnetized advection-dominated accretion on a non-spinning black hole: role of outflows. MNRAS426(4):3241–3259. https://doi.org/10.1111/j.1365-2966.2012.22002.x. arXiv:1206.1213 [astro-ph.HE]

Netzer H (2015) Revisiting the Unified Model of Active Galactic Nuclei. ARA&A53:365–408. https://doi.org/10.1146/annurev-astro-082214-122302. arXiv:1505.00811 [astro-ph.GA]

Norris RP, Hopkins AM, Afonso J, Brown S, Condon JJ, Dunne L, Feain I, Hollow R, Jarvis M, Johnston-Hollitt M, Lenc E, Middelberg E, Padovani P, Prandoni I, Rudnick L, Seymour N, Umana G, Andernach H, Alexander DM, Appleton PN, Bacon D, Banfield J, Becker W, Brown MJI, Ciliegi P, Jackson C, Eales S, Edge AC, Gaensler BM, Giovannini G, Hales CA, Hancock P, Huynh MT, Ibar E, Ivison RJ, Kennicutt R, Kimball AE, Koekemoer AM, Koribalski BS, López-Sánchez ÁR, Mao MY, Murphy T, Messias H, Pimbblet KA, Raccanelli A, Randall KE, Reiprich TH, Roseboom IG, Röttgering H, Saikia DJ, Sharp RG, Slee OB, Smail I, Thompson MA, Urquhart JS, Wall JV, Zhao GB (2011) EMU: Evolutionary Map of the Universe. PASA28(3):215–248. https://doi.org/10.1071/AS11021. arXiv:1106.3219 [astro-ph.CO]

Nyland K, Alatalo K, Wrobel JM, Young LM, Morganti R, Davis TA, de Zeeuw PT, Deustua S, Bureau M (2013) Detection of a High Brightness Temperature Radio Core in the Active-galactic-nucleus-driven Molecular Outflow Candidate NGC 1266. ApJ779(2):173. https://doi.org/10.1088/0004-637X/779/2/173. arXiv:1310.7588 [astro-ph.CO]

Nyland K, Young LM, Wrobel JM, Sarzi M, Morganti R, Alatalo K, Blitz L, Bournaud F, Bureau M, Cappellari M, Crocker AF, Davies RL, Davis TA, de Zeeuw PT, Duc PA, Emsellem E, Khochfar S, Krajnović D, Kuntschner H, McDermid RM, Naab T, Oosterloo T, Scott N, Serra P, Weijmans AM (2016) The ATLAS^{3D} Project - XXXI. Nuclear radio emission in nearby early-type galaxies. MNRAS458:2221–2268. https://doi.org/10.1093/mnras/stw391. arXiv:1602.05579

Nyland K, Harwood JJ, Mukherjee D, Jagannathan P, Rujopakarn W, Emonts B, Alatalo K, Bicknell GV, Davis TA, Greene JE, Kimball A, Lacy M, Lonsdale C, Lonsdale C, Maksym WP, Molnár DC, Morabito L, Murphy EJ, Patil P, Prandoni I, Sargent M, Vlahakis C (2018a) Revolutionizing Our Understanding of AGN Feedback and its Importance to Galaxy Evolution in the Era of the Next Generation Very Large Array. ApJ859(1):23. https://doi.org/10.3847/1538-4357/aab3d1. arXiv:1803.02357 [astro-ph.GA]

Nyland K, Mukherjee D, Lacy M, Prandoni I, Harwood JJ, Alatalo K, Bicknell G, Emonts B (2018b) Science with an ngVLA: Radio Jet-ISM Feedback on Sub-galactic Scales. arXiv e-prints arXiv:1810.07526. arXiv:1810.07526 [astro-ph.GA]

Nyland K, Dong DZ, Patil P, Lacy M, van Velzen S, Kimball AE, Sarbadhicary SK, Hallinan G, Baldassare V, Clarke TE, Goulding AD, Greene J, Hughes A, Kassim N, Kunert-Bajraszewska M, Maccarone TJ, Mooley K, Mukherjee D, Peters W, Petrov L, Polisensky E, Rujopakarn W, Whittle M, Vaccari M (2020) Quasars That Have Transitioned from Radio-quiet to Radio-loud on Decadal Timescales Revealed by VLASS and FIRST. ApJ905(1):74. https://doi.org/10.3847/1538-4357/abc341. arXiv:2011.08872 [astro-ph.GA]

Ocaña Flaquer B, Leon S, Combes F, Lim J (2010) TANGO I: Interstellar medium in nearby radio galaxies. Molecular gas. A&A518:A9. https://doi.org/10.1051/0004-6361/200913392. arXiv:1001.5009 [astro-ph.CO]

O'Dea CP (1998) The Compact Steep-Spectrum and Gigahertz Peaked-Spectrum Radio Sources. PASP110(747):493–532. https://doi.org/10.1086/316162

O'Dea CP, Baum SA (1997) Constraints on Radio Source Evolution from the Compact Steep Spectrum and GHz Peaked Spectrum Radio Sources. AJ113:148–161. https://doi.org/10.1086/118241

O'Dea CP, Saikia DJ (2021) Compact steep-spectrum and peaked-spectrum radio sources. A&A Rev.29(1):3. https://doi.org/10.1007/s00159-021-00131-w. arXiv:2009.02750 [astro-ph.GA]

O'Dea CP, Daly RA, Kharb P, Freeman KA, Baum SA (2009) Physical properties of very powerful FRII radio galaxies. A&A494(2):471–488. https://doi.org/10.1051/0004-6361:200809416. arXiv:0810.1213 [astro-ph]

O'Dell SL (1978) The continuum radiation of compact extragalactic objects. In: Wolfe AM (ed) BL Lac Objects. pp 312–325

Ohsuga K, Mineshige S, Mori M, Kato Y (2009) Global Radiation-Magnetohydrodynamic Simulations of Black-Hole Accretion Flow and Outflow: Unified Model of Three States. PASJ61(3):L7–L11. https://doi.org/10.1093/pasj/61.3.L7. arXiv:0903.5364 [astro-ph.HE]

Orienti M (2016) Radio properties of Compact Steep Spectrum and GHz-Peaked Spectrum radio sources. Astronomische Nachrichten 337(1-2):9. https://doi.org/10.1002/asna.201512257. arXiv:1511.00436 [astro-ph.GA]

Orienti M, Dallacasa D, Stanghellini C (2007) Constraining the nature of high frequency peakers. The spectral variability. A&A475(3):813–820. https://doi.org/10.1051/0004-6361:20078105. arXiv:0708.3979 [astro-ph]

Orienti M, Murgia M, Dallacasa D (2010) The last breath of the young gigahertz-peaked spectrum radio source PKS1518+047. MNRAS402:1892–1898. https://doi.org/10.1111/j.1365-2966.2009.16016.x. arXiv:0911.1723

O'Sullivan SP, Gaensler BM, Lara-López MA, van Velzen S, Banfield JK, Farnes JS (2015) The Magnetic Field and Polarization Properties of Radio Galaxies in Different Accretion States. ApJ806(1):83. https://doi.org/10.1088/0004-637X/806/1/83. arXiv:1504.06679 [astro-ph.GA]

Padovani P (2016) The faint radio sky: radio astronomy becomes mainstream. A&A Rev.24(1):13. https://doi.org/10.1007/s00159-016-0098-6. arXiv:1609.00499 [astro-ph.GA]

Padovani P, Alexander DM, Assef RJ, De Marco B, Giommi P, Hickox RC, Richards GT, Smolčić V, Hatziminaoglou E, Mainieri V, Salvato M (2017) Active galactic nuclei: what's in a name? A&A Rev.25(1):2. https://doi.org/10.1007/s00159-017-0102-9. arXiv:1707.07134 [astro-ph.GA]

Paliya VS (2021) A New Gamma-Ray-emitting Population of FR0 Radio Galaxies. ApJ918(2):L39. https://doi.org/10.3847/2041-8213/ac2143. arXiv:2108.11701 [astro-ph.HE]

Panessa F, Baldi RD, Laor A, Padovani P, Behar E, McHardy I (2019) The origin of radio emission from radio-quiet active galactic nuclei. Nature Astronomy 3:387–396. https://doi.org/10.1038/s41550-019-0765-4. arXiv:1902.05917 [astro-ph.GA]

Parma P, Fanti C, Fanti R, Morganti R, de Ruiter HR (1987) VLA observations of low-luminosity radio galaxies. VI - Discussion of radio jets. A&A181:244–264

Perucho M, Martí JM, Laing RA, Hardee PE (2014) On the deceleration of Fanaroff-Riley Class I jets: mass loading by stellar winds. MNRAS441(2):1488–1503. https://doi.org/10.1093/mnras/stu676. arXiv:1404.1209 [astro-ph.HE]

Phillips RB, Mutel RL (1982) On symmetric structure in compact radio sources. A&A106:21–24

Prandoni I, Seymour N (2014) Proceedings of 'Advancing Astrophysics with the SKA' (AASKA14) - Continuum Science' Chapters. arXiv e-prints arXiv:1412.6942. arXiv:1412.6942 [astro-ph.GA]

Prandoni I, Seymour N (2015) Revealing the Physics and Evolution of Galaxies and Galaxy Clusters with SKA Continuum Surveys. In: Advancing Astrophysics with the Square Kilometre Array (AASKA14). p 67. https://doi.org/10.22323/1.215.0067. arXiv:1412.6512 [astro-ph.IM]

Prestage RM, Peacock JA (1988) The cluster environments of powerful radio galaxies. MNRAS230:131–160. https://doi.org/10.1093/mnras/230.1.131

Pringle JE (1981) Accretion discs in astrophysics. ARA&A19:137–162. https://doi.org/10.1146/annurev.aa.19.090181.001033

Rafferty DA, McNamara BR, Nulsen PEJ, Wise MW (2006) The Feedback-regulated Growth of Black Holes and Bulges through Gas Accretion and Starbursts in Cluster Central Dominant Galaxies. ApJ652(1):216–231. https://doi.org/10.1086/507672. arXiv:astro-ph/0605323 [astro-ph]

Rani B (2019) Radio Galaxies—The TeV Challenge. Galaxies 7(1):23. https://doi.org/10.3390/galaxies7010023. arXiv:1811.00567 [astro-ph.HE]

Rawlings S, Saunders R (1991) Evidence for a common central-engine mechanism in all extragalactic radio sources. Nature349:138–140

Readhead ACS (1995) Evolution of Powerful Extragalactic Radio Sources. Proceedings of the National Academy of Science 92(25):11447–11450. https://doi.org/10.1073/pnas.92.25.11447

Readhead ACS, Xu W, Pearson TJ, Wilkinson PN, Polatidis AG (1994) Compact Symmetric Objects. In: Zensus JA, Kellermann KI (eds) Compact Extragalactic Radio Sources. p 17

Reynolds CS (2014) Measuring Black Hole Spin Using X-Ray Reflection Spectroscopy. Space Sci. Rev.183(1-4):277–294. https://doi.org/10.1007/s11214-013-0006-6. arXiv:1302.3260 [astro-ph.HE]

Rieger F, Levinson A (2018) Radio Galaxies at VHE Energies. Galaxies 6(4):116. https://doi.org/10.3390/galaxies6040116. arXiv:1810.05409 [astro-ph.HE]

Riggi S, Umana G, Trigilio C, Cavallaro F, Ingallinera A, Leto P, Bufano F, Norris RP, Hopkins AM, Filipović MD, Andernach H, van Loon JT, Michałowski MJ, Bordiu C, An T, Buemi C, Carretti E, Collier JD, Joseph T, Koribalski BS, Kothes R, Loru S, McConnell D, Pommier M, Sciacca E, Schillirò F, Vitello F, Warhurst K, Whiting M (2021) Evolutionary map of the Universe (EMU): Compact radio sources in the SCORPIO field towards the galactic plane. MNRAS502(1):60–79. https://doi.org/10.1093/mnras/stab028. arXiv:2101.03843 [astro-ph.GA]

Rogstad DH, Ekers RD (1969) Radio Sources and Elliptical Galaxies. ApJ157:481. https://doi.org/10.1086/150089

Rossi P, Bodo G, Massaglia S, Capetti A (2020) The different flavors of extragalactic jets: The role of relativistic flow deceleration. A&A642:A69. https://doi.org/10.1051/0004-6361/202038725. arXiv:2007.11423 [astro-ph.HE]

Ruffa I, Davis TA, Prandoni I, Laing RA, Paladino R, Parma P, de Ruiter H, Casasola V, Bureau M, Warren J (2019) The AGN fuelling/feedback cycle in nearby radio galaxies - II. Kinematics of the molecular gas. MNRAS489(3):3739–3757. https://doi.org/10.1093/mnras/stz2368. arXiv:1908.09229 [astro-ph.GA]

Rulten C (2022) Radio Galaxies at TeV Energies. Galaxies 10(3):61. https://doi.org/10.3390/galaxies10030061

Sabater J, Best PN, Hardcastle MJ, Shimwell TW, Tasse C, Williams WL, Brüggen M, Cochrane RK, Croston JH, de Gasperin F, Duncan KJ, Gürkan G, Mechev AP, Morabito LK, Prandoni I, Röttgering HJA, Smith DJB, Harwood JJ, Mingo B, Mooney S, Saxena A (2019) The LoTSS view of radio AGN in the local Universe. The most massive galaxies are always switched on. A&A622:A17. https://doi.org/10.1051/0004-6361/201833883. arXiv:1811.05528 [astro-ph.GA]

Sadler EM (1984) Radio and optical observations of a complete sample of E and SO galaxies. III. A radio continuum survey at 2.7 and 5.0 GHz. AJ89. https://doi.org/10.1086/113483

Sadler EM (2016) GPS/CSS radio sources and their relation to other AGN. Astron Nachr 337:105. https://doi.org/10.1002/asna.201512274. arXiv:1512.01851

Sadler EM, Ekers RD, Mahony EK, Mauch T, Murphy T (2014) The local radio-galaxy population at 20 GHz. MNRAS438:796–824. https://doi.org/10.1093/mnras/stt2239. arXiv:1304.0268

Saikia DJ (2022) Jets in radio galaxies and quasars: an observational perspective. Journal of Astrophysics and Astronomy 43(2):97. https://doi.org/10.1007/s12036-022-09863-2. arXiv:2206.05803 [astro-ph.GA]

Saikia P, Körding E, Coppejans DL, Falcke H, Williams D, Baldi RD, McHardy I, Beswick R (2018) 15-GHz radio emission from nearby low-luminosity active galactic nuclei. A&A616:A152. https://doi.org/10.1051/0004-6361/201833233. arXiv:1805.06696 [astro-ph.HE]

Schawinski K, Lintott C, Thomas D, Sarzi M, Andreescu D, Bamford SP, Kaviraj S, Khochfar S, Land K, Murray P, Nichol RC, Raddick MJ, Slosar A, Szalay A, Vandenberg J, Yi SK (2009) Galaxy Zoo: a sample of blue early-type galaxies at low redshift. MNRAS396:818–829. https://doi.org/10.1111/j.1365-2966.2009.14793.x. arXiv:0903.3415

Schaye J, Crain RA, Bower RG, Furlong M, Schaller M, Theuns T, Dalla Vecchia C, Frenk CS, McCarthy IG, Helly JC, Jenkins A, Rosas-Guevara YM, White SDM, Baes M, Booth CM, Camps P, Navarro JF, Qu Y, Rahmati A, Sawala T, Thomas PA, Trayford J (2015) The EAGLE project: simulating the evolution and assembly of galaxies and their environments. MNRAS446(1):521–554. https://doi.org/10.1093/mnras/stu2058. arXiv:1407.7040 [astro-ph.GA]

Scheuer PAG (1974) Models of extragalactic radio sources with a continuous energy supply from a central object. MNRAS166:513–528. https://doi.org/10.1093/mnras/166.3.513

Schmidt M (1963) 3C 273 : A Star-Like Object with Large Red-Shift. Nature197(4872):1040. https://doi.org/10.1038/1971040a0

Schmidt M (1968) Space Distribution and Luminosity Functions of Quasi-Stellar Radio Sources. ApJ151:393. https://doi.org/10.1086/149446

Shabala SS, Ash S, Alexander P, Riley JM (2008) The duty cycle of local radio galaxies. MNRAS388:625–637. https://doi.org/10.1111/j.1365-2966.2008.13459.x. arXiv:0805.4152

Shabala SS, Deller A, Kaviraj S, Middelberg E, Turner RJ, Ting YS, Allison JR, Davis TA (2017) Delayed triggering of radio active galactic nuclei in gas-rich minor mergers in the local Universe. MNRAS464(4):4706–4720. https://doi.org/10.1093/mnras/stw2536. arXiv:1608.04178 [astro-ph.GA]

Shabala SS, Jurlin N, Morganti R, Brienza M, Hardcastle MJ, Godfrey LEH, Krause MGH, Turner RJ (2020) The duty cycle of radio galaxies revealed by LOFAR: remnant and restarted radio source populations in the Lockman Hole. MNRAS496(2):1706–1717. https://doi.org/10.1093/mnras/staa1172. arXiv:2004.08979 [astro-ph.GA]

Shakura NI, Sunyaev RA (1973) Black holes in binary systems. Observational appearance. A&A24:337–355

Shang Z, Brotherton MS, Wills BJ, Wills D, Cales SL, Dale DA, Green RF, Runnoe JC, Nemmen RS, Gallagher SC, Ganguly R, Hines DC, Kelly BJ, Kriss GA, Li J, Tang B, Xie Y (2011) The Next Generation Atlas of Quasar Spectral Energy Distributions from Radio to X-Rays. ApJS196(1):2. https://doi.org/10.1088/0067-0049/196/1/2. arXiv:1107.1855 [astro-ph.CO]

Shankar F (2009) The demography of supermassive black holes: Growing monsters at the heart of galaxies. New A Rev.53(4-6):57–77. https://doi.org/10.1016/j.newar.2009.07.006. arXiv:0907.5213 [astro-ph.CO]

Shimwell TW, Röttgering HJA, Best PN, Williams WL, Dijkema TJ, de Gasperin F, Hardcastle MJ, Heald GH, Hoang DN, Horneffer A, Intema H, Mahony EK, Mandal S, Mechev AP, Morabito L, Oonk JBR, Rafferty D, Retana-Montenegro E, Sabater J, Tasse C, van Weeren RJ, Brüggen M, Brunetti G, Chyzy KT, Conway JE, Haverkorn M, Jackson N, Jarvis MJ, McKean JP, Miley GK, Morganti R, White GJ, Wise MW, van Bemmel IM, Beck R, Brienza M, Bonafede A, Calistro Rivera G, Cassano R, Clarke AO, Cseh D, Deller A, Drabent A, van Driel W, Engels D, Falcke H, Ferrari C, Fröhlich S, Garrett MA, Harwood JJ, Heesen V, Hoeft M, Horellou C, Israel FP, Kapińska AD, Kunert-Bajraszewska M, McKay DJ, Mohan NR, Orrú E, Pizzo RF, Prandoni I, Schwarz DJ, Shulevski A, Sipior M, Smith DJB, Sridhar SS, Steinmetz M, Stroe A, Varenius E, van der Werf PP, Zensus JA, Zwart JTL (2017) The LOFAR Two-metre Sky Survey. I. Survey description and preliminary data release. A&A598:A104. https://doi.org/10.1051/0004-6361/201629313. arXiv:1611.02700 [astro-ph.IM]

Shimwell TW, Tasse C, Hardcastle MJ, Mechev AP, Williams WL, Best PN, Röttgering HJA, Callingham JR, Dijkema TJ, de Gasperin F, Hoang DN, Hugo B, Mirmont M, Oonk JBR, Prandoni I, Rafferty D, Sabater J, Smirnov O, van Weeren RJ, White GJ, Atemkeng M, Bester L, Bonnassieux E, Brüggen M, Brunetti G, Chyzy KT, Cochrane R, Conway JE, Croston JH, Danezi A, Duncan K, Haverkorn M, Heald GH, Iacobelli M, Intema HT, Jackson N, Jamrozy M, Jarvis MJ, Lakhoo R, Mevius M, Miley GK, Morabito L, Morganti R, Nisbet D, Orrú E, Perkins S, Pizzo RF, Schrijvers C, Smith DJB, Vermeulen R, Wise MW, Alegre L, Bacon DJ, van Bemmel IM, Beswick RJ, Bonafede A, Botteon A, Bourke S, Brienza M, Calistro Rivera G, Cassano R, Clarke AO, Conselice CJ, Dettmar RJ, Drabent A, Dumba C, Emig KL, Enßlin TA, Ferrari C, Garrett MA, Génova-Santos RT, Goyal A, Gürkan G, Hale C, Harwood JJ, Heesen V, Hoeft M, Horellou C, Jackson C, Kokotanekov G, Kondapally R, Kunert-Bajraszewska M, Mahatma V, Mahony EK, Mandal S, McKean JP, Merloni A, Mingo B, Miskolczi A, Mooney S, Nikiel-Wroczyński B, O'Sullivan SP, Quinn J, Reich W, Roskowiński C, Rowlinson A, Savini F, Saxena A, Schwarz DJ, Shulevski A, Sridhar SS, Stacey HR, Urquhart S, van der Wiel MHD, Varenius E, Webster B, Wilber A (2019) The LOFAR Two-metre Sky Survey. II. First data release. A&A622:A1. https://doi.org/10.1051/0004-6361/201833559. arXiv:1811.07926

Shlosman I (2013) Cosmological Evolution of Galaxies. In: Falcón-Barroso J, Knapen JH (eds) Secular Evolution of Galaxies. p 555

Sikora M, Begelman MC (2013) Magnetic Flux Paradigm for Radio Loudness of Active Galactic Nuclei. ApJ764(2):L24. https://doi.org/10.1088/2041-8205/764/2/L24. arXiv:1301.5638 [astro-ph.HE]

Sikora M, Stawarz Ł, Lasota JP (2007) Radio Loudness of Active Galactic Nuclei: Observational Facts and Theoretical Implications. ApJ658:815–828. https://doi.org/10.1086/511972. astro-ph/0604095

Singh CB, Garofalo D, Kennedy K (2019) The Generalized Hardness-Intensity Diagram for Black Hole and Neutron Star X-Ray Binaries. ApJ887(2):164. https://doi.org/10.3847/1538-4357/ab4656. arXiv:1909.08932 [astro-ph.HE]

Singh V, Ishwara-Chandra CH, Sievers J, Wadadekar Y, Hilton M, Beelen A (2015a) Discovery of rare double-lobe radio galaxies hosted in spiral galaxies. MNRAS454(2):1556–1572. https://doi.org/10.1093/mnras/stv2071. arXiv:1509.01559 [astro-ph.GA]

Singh V, Ishwara-Chandra CH, Wadadekar Y, Beelen A, Kharb P (2015b) Kiloparsec-scale radio emission in Seyfert and LINER galaxies. MNRAS446(1):599–612. https://doi.org/10.1093/mnras/stu2124. arXiv:1410.2720 [astro-ph.GA]

Sirothia SK, Dennefeld M, Saikia DJ, Dole H, Ricquebourg F, Roland J (2009) 325-MHz observations of the ELAIS-N1 field using the Giant Metrewave Radio Telescope. MNRAS395(1):269–281. https://doi.org/10.1111/j.1365-2966.2009.14317.x. arXiv:0812.0813 [astro-ph]

Slee OB, Sadler EM, Reynolds JE, Ekers RD (1994) Parsecscale Radio Cores in Early Type Galaxies. MNRAS269:928. https://doi.org/10.1093/mnras/269.4.928

Smethurst RJ, Simmons BD, Lintott CJ, Shanahan J (2019) Secularly powered outflows from AGNs: the dominance of non-merger driven supermassive black hole growth. MNRAS489(3):4016–4031. https://doi.org/10.1093/mnras/stz2443. arXiv:1909.01355 [astro-ph.GA]

Smith EP, Heckman TM, Bothun GD, Romanishin W, Balick B (1986) On the Nature of QSO Host Galaxies. ApJ306:64. https://doi.org/10.1086/164321

Snellen IAG, Schilizzi RT, de Bruyn AG, Miley GK, Rengelink RB, Roettgering HJ, Bremer MN (1998) A new sample of faint Gigahertz Peaked Spectrum radio sources. A&AS131:435–449. https://doi.org/10.1051/aas:1998281. arXiv:astro-ph/9803140 [astro-ph]

Snellen IAG, Schilizzi RT, Miley GK, de Bruyn AG, Bremer MN, Röttgering HJA (2000) On the evolution of young radio-loud AGN. MNRAS319(2):445–456. https://doi.org/10.1046/j.1365-8711.2000.03935.x. arXiv:astro-ph/0002130 [astro-ph]

Sol H, Pelletier G, Asseo E (1989) Two-flow model for extragalactic radio jets. MNRAS237:411–429. https://doi.org/10.1093/mnras/237.2.411

Spencer RE, McDowell JC, Charlesworth M, Fanti C, Parma P, Peacock JA (1989) MERLIN and VLA observations of compact steep-spectrum radio sources. MNRAS240:657–687. https://doi.org/10.1093/mnras/240.3.657

Stanghellini C, O'Dea CP, Dallacasa D, Baum SA, Fanti R, Fanti C (1998) A complete sample of GHz-peaked-spectrum radio sources and its radio properties. A&AS131:303–315. https://doi.org/10.1051/aas:1998270. arXiv:astro-ph/9803222 [astro-ph]

Stecker FW, Shrader CR, Malkan MA (2019) The Extragalactic Gamma-Ray Background from Core-dominated Radio Galaxies. ApJ879(2):68. https://doi.org/10.3847/1538-4357/ab23ee. arXiv:1903.06544 [astro-ph.GA]

Strateva I, Ivezić Ž, Knapp GR, Narayanan VK, Strauss MA, Gunn JE, Lupton RH, Schlegel D, Bahcall NA, Brinkmann J, Brunner RJ, Budavári T, Csabai I, Castander FJ, Doi M, Fukugita M, Győry Z, Hamabe M, Hennessy G, Ichikawa T, Kunszt PZ, Lamb DQ, McKay TA, Okamura S, Racusin J, Sekiguchi M, Schneider DP, Shimasaku K, York D (2001) Color Separation of Galaxy Types in the Sloan Digital Sky Survey Imaging Data. AJ122:1861–1874. https://doi.org/10.1086/323301. arXiv:astro-ph/0107201

Sutherland RS, Bicknell GV (2007) Interaction of jets with the ISM of radio galaxies. Ap&SS311(1-3):293–303. https://doi.org/10.1007/s10509-007-9580-y. arXiv:0707.3669 [astro-ph]

Tadhunter C (2016a) Radio AGN in the local universe: unification, triggering and evolution. A&A Rev.24(1):10. https://doi.org/10.1007/s00159-016-0094-x. arXiv:1605.08773 [astro-ph.GA]

Tadhunter C (2016b) The impact of compact radio sources on their host galaxies: observations. Astronomische Nachrichten 337(1-2):159. https://doi.org/10.1002/asna.201512286

Tadhunter C, Morganti R, Santoro F, Bernhard E (2021) Compact radio sources: Triggering and feedback. Astronomische Nachrichten 342(1200):1200–1206. https://doi.org/10.1002/asna.20210048

Tavecchio F, Righi C, Capetti A, Grandi P, Ghisellini G (2018) High-energy neutrinos from FR0 radio galaxies? MNRAS475(4):5529–5534. https://doi.org/10.1093/mnras/sty251. arXiv:1711.03757 [astro-ph.HE]

Tchekhovskoy A, Narayan R, McKinney JC (2010) Black Hole Spin and The Radio Loud/Quiet Dichotomy of Active Galactic Nuclei. ApJ711:50–63. https://doi.org/10.1088/0004-637X/711/1/50. arXiv:0911.2228 [astro-ph.HE]

Tchekhovskoy A, Narayan R, McKinney JC (2011) Efficient generation of jets from magnetically arrested accretion on a rapidly spinning black hole. MNRAS418:L79–L83. https://doi.org/10.1111/j.1745-3933.2011.01147.x. arXiv:1108.0412 [astro-ph.HE]

Terashima Y, Wilson AS (2003) Chandra Snapshot Observations of Low-Luminosity Active Galactic Nuclei with a Compact Radio Source. ApJ583(1):145–158. https://doi.org/10.1086/345339. arXiv:astro-ph/0209607 [astro-ph]

The Fermi-LAT collaboration, :, Ajello M, Baldini L, Ballet J, Bastieri D, Becerra Gonzalez J, Bellazzini R, Berretta A, Bissaldi E, Bonino R, Brill A, Bruel P, Buson S, Caputo R, Caraveo P, Cheung T, Chiaro G, Cibrario N, Ciprini S, Crnogorcevic M, Cutini S, D'Ammando F, De Gaetano S, Di Lalla N, Di Venere L, Dominguez A, Fallah Ramazani V, Ferrara E, Fiori A, Fukazawa Y, Funk S, Fusco P, Gammaldi V, Gargano F, Garrappa S, Gasparrini D, Giglietto N, Giordano F, Giroletti M, Green D, Grenier I, Guiriec S, Horan D, Hou X, Kayanoki T, Kuss M, Larsson S, Latronico L, Lewis T, Li J, Liodakis I, Longo F, Loparco F, Lott B, Lovellette M, Lubrano P, Madejski G, Maldera S, Manfreda A, Marti-Devesa G, Mazziotta MN, Mereu I, Michelson P, Mirabal N, Mitthumsiri W, Mizuno T, Monzani ME, Morselli A, Moskalenko I, Negro M, Ojha R, Orienti M, Orlando E, Ormes JF, Pei Z, Pena-Herazo HA, Persic M, Pesce-Rollins M, Petrosian V, Pillera R, Poon H, Porter T, Principe G, Raino S, Rando R, Rani B, Razzano M, Razzaque S, Reimer A, Reimer O, Scargle J, Scotton L, Serini D, Sgro C, Siskind EJ, Spandre G, Spinelli P, Suson D, Tajima H, Torres DF, Valverde J, Yassin H, Zaharijas G (2022) The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope – Data Release 3. arXiv e-prints arXiv:2209.12070. arXiv:2209.12070 [astro-ph.HE]

Thorne KS, Price RH, MacDonald DA (1986) Book-Review - Black-Holes - the Membrane Paradigm. Science 234:224

Torresi E (2020) Gamma-ray emission in radio galaxies, from MeV to TeV. In: Asada K, de Gouveia Dal Pino E, Giroletti M, Nagai H, Nemmen R (eds) Perseus in Sicily: From Black Hole to Cluster Outskirts. vol 342. pp 158–166. https://doi.org/10.1017/S1743921318007895. arXiv:1809.08074 [astro-ph.HE]

Torresi E, Grandi P, Capetti A, Baldi RD, Giovannini G (2018) X-ray study of a sample of FR0 radio galaxies: unveiling the nature of the central engine. MNRAS476(4):5535–5547. https://doi.org/10.1093/mnras/sty520. arXiv:1802.08581 [astro-ph.HE]

Torresi E, Balmaverde B, Liuzzo E, Giovannini G, Paladino R, Baldi RD, Boccardi B, Capetti A, Ciprini S, Dadina M, D'Ammando F, Gasparrini D, Giroletti M, Grandi P, Lico R, Macconi D, Migliori G, Prandoni I, Raiteri CM, Ruffa I, Vignali C (2022) Exploring the radio morphology-accretion mode link in radio galaxies at high energies. 93(2-3):81

Trinchieri G, Marino A, Mazzei P, Rampazzo R, Wolter A (2012) Hot gas in groups: NGC 5328 and the intriguing case of NGC 4756 with XMM-Newton. A&A545:A140. https://doi.org/10.1051/0004-6361/201219775. arXiv:1208.1408 [astro-ph.CO]

Ubertosi F, Gitti M, Torresi E, Brighenti F, Grandi P (2021a) A Chandra study of Abell 795 - a sloshing cluster with an FR0 radio galaxy at its centre. MNRAS503(3):4627–4645. https://doi.org/10.1093/mnras/stab819. arXiv:2103.08682 [astro-ph.GA]

Ubertosi F, Gitti M, Torresi E, Brighenti F, Grandi P (2021b) The central FR0 in the sloshing cluster Abell 795: Indications of mechanical feedback from Chandra data. Astronomische Nachrichten 342(1207):1207–1211. https://

doi.org/10.1002/asna.20210055. arXiv:2111.02160 [astro-ph.GA]

Urry CM, Padovani P (1995) Unified Schemes for Radio-Loud Active Galactic Nuclei. PASP107:803–+

van Breugel W, Miley G, Heckman T (1984) Studies of kiloparsec-scale, steep-spectrum radio cores. I. VLA maps. AJ89:5–22. https://doi.org/10.1086/113480

van der Wolk G, Barthel PD, Peletier RF, Pel JW (2010) Dust tori in radio galaxies. A&A511:A64. https://doi.org/10.1051/0004-6361/200912435. arXiv:0911.3734 [astro-ph.GA]

Vardoulaki E, Jiménez Andrade EF, Delvecchio I, Smolčić V, Schinnerer E, Sargent MT, Gozaliasl G, Finoguenov A, Bondi M, Zamorani G, Badescu T, Leslie SK, Ceraj L, Tisanić K, Karim A, Magnelli B, Bertoldi F, Romano-Diaz E, Harrington K (2021) FR-type radio sources at 3 GHz VLA-COSMOS: Relation to physical properties and large-scale environment. A&A648:A102. https://doi.org/10.1051/0004-6361/202039488. arXiv:2009.10721 [astro-ph.GA]

Vattakunnel S, Trussoni E, Capetti A, Baldi RD (2010) Accretion and nuclear activity in Virgo early-type galaxies. A&A 522:A89. https://doi.org/10.1051/0004-6361/201014611. arXiv:1007.3845 [astro-ph.CO]

Venturi G, Cresci G, Marconi A, Mingozzi M, Nardini E, Carniani S, Mannucci F, Marasco A, Maiolino R, Perna M, Treister E, Bland-Hawthorn J, Gallimore J (2021) MAGNUM survey: Compact jets causing large turmoil in galaxies. Enhanced line widths perpendicular to radio jets as tracers of jet-ISM interaction. A&A648:A17. https://doi.org/10.1051/0004-6361/202039869. arXiv:2011.04677 [astro-ph.GA]

Venturi T, Castaldini C, Cotton WD, Feretti L, Giovannini G, Lara L, Marcaide JM, Wehrle AE (1995) VLBI Observations of a Complete Sample of Radio Galaxies. VI. The Two FR I Radio Galaxies B2 0836+29 and 3C 465. ApJ454:735–+. https://doi.org/10.1086/176525

Verdoes Kleijn GA, Baum SA, de Zeeuw PT, O'Dea CP (2002a) Core Radio and Optical Emission in the Nuclei of nearby FR I Radio Galaxies. AJ123(3):1334–1356. https://doi.org/10.1086/339177. arXiv:astro-ph/0112356 [astro-ph]

Verdoes Kleijn GA, Baum SA, de Zeeuw PT, O'Dea CP (2002b) Core Radio and Optical Emission in the Nuclei of nearby FR I Radio Galaxies. AJ123:1334–1356

Vogelsberger M, Genel S, Springel V, Torrey P, Sijacki D, Xu D, Snyder G, Nelson D, Hernquist L (2014) Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. MNRAS444(2):1518–1547. https://doi.org/10.1093/mnras/stu1536. arXiv:1405.2921 [astro-ph.CO]

Wagner AY, Bicknell GV (2011) Relativistic Jet Feedback in Evolving Galaxies. ApJ728(1):29. https://doi.org/10.1088/0004-637X/728/1/29. arXiv:1012.1092 [astro-ph.CO]

Webster B, Croston JH, Harwood JJ, Baldi RD, Hardcastle MJ, Mingo B, Röttgering HJA (2021a) Investigating the spectra and physical nature of galaxy scale jets. MNRAS508(4):5972–5990. https://doi.org/10.1093/mnras/stab2939. arXiv:2110.04018 [astro-ph.GA]

Webster B, Croston JH, Mingo B, Baldi RD, Barkus B, Gürkan G, Hardcastle MJ, Morganti R, Röttgering HJA, Sabater J, Shimwell TW, Tasse C, White GJ (2021b) A population of galaxy-scale jets discovered using LOFAR. MNRAS500(4):4921–4936. https://doi.org/10.1093/mnras/staa3437. arXiv:2011.01015 [astro-ph.GA]

Whittam IH, Riley JM, Green DA, Jarvis MJ (2016) The faint source population at 15.7 GHz - III. A high-frequency study of HERGs and LERGs. MNRAS462:2122–2137. https://doi.org/10.1093/mnras/stw1725. arXiv:1607.03709

Whittam IH, Prescott M, McAlpine K, Jarvis MJ, Heywood I (2018) The Stripe 82 1-2 GHz Very Large Array Snapshot Survey: host galaxy properties and accretion rates of radio galaxies. MNRAS480(1):358–370. https://doi.org/10.1093/mnras/sty1787. arXiv:1806.10143 [astro-ph.GA]

Whittam IH, Green DA, Jarvis MJ, Riley JM (2020) The faint radio source population at 15.7 GHz - IV. The dominance of core emission in faint radio galaxies. MNRAS493(2):2841–2853. https://doi.org/10.1093/mnras/staa306. arXiv:2001.10961 [astro-ph.GA]

Willott CJ, Rawlings S, Blundell KM, Lacy M (1999) The emission line-radio correlation for radio sources using the 7C Redshift Survey. MNRAS309:1017–1033. https://doi.org/10.1046/j.1365-8711.1999.02907.x. astro-ph/9905388

Wójtowicz A, Stawarz Ł, Cheung CC, Werner N, Rudka D (2022) Radio Emission of Nearby Early-type Galaxies at Low and Very-Low Radio Luminosity Range. arXiv e-prints arXiv:2209.14638. arXiv:2209.14638 [astro-ph.GA]

Wright EL, Eisenhardt PRM, Mainzer AK, Ressler ME, Cutri RM, Jarrett T, Kirkpatrick JD, Padgett D, McMillan RS, Skrutskie M, Stanford SA, Cohen M, Walker RG, Mather JC, Leisawitz D, Gautier I Thomas N, McLean I, Benford D, Lonsdale CJ, Blain A, Mendez B, Irace WR, Duval V, Liu F, Royer D, Heinrichsen I, Howard J, Shannon M, Kendall M, Walsh AL, Larsen M, Cardon JG, Schick S, Schwalm M, Abid M, Fabinsky B, Naes L, Tsai CW (2010) The Wide-field Infrared Survey Explorer (WISE): Mission Description and Initial On-orbit Performance. AJ140(6):1868–1881. https://doi.org/10.1088/0004-6256/140/6/1868. arXiv:1008.0031 [astro-ph.IM]

Wrobel JM, Heeschen DS (1991) Radio-continuum sources in nearby and bright E/S0 galaxies - Active nuclei versus star formation. AJ101:148–169

Xu C, Baum SA, O'Dea CP, Wrobel JM, Condon JJ (2000) VLBA Observations of a Sample of Nearby FR I Radio Galaxies. AJ120:2950–2964

York DG, Adelman J, Anderson JE Jr, Anderson SF, Annis J, Bahcall NA, Bakken JA, Barkhouser R, Bastian S, Berman E, Boroski WN, Bracker S, Briegel C, Briggs JW, Brinkmann J, Brunner R, Burles S, Carey L, Carr MA, Castander FJ, Chen B, Colestock PL, Connolly AJ, Crocker JH, Csabai I, Czarapata PC, Davis JE, Doi M, Dombeck T, Eisenstein D, Ellman N, Elms BR, Evans ML, Fan X, Federwitz GR, Fiscelli L, Friedman S, Frieman JA, Fukugita M, Gillespie B, Gunn JE, Gurbani VK, de Haas E, Haldeman

M, Harris FH, Hayes J, Heckman TM, Hennessy GS, Hindsley RB, Holm S, Holmgren DJ, Huang Ch, Hull C, Husby D, Ichikawa SI, Ichikawa T, Ivezić Ž, Kent S, Kim RSJ, Kinney E, Klaene M, Kleinman AN, Kleinman S, Knapp GR, Korienek J, Kron RG, Kunszt PZ, Lamb DQ, Lee B, Leger RF, Limmongkol S, Lindenmeyer C, Long DC, Loomis C, Loveday J, Lucinio R, Lupton RH, MacKinnon B, Mannery EJ, Mantsch PM, Margon B, McGehee P, McKay TA, Meiksin A, Merelli A, Monet DG, Munn JA, Narayanan VK, Nash T, Neilsen E, Neswold R, Newberg HJ, Nichol RC, Nicinski T, Nonino M, Okada N, Okamura S, Ostriker JP, Owen R, Pauls AG, Peoples J, Peterson RL, Petravick D, Pier JR, Pope A, Pordes R, Prosapio A, Rechenmacher R, Quinn TR, Richards GT, Richmond MW, Rivetta CH, Rockosi CM, Ruthmansdorfer K, Sandford D, Schlegel DJ, Schneider DP, Sekiguchi M, Sergey G, Shimasaku K, Siegmund WA, Smee S, Smith JA, Snedden S, Stone R, Stoughton C, Strauss MA, Stubbs C, SubbaRao M, Szalay AS, Szapudi I, Szokoly GP, Thakar AR, Tremonti C, Tucker DL, Uomoto A, Vanden Berk D, Vogeley MS, Waddell P, Wang Si, Watanabe M, Weinberg DH, Yanny B, Yasuda N (2000) The Sloan Digital Sky Survey: Technical Summary. AJ120:1579–1587. https://doi.org/10.1086/301513. arXiv:astro-ph/0006396

Yuan F, Narayan R (2014) Hot Accretion Flows Around Black Holes. ARA&A52:529–588. https://doi.org/10.1146/annurev-astro-082812-141003. arXiv:1401.0586 [astro-ph.HE]

Zajaček M, Busch G, Valencia-S M, Eckart A, Britzen S, Fuhrmann L, Schneeloch J, Fazeli N, Harrington KC, Zensus JA (2019) Radio spectral index distribution of SDSS-FIRST sources across optical diagnostic diagrams. A&A630:A83. https://doi.org/10.1051/0004-6361/201833388. arXiv:1906.08877 [astro-ph.GA]

Zamaninasab M, Clausen-Brown E, Savolainen T, Tchekhovskoy A (2014) Dynamically important magnetic fields near accreting supermassive black holes. Nature510(7503):126–128. https://doi.org/10.1038/nature13399

Zanni C, Ferrari A, Rosner R, Bodo G, Massaglia S (2007) MHD simulations of jet acceleration from Keplerian accretion disks. The effects of disk resistivity. A&A469(3):811–828. https://doi.org/10.1051/0004-6361:20066400. arXiv:astro-ph/0703064 [astro-ph]

Zheng XC, Röttgering HJA, Best PN, van der Wel A, Hardcastle MJ, Williams WL, Bonato M, Prandoni I, Smith DJB, Leslie SK (2020) Link between radio-loud AGNs and host-galaxy shape. A&A644:A12. https://doi.org/10.1051/0004-6361/202038646. arXiv:2010.07851 [astro-ph.GA]

Zirbel EL (1997) The Megaparsec Environments of Radio Galaxies. ApJ476:489–+