Multi-band properties of FR0 radio galaxies

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Radio Galaxies are RL AGNs ($L_{\text{radio}}/L_{\text{optical}} > 10$) with $L_r = 10^{36} - 10^{46}$ erg s$^{-1}$.

- Morphologies of extended radio galaxies from pc to Mpc
- **Collimated relativistic jets** connecting the optical galaxy with the extended lobes/plumes
- Typically associated with red massive elliptical galaxies and $M_{\text{BH}} > 10^8 M_\odot$ (but exceptions)

**Fanaroff & Riley (1974): pure morphological classification**
Two AGN modes

..from emission line ratios (BPT diagrams, e.g. Kewley et al 2006, Buttiglione et al 2010)

**RADIATIVE MODE**

- Radiatively efficient disc (S&S disc)
- Seyfert/HERG
- Red & blue massive galaxies
- High accretion rate ($\lambda_{\text{Edd}} > 10^{-2}$)
- Cold gas accretion
- Powerful jets (FRII)

Heckman & Best (2014)
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JET-MODE

- RIAF disc
- LINER/LERG
- Red massive galaxies
- Low accretion rate ($\lambda_{\text{Edd}} < 10^{-2}$)
- Hot gas accretion
- Weak and powerful jets (FRI-FRII)

Heckman & Best (2014)
Orientation-based unification scheme can explain the general radio morphological and multi-band properties of RL AGN, but is not fully successful in describing the details of each class.

Urry & Padovani (1995)
Radio size and luminosity can be used as proving of an evolving jetted structure.

The high luminosity young RGs (CSO, CSS/GPS) could be evolving largely into FRII sources, while the low-luminosity young RGs into FRIs (e.g. Kunert-Bajraszewska et al 2010, An & Baan 2012, Kunert-Kunert-Bajraszewska 2016).
At lower radio luminosities and sizes the RL AGN models start to be uncertain and no clear picture on their evolution.

The bulk of the low-luminosity RG population is still unexplored.

Heckman & Best (2014)
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Heckman & Best (2014)
Why Low-Luminosity radio galaxies are important?

★ The bulk of RL AGN population

★ low-power galactic-scale jets can have a tremendous impact on their hosts by continuously injecting and depositing energy into the host as supported by the state-of-the-art jet simulations.


See talk of F. Ubertosi & C. Tadhunter
Studying low luminosity (compact) RGs is crucial to explore the validity of US and ES of RL AGN
Most of the Best et al. sample shows a clear deficit in total radio emission with respect to the classical RG (FRI and FRII).

Best et al. (2005/2012) select 2215/7302 low-luminosity radio-loud AGN cross-matching SDSS (DR2/DR7) and NVSS and FIRST with Flux > 5 mJy in the local Universe (z < 0.3)
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Local Radio-Loud AGN population

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Radiative-mode AGN
Jet-mode AGN
radio-quiet Seyfert
FR0

FIRST: resolution 5', ~10-20 kpc
At 20 GHz, Sadler (2016) found most of FR0s in AT20G-6dfGS sample: mix of LERG and HERG and ETG and LTG.

Whittam et al. (2016) selected ~65 FR0s (>0.5 Jy) from 10C survey at 16 GHz.

At 150 MH with LOFAR, Shimwell et al. (2017) found that most of LOTSS radio sources are unresolved at ~6”.

Deep observations of ELAIS-N1 field at 610 MHz reveal a large population of FR0s (Sirothia et al 2009, Iswara-Chandra et al 2020).

FR0s represent 70-80% of RL AGN population.
FR0s consists of a composite population: LERG, HERG, elliptical, spirals and YRG.

See talk of I. Whittam.
FR 0 radio galaxies

Ghisellini (2014) and Sadler (2016) «a convenient way of linking the compact radio sources ... into the canonical FR classification scheme»

Are they a new class? NO.
Compact radio-sources at the center of early type galaxies (ETG) has been already recognized in the ’70s (Ekers & Ekers 1973) and later (Wrobel & Heeschen 1991, Sadler 1984, Slee et al. 1994)

Are they a well defined class? NO.
The «compact source» definition depends on the survey depth, resolution, frequency, and on the source distance.

Are they an interesting class? YES (I think so...).
Why most radio galaxies extend to, at most, a few kpc? How are they connected to the large objects? Are they small because they are young? Or are they different?
Baldi et al (2018) compiled a catalogue of 104 (bona-fide radio-loud) FR0s with $z<0.05$ with sizes <10 kpc:

- Unresolved in FIRST (5"")
- Red massive ETGs ($-21 > M_r > -23$)
- Massive BHs ($10^{7.5} - 10^9 M_\odot$)
- LERG

FR0s consist of (compact) radio-loud AGN with nuclear and host properties, typical of FRIs and LERGs in general: *Jet-mode AGN!*
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- Jet-mode AGN!

Similarity with FRI/LERGs: host properties (e.g. lack of cold gas) are not responsible to confine the jets of FR0s.
Luminosity Function

FR-0/I/II radio galaxies in FIRST/SDSS catalogue

FR0s are 5 times more abundant than FRIs

Baldi & Capetti A&A review in prep.
JVLA observations

in 2015 we got JVLA data for a Pilot sample of 7 FR0s. Only 2 sources show extended jets on kpc scale

Radio maps: < 0.2", < 3kpc

Observations at 1.4, 4.5, and 7.5 GHz with resolution 1.2"-0.2": core, core-jet, twin jet
new JVLA observations for 18 sources

4/18 show jets

Baldi, Capetti, Giovannini 2019
new JVLA observations for 18 sources

19/25 FR0s are compact:
where is the jet?

Baldi, Capetti, Giovannini 2019
GHz-regime properties

radio spectra

flat-spectrum core-dominated sources (A factor ~10 more core-dominated than 3C/FRIs)

Baldi, Capetti & Giovannini (2015, 2019)
Baldi, Capetti, Massaro (2018)

No boosting/similar engine

RGs with similar AGN powers, radio core powers, BH masses and host properties can produce different jet structures
Low-frequency radio observations are ideal to detect extended radio emission (possibly from past radio activity)
• We cross-correlate the FR0 catalogue and the LOFAR survey (LoTTS, DR2, Shimwell et al 2019, at 150 MHz and 6")

Data available for 45 FR0CAT sources. (FOV 2’, 80 kpc).

Only 12 extended sources

No diffuse emission: $S < 10^{22} \text{ W/Hz}$ within 100x100 kpc, compared to $10^{26}$ of the 3C FRI

Capetti, Brienza, Baldi et al (2020)
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**FR0s were not FRI/II in the past (activity)**

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*Capetti, Brienza, Baldi et al (2020)*
Many FR0s show convex spectra but with low curvature (not like YRG).
Are FRO young FRI?

Clues from number densities

FR0 can not ALL evolve into FRI because their relative number density is too high.
Are FR0 young FRI?
Clues from number densities

Most of FR0s are not just simply YRGs, which will become FRI/IIs. But 10% of FR0s could be YRG see e.g. talk of A. Mikhailov

FR0 can not ALL evolve into FRI because their relative number density is too high.
emERLIN observations of 5 FR0s at 5 GHz:

- resolution: 40 mas, 10 higher than JVLA resolution
- flux a few mJy; ~5 times weaker than JVLA cores

No clear jets appear!!

Baldi et al in prep.
eMERLIN-VLA

VLA combined eMERLIN

4 kpc

VLA combined eMERLIN

2 kpc
Extended jets are present in (all?) FR0s but visible only by combining short and long baselined observations.
EVN observations (no eMERLIN included) of 10 FR0s from FR0CAT at 1.5 GHz with an angular resolution of ~20 mas

- flux some mJy; 2-3 times weaker than JVLA cores, high $T_B$
- 6 objects: core/core-jet, size < 20 pc
EVN OBSERVATIONS

4 objects with extended morphologies:
- double/triple sources
- twin jets
- size ~30-115 pc

Cheng & An (2018)
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Different radio arrays probe different structures: broad and continuous distribution of FR0 radio properties
19 FR0s selected in radio (>30 mJy) and in X-ray (archival data available from Chandra, XMM, Swift)

- The X-ray photons are likely produced by the jet
- X-ray properties of FRI and FR0 are indistinguishable: 

  No nuclear intermittence expected
Gamma-ray

Tol 1326–379 is a FR0 detected by FERMI
$L_{>1\text{GeV}} \sim 2 \times 10^{42}\text{ erg s}^{-1}$, typical of FR Is, but with a steeper $\gamma$-ray spectrum ($\Gamma = 2.8$)

FR0s might contribute to 4-18% of the $\gamma$-ray sky background observed by Fermi (Stecker et al 2019).

FR0s are candidate sources for high-energy neutrinos (Tavecchio et al 2018) and ultra-high-energy cosmic rays (Lukas et al 2021).
We explore the properties of the large-scale environment (< 2 Mpc) of FR0s using optical SDSS data.

Most of FR 0s live in rich environment but a factor two lower density (< 15 members), on average, than FRIs.

Capetti, Massaro & Baldi (2020)

Cosmological neighbours: galaxies within 2 Mpc and $\Delta z = 0.005$

Different cosmological evolution!?
What sets a FR0?

To account for the radio properties, the large abundance and for the environment of FR0s in the local Universe, the most plausible scenario is:
What sets a FR0?

To account for the radio properties, the large abundance and for the environment of FR0s in the local Universe, the most plausible scenario is:

- No recurrence
- No jet frustration

*low jet bulk speed $\Gamma \sim 1-2$*
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low jet bulk speed $\Gamma \sim 1-2$

the ultimate origin of the low jet speed?

Low BH spin
Spin evolution driven by accretion or mergers

Baldi & Capetti (A&A review, in prep)

ACCRETION DRIVEN SPIN
An evolutionary scheme for radio galaxies, including the FR0s (Garofalo & Singh 2019)

From retrograde to prograde BH spin

FR0 are transition objects between FRII HERGs and FRI. An FR0 becomes an FRI after an accretion of 1/3 of its BH mass: the FR0 phase might last longer in a poorer environment

MERGERs DRIVEN SPIN
The BH spin is mainly the result of BH-BH coalescence events.

In a poor environment major mergers of equal mass galaxies are rare. Difficult to obtain highly rotating SMBH.

The large scale environment generates differences in the BH spin distribution

environment → BH spin → jet speed → morphology
Poor       low    low       FR0
Rich       high   high       FRI
FR0 population is the dominant class of RG in the local Universe
VLA reveal kpc-scale extended jets only for 6 out of 25 FR0s
150-MHz (LOFAR): no clear jets and gentle convex spectra
eMERLIN show cores but combined VLA-eMERLIN visibilities reveal the presence of low-brightness extended jets
EVN/VLBI show cores and extended jetted FR0 on pc scale
Most of FR0s are not just simply young RGs or consistent with FRI/II in the past
X-ray properties are similar to those of FRI: a jet origin.
FR0 can emit $\gamma$-ray emission: (mildly)-relativistic jet?
Large-scale environment: FR0s live in less rich environments than FRIs
Slow jets (low $\Gamma$) due to low BH spins may account for FR0 multi-band properties
what next? radio (high resolution), deep X-ray, ad-hoc numerical simulations