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Exploring the radio morphology-accretion mode link in radio galaxies at high energies

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Abstract. We review recent results within the accretion-ejection framework in radio galaxies. The existence of a large number of FRII low-excitation radio galaxies (FRII-LERG) in the local Universe has questioned the usual connection between accretion mode and large-scale morphology, i.e., FRI-LERG and FRII-HERG (high-excitation radio galaxies). FRII-LERG could be evolving sources experiencing a switch of the accretion regime from efficient to inefficient, or they could represent a separate class of inefficiently accreting objects. In this second case, other factors concur in shaping the radio morphology, for example, the large-scale environment and/or the black hole spin or the magnetic field at the horizon. To have a comprehensive view of the whole problem, moving far away from the central engine is also necessary. We show how studies of the warm ionized gas and cold molecular gas phases can complement our investigation. Finally, we overview the radio through X-ray properties of the new class of low-power compact FR0 and explore their possible (very)-high energy emission. Indeed, despite many similarities with extended FRI, from host galaxy to central engine properties, it is still unknown why FR0 cannot expand their relativistic jets.

Key words. Galaxies: active – Galaxies: jets – X-rays: Galaxies – Catalogs

1. Introduction

Radio galaxies (RGs), i.e., *jetted* AGN (Padovani 2016) whose jets point at large inclination angles with respect to the line-of-sight, are extremely relevant to address important unknowns related to accretion onto supermassive black holes (SMBH) and ejection of relativistic plasma. Following the AGN population division proposed by Heckman & Best (2014), RGs can be separated into *radiative-mode* and *jet-mode* RGs. In the first case, the potential energy of the gas accreted by the SMBH is efficiently converted into radiation. FR type II sources (FRII)[1] (Fanaroff & Riley 1974), optically classified as high-excitation radio galaxies (HERG)[2] (Laing et al. 1994; Jackson & Rawlings 1997; Buttiglione et al. 2010), belong to this category. On the contrary, the SMBH of jet-mode RGs typically accretes inefficiently, and relativistic outflows transport the bulk of the AGN energetic output. They are generally called FR type I low-excitation radio galaxies, i.e., FRI-LERG. This simple one-to-one correspondence points toward the existence of a direct link between the accretion power and the plasma ejection [see, e.g., Ghisellini & Celotti (2001)]. However, the population of radio galaxies is more variegated; cross-population radio sources exist (Best & Heckman 2012; Gendre et al. 2013): i) low radio power FRIs with radiatively efficient accretion disks, i.e., FRI-HERG, and ii) powerful FRII radio sources hosting an inefficient hot thick flow, i.e., FRII-LERG. This fact suggests that the accretion rate is not the only parameter driving the radio morphology, and other ingredients should be considered. While FRI-HERG seem to be rare systems in nature, the prototypical example being 3C 120, FRII-LERG represent a non-negligible portion of radio-loud sources in the northern and southern sky. They are $\sim$24% of the 3CR sources at z<0.3 (Buttiglione et al. 2010) and 23% of the FRII belonging to the 2Jy sample (Tadhunter et al. 1998). In the next Section, we will focus on FRII-LERG sources as key targets to investigate the mutual relationship between accretion and jet power, independent of radio or optical classification.

2. FRII-LERG: from 3CR to FRCat samples

Macconi et al. (2020) (hereafter M20) studied the X-ray properties of a complete sample of 3CR FRII-LERG at z<0.3 to reconcile the co-existence of an inefficiently accreting engine and an extended FRII morphology, signature of a powerful jet. This systematic X-ray study allowed us to definitively exclude that FRII-LERG are highly obscured sources, pointing out their intermediate properties. The moderate intrinsic column density ($N_{HX} \sim 10^{22}$ cm^{-2}) and Eddington-scaled X-ray luminosities in between FRII-HERG and FRI-LERG (Fig.1-upper panel), suggest that FRII-LERG are in a *transitional phase* [3]. Indeed, the largest column density ($N_{HX} \geq 10^{23}$ cm^{-2}) is found in efficiently accreting sources (FRII-HERG). The lower N_{HX} values of FRII-LERG could suggest that they represent an *evolutionary stage* of classical FRII. They accreted efficiently in the past, producing powerful jets, and recently switched off their nuclear activity because, for example, they have exhausted the cold gas fuel (see Section 2.1). However, it is also possible that FRII-LERG are not switched-off sources, i.e., their accretion mode was, and still is, inefficient, and the radio morphology depends on other factors such as the environment. By comparing the environment in terms of cluster richness [4] with the estimated accretion rate for the three classes of RGs, M20 attested the presence of a correlation. This finding suggests that the environment can effectively impact the accretion regime and that the FRII radio morphology of LERG could be due to favorable environmental conditions (see Fig. 7

[1] FRI and FRII were divided on the basis of their extended radio morphology that changes below or above a critical radio luminosity $L_{178\,\mathrm{MHz}} \sim 10^{25}$ W Hz^{-1} sr^{-1}.

[2] HERG are characterized by: [OIII]/Hα >0.2 or [OIII] equivalent width >3Å or Excitation Index (EI=Log([OIII]/Hβ)-1/3(Log([NII]/Hα)+Log([SII]/Hα)+Log([OI]/Hα))) >0.95.

[3] It is worth noting that the same trend is found considering the [OIII]λ5007 luminosity as a proxy of the accretion rate instead of the X-ray luminosity (Buttiglione et al. 2009).

[4] The richness factor (CR) was computed by Gendre et al. (2013) and corresponds to the number of SDSS galaxies with absolute magnitude brighter than M_r=-19 within a disk of 1 Mpc radius around each target.

of M20). However, 3CR RGs represent the tip of the iceberg of a more variegated population of radio sources. In fact, in the local Universe (z<0.15), the role of the environment seems to be reduced as FRI and FRII, both LERG and HERG, live in galaxy-rich large-scale environments with the same richness (Massaro et al. 2019).

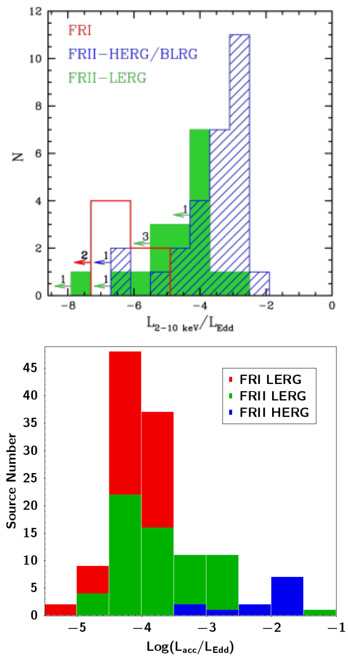

Fig. 1. *Upper panel*: Eddington-scaled 2-10 keV X-ray luminosity for 3CR sources: FRII-LERG are in *green*, FRII-HERG are in *blue* and FRI-LERG are in *red*. Figure adapted from Macconi et al. (2020). *Lower panel*: Eddington-scaled radiative luminosity distribution for FRCat sources (here, the label FRII-HERG refers to both Narrow- and Broad-line Radio Galaxies). Color code as in the upper panel. L_{acc} has been estimated from the [OIII]λ5007 luminosity applying the relation L_{acc}=3500×$L_{[OIII]}$ (Heckman et al. 2004). Figure adapted from Grandi et al. (2021).

The evolutionary scenario invoked by M20 is also supported by a recent study performed by Grandi et al. (2021) on the sources belonging to the FR catalogs (Capetti et al. 2017a,b; Baldi et al. 2018) of RGs in the local (z<0.15) mJy Universe. These new catalogs took advantage of the recent large-area surveys (Best & Heckman 2012) (e.g., NVSS, FIRST, and SDSS), offering the unprecedented opportunity to expand the study of radio galaxies, well characterized both in the radio and optical bands, down to mJy radio fluxes[5]. In the mJy regime, the RG population appears different from the Jy catalogs. In particular, while in the 3CR catalog, more than 40% are FRII-HERG, they reduce to 4% in FR catalogs, attesting the predominance of LERG in the FRII population. The statistical study presented by Grandi et al. (2021) showed that the majority of nearby objects are in a late stage of their life. In particular, FRII-LERG seem to be more similar to evolved FRI-LERG, in terms of accretion rate and stellar activity, than FRII-HERG. Fig.1 (lower panel) shows the histogram of the accretion rate, expressed in terms of L_{acc}/L_{Edd}, for the three classes of RGs. Differently from 3CR sources (upper panel), where FRII-LERG clearly show intermediate accretion rates, mJy FRII-LERG sources seem aged FRII-HERG that, once exhausted their fuel, they changed the accretion configuration. At the same time, the extended radio structures still trace past activity. Although this scenario is quite robust, the hypothesis that FRII-LERG are a separate class of sources cannot be rejected entirely. In fact, from the work of Grandi et al. (2021), it emerges that LERG, with similar masses and accretion rates, can expel jets of different powers. The black hole spin and/or the magnetic field at its horizon (Blandford & Znajek 1977) should be additionally considered. FRII-LERG should have the fastest black hole spin and/or the most intense magnetic field within this context.

2.1. Warm and cold gas phases

X-rays are fundamental to reaching the innermost regions of the AGN. However, to understand the feeding and feedback phenomena as a whole, it is necessary to move far away from the central engine and study different phases

[5] NVSS flux density larger than 5 mJy.

of the interstellar medium (ISM), in particular the warm and cold ones. The MURALES (MUse RAdio Loud Emission line Snapshot survey) survey (Balmaverde et al. 2019, 2021) observed 37 3C low-redshift (z<0.3) sources with the VLT/MUSE optical integral field spectrograph intending to explore the AGN feedback processes at different spatial scales. Balmaverde et al. (2019) attested a connection between the radio morphology (FRI/FRII) and the warm ionized gas structures detected in the MURALES sources (see Fig.2-upper panel as an example). Indeed, FRI do not present extended line emission, while in all FRII of the sample, ionized gas extending beyond kpc distances is observed. Interestingly, there is no apparent difference between FRII-HERG and LERG; actually, they show a similar large reservoir of warm ionized gas despite their different accretion rates. This result could suggest that the difference between these two types of FRII sources is not in the gas content (fuel) but the pathway it follows to reach the AGN central regions [see, e.g. Gaspari et al. (2013, 2015, 2017)]. Nonetheless, it is important to note that MUSE observes only the portion of gas that is ionized through AGN photoionization or shocks (Balmaverde et al. 2019). To better comprehend the entire gas content, exploring the cold (atomic and molecular) gas phase is necessary.

CO line emission represents the best tracer of the molecular ISM, considered a possible fuel triggering the AGN activity (Struve & Conway 2012). Previous studies exploring the cold molecular gas properties in different samples of radio sources found no univocal results. However, there are indications that the cold gas masses in FRII are larger than in FRI RGs (Evans et al. 2005; Ocaña Flaquer et al. 2010). The same seems to apply to HERG that tend to have larger masses [e.g., by a factor of ~7 (Smolčić & Riechers 2011)] than LERG. A merger event or strong tidal interaction might provide the abundance of cold gas in HERG (Heckman & Best 2014). In contrast, in LERG, much of the circumnuclear hot gas could condense into filaments of cold gas that fall towards the nucleus through cloud-cloud collisions (Gaspari et al. 2013, 2015; Tadhunter 2016). Indeed, a significant amount of molecular gas is frequently detected in LERG sources. For example, Ruffa et al. (2019a) found ALMA ^{12}CO(2-1) emission in 6 out of 9 LERG with M_{H2} $\sim 10^7$-10^8 $M_\odot$. The emission appears distributed in rotating disk-like structures on scales ranging between a few hundred pc to a few kpc (Fig.2-lower panel). The bulk of the gas is in ordered rotation, and the dominant radial motions are likely to be inflows, supporting the scenario in which cold gas provides the fuel to the AGN (Ruffa et al. 2019b). However, if the picture is clear enough for FRI-LERG, it is not the same for the other two classes, FRII-HERG and LERG. It is not clear whether the difference in mass content is an effect of Malmquist bias (i.e., FRIIs are systematically found at higher redshifts), as invoked by Ocaña Flaquer et al. (2010) or whether it is real, as argued by Smolčić & Riechers (2011). Yet having an idea of the properties of cold molecular gas is critical to understanding whether the differences we see in the accretion rate are attributable to the ISM cold phase and if depletion of cold gas can determine a change in the accretion mode of FRII-LERG, as hypothesized by M20.

3. FR0 at high-energies

A significant result raised by studying the mJy Universe is that 80% of the radio-loud AGN population appears unresolved or barely resolved at the 5" FIRST resolution (Baldi et al. 2018). These compact radio sources, named FR0 (Ghisellini 2011), possess a minimum 1.4 GHz flux density of 5 mJy at z<0.05 and are all optically classified as LERG. FR0 show host galaxy properties similar to FRI, although they are generally less massive (Baldi et al. 2018; Grandi et al. 2021). The most noticeable difference between these two classes is the lack of extended radio emission in FR0, which is still unexplained. They could be characterized by intermittent activity not long enough for radio jets to develop at large distances from the black hole, or they could live in a hostile ambient which causes the premature disruption of the radio jets (Bodo et al. 2013). However, observations do not support this in-

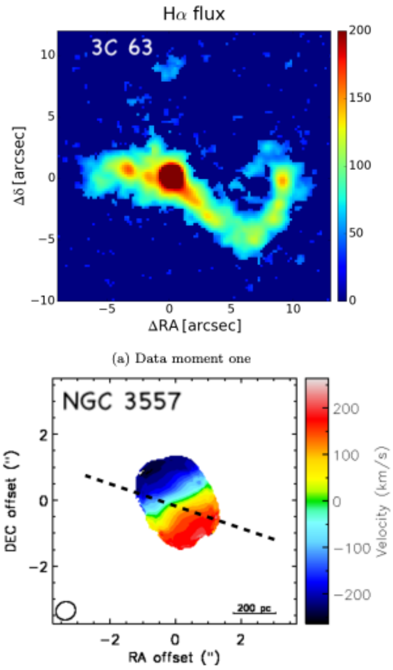

Fig. 2. *Upper panel*: MUSE Hα emission line image of the FRII-HERG 3C 63 adapted from Balmaverde et al. (2019). *Lower panel*: observed mean velocity map of the CO emission in the FRI-LERG NGC 3557. The black dashed line indicates the direction of the radio jet axis. Adapted from Ruffa et al. (2019b).

terpretation (see Capetti et al. (2020); Ubertosi et al. (2021)). Alternatively, FR0 could have a lower jet Lorentz factor caused by a low black hole spin that reduces the ability of their jets to penetrate the galaxy medium (Tchekhovskoy et al. 2010; Maraschi et al. 2012; Baldi et al. 2019). At higher energies, Torresi et al. (2018) performed the first X-ray study of a sample of FR0 sources, finding X-ray (2-10 keV) luminosities in the range $L_X=10^{40}$-10^{43} erg s^{-1}, similar to FRI. This luminosity correlates with the radio one indicating a non-thermal origin (jet) of the X-ray emission. In 2016, Grandi et al. (2016) proposed the association of a γ-ray source detected by the Fermi-LAT satellite with the FR0 Tol1326-379. Its γ-ray flux is $F_{(>1GeV)}=(3.1\pm0.8)\times10^{-10}$ ph cm^{-2} s^{-1}, similar to FRI, but the spectrum is steeper, $\Gamma=2.78\pm0.14$. Up to now, Tol1326-379 is the only FR0 revealed above 100 MeV. However, as discussed by Baldi et al. (2019), who performed an explorative study of this class of objects in the high-energy domain, we could be missing γ-ray FR0 [see also Foschini et al. (2021)]. They could hide in the large number of blazar candidates of uncertain type (BCU), which show GeV fluxes and photon indices compatible with Tol ones. Or, given the high detection threshold (5σ) of the Fermi catalogs, fainter sources could be left out, and dedicated analysis of individual targets would be necessary. Beyond detecting single sources, it is important to emphasize that given the abundance of FR0 in the local Universe, they can represent a significant component of the unresolved γ-ray background below 50 MeV (Stecker et al. 2019). As shown by Baldi et al. (2019), it is even more difficult to detect FR0 in the very-high-energy (VHE) domain (>100 TeV). From Fig. 3, it is evident that the VHE emission of Tol1326-379 is well below the sensitivity of the current Cherenkov telescopes. However, since we know very little about the VHE behavior of FR0 it is important to keep investigating this class of objects in the future with observatories like the Cherenkov Telescope Array (CTA). More in general, it is crucial to keep studying radio galaxies at very-high energies. So far, only six of them have been revealed in the TeV band, all being nearby FRI[6]. The last in temporal order and the second farthest away was 3C 264 (z=0.0217), detected in March 2018 by the Cherenkov telescope VERITAS (Mukherjee 2018). Recently, Boccardi et al. (2019) presented a radio and X-ray analysis of the jet of 3C 264 together with the modelization of the multi-band SED (considering the TeV detection). From VLBI data the jet appears limb-brightened (Fig.4) and the SED can be reproduced within the framework of leptonic models by assuming that the high-energy component is associated to a second emitting region that could be located at the end of the acceleration zone. This is another example of the importance of observing RGs at high

[6] `http://tevcat.uchicago.edu/`
[6] `https://www.ssdc.asi.it/tgevcat/`

and very-high energies since they allow to put strong constraints on the theoretical emission models.

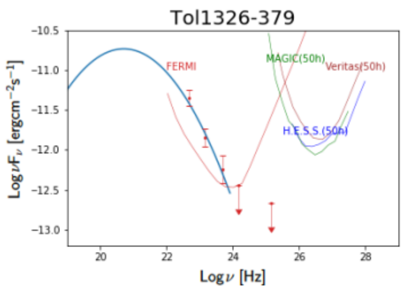

Fig. 3. SED of Tol1326-379 in the high energy band. The red points are Fermi-LAT measurements. The cyan line is a power-law with high-energy cut-off modeling of these data. The red line is the Fermi-LAT sensitivity curve. The expected differential sensitivity curves for 50 h of exposure of MAGIC (in green), VERITAS (in brown) and H.E.S.S telescopes (in blue) are also plotted for reference. Adapted from Baldi et al. (2019).

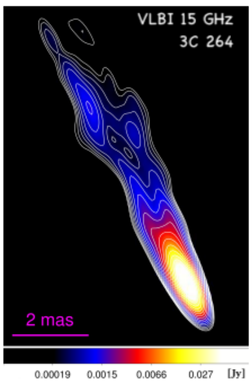

Fig. 4. Stacked VLBI image of 3C 264 at 15 GHz showing the limb-brightened structure of the jet. Adapted from Boccardi et al. (2019).

4. Summary

This paper focuses on the jet-accretion connection in radio galaxies. FRII-LERG radio sources are best suited to investigate the mutual relationship between accretion and jet power, independent of radio or optical classifications. From the studies of 3CR and mJy FRII-LERG, two scenarios emerge: (i) they are *aged* HERG, that after exhausting the cold gas fuel changed the accretion regime; (ii) they are a separate class of sources, and other factors contribute to shaping the radio morphology. The intermediate column density values and accretion rates measured through X-ray observations of 3CR FRII-LERG favor the first scenario. Further support to this hypothesis comes from mJy LERG, which appear very similar independently of their radio morphology. However, these results cannot completely rule out the second hypothesis i.e., FRII-LERG are inefficiently accreting sources still able to produce powerful radio structures, favored by extrinsic factors such as the environment or intrinsic properties such as the spin and/or the magnetic field. Large-area surveys not only revealed the great abundance of FRII-LERG in the local Universe, but also that the bulk of the radio-loud AGN population consists of compact FR0 (at z<0.05). We reviewed the radio-to-X-ray properties of FR0 and discussed possible perspectives of observations in the GeV and TeV sky with current and future facilities.

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