NUCLEAR AND HOST PROPERTIES OF LOCAL AND DISTANT RADIO GALAXIES (FRO-FRI-FRII): SIMILARITIES AND DIFFERENCES

Ranieri D. Baldi
A. Capetti, M. Chiaberge, A. Celotti, E. Behar, A. Laor, and A. Horesh
1. Introduction on AGN and radio galaxies.

2. Radio galaxies in the local \((z < 0.3)\) Universe.

3. Properties of local radio galaxies: nuclei, host, and star formation.

4. New radio-loud AGN population: FR0, dominant class in the local Universe?

5. Distant radio galaxies \((z < 0.7)\) in the COSMOS field: host and AGN properties

6. Similarities and differences between local and distant RG

We now know that almost all galaxy bulges harbour black holes (BH) in their nuclei. Most are quiet/silent and are detectable only via near-nuclear orbital dynamics. A few are accreting gas which makes them visible through the release of potential energy. Such nuclei are called **Active Galactic Nuclei (AGN)** and their hosts are called **Active Galaxies**.
STRUCTURE OF AGN

AGN, an artist’s view

Central black hole

Relativistic jet

Illumination cone

Accretion disk

Narrow line region

Broad line region

Black hole: $R \sim 10^{-6} - 10^{-5}$ pc

Accretion disk: $R \sim 10^{-3} - 10^{-2}$ pc

Broad line region: $R \sim 0.1 - 1$ pc

Narrow line region: $R \sim 10 - 10^2$ pc

Obscuring torus or disk: $R \sim 10^2 - 10^3$ pc

Obscuring dusty torus
Among the many differences distinguishing AGN one of the best known and studied effect is the presence of two populations of AGN, which can be separated on the basis of their radio luminosity with respect to the light emitted in the optical band.

The dichotomy can be parametrized numerically, with a threshold of $L_{\text{radio}}/L_\odot = 10$ (Kellerman + 97) or in X-ray (Terashima & Wilson 03), but in most cases radio-loud AGN can be recognized by the presence of very extended radio-structures clearly associated to large scale jets.
Radio Galaxies are RL AGNs with $L_r = 10^{39}$ up to $10^{46} \text{ erg s}^{-1}$.

- Morphologies of extended radio galaxies from pc to Mpc
- Collimated jets connecting the optical galaxy and the extended lobes
- Associated with elliptical galaxies and $M_{\text{BH}} > 10^8 \text{ M}_\odot$
• Massive Early-type galaxies host RG
• FRI in rich environment, FRII in galaxy group
Multi-wavelength approach
Spectral Energy Distribution

Standard disk / ADAF-RIAF

Relativistic Jet

<table>
<thead>
<tr>
<th>Type of AGN</th>
<th>$L_{bol} \text{ (ergs s}^{-1}\text{)}$</th>
<th>Typical $\dot{M}<em>{bh} \text{ (M}</em>\odot \text{ yr}^{-1}\text{)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard disk</td>
<td>$10^{46} - 10^{48}$</td>
<td>$10^{-3} - 10^{-2}$</td>
</tr>
<tr>
<td>RIAF</td>
<td>$10^{40} - 10^{45}$</td>
<td>$10^{-5} - 10^{-4}$</td>
</tr>
</tbody>
</table>
OPTICAL SPECTRA

BL Lac 0814+425
quasar type

Seyfert 1 NGC4151

Seyfert 2 NGC4941

Standard galaxy NGC3368

BLRG: Broad Line Radio Galaxy
Radio Galaxie à Raies Larges

NLRG: Narrow Line Radio Galaxy
Radio Galaxie à Raies Etroites

Wavelength (Å)
AGN can be classified on the basis of the emission line ratios.

**OPTICAL CLASSIFICATION**

- **LOW EXCITATION GALAXIES (LEG)** (FRI-FRII)
  - Narrow EL

- **HIGH EXCITATION GALAXIES (HEG e BLO)** (FRII)
  - Narrow and broad EL

**BPT:** Baldwin+81, Kewley+06, Buttiglione+10

- **SEYFERT**
- **LINER**
- **STAR FORMING**

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**LOW EXCITATION GALAXIES (LEG)** (FRI-FRII)
- Narrow EL
The simple principle of the Unification model which try to explain the AGN phenomenology is that the differences among various types of AGN arise from orientation dependence.

- **RL AGN**: Urry & Padovani 95
- **RQ AGN**: Antonucci & Miller 85

The narrowed-line HEGs are the obscured counterpart of BLOs.
The fundamental questions:

• what sets the level of activity of local radio galaxies?

• Which are the properties of the hosts of local radio galaxies?

• Which is the link between star formation and nuclear activity?

• Which are the merger histories of local radio galaxies?
Radio-optical-infrared-Xray correlation: Synchrotron-dominated nuclei

Sub-Eddington, low radiatively efficient disk

No torus (for FRI)
ACCRETION-JET

Energy Input

Energy Output
Secular hot gas accretion sets the level of nuclear activity.

Balmaverde, Baldi & Capetti 08
Allen+ 06, Nemmen & Tchekhovskoy 14
No correlation between radio and IR nuclei: no synchrotron origin

SED analysis: IR origin from the torus and disk.

~fraction of Eddington rate, high radiatively efficient disk (standard thin disk)

Torus (49.7° Baldi+13)
Radio-loud AGN are in massive host galaxies ($\sim 10^{10.5} - 10^{11.5} M_\odot$)
FRI ETG are on average brighter (massive) $\sim 0.5$ mag than FRII
**STAR FORMATION**

**HEG: extended star formation**
AGN activity triggered by a recent “wet” (gas rich) merger.
The freshly acquired gas form stars (SFR up to \( \sim 30 \, M_\odot \, yr^{-1} \)) and power the AGN.

**LEG and FRI: no star formation**
No link between AGN and mergers.
No merger or “dry” (gas poor) merger.
Read and dead host galaxies (SFR \( \sim \) few \( M_\odot \, yr^{-1} \))

Baldi & Capetti 08
Are FRI and FRII representative of the “main sequence” radio galaxy population?

Most of the radio galaxies in the (local) Universe are FRI or FRII?
Best et al (2005) select 2215 low-luminosity radio-loud AGN ($F > 5\text{mJy}$) cross-matching SDSS (DR2) and NVSS and FIRST in the local Universe ($z < 0.3$).

Most of the Best et al. sample shows a clear deficit in total radio emission with respect the classical radio galaxies FRI and FRII.
BR 0 radio galaxies

Baldi & Capetti 09; Baldi, Capetti, Giovannini 15

• Compact radio morph < some kpc

• Lack of substantial extended radio emission

• High core dominance

• Nuclear luminosity \( \sim 10^{40} \) erg/s similar to FRI \( \rightarrow \) hot gas accretion

• LEG spectrum

• Red (elliptical) hosts

• Dominant radio class of the radio-loud AGN population

Radio maps: < 0.2”, < 3kpc

Sadler+ 14

Compact FR0 are the dominant source population at 20 GHz (AT20G-6dFGS sample)
LOCAL RADIO GALAXIES

LOW-POWER RG -> RED HOST
HOT GAS ACCRETION MODE

HIGH-POWER RG -> BLUE HOST
COLD GAS ACCRETION MODE
Our knowledge of RG at high z is exclusively based on studies of FRII.

The missing piece of the puzzle? study of FRI at high z.

Dunlop & Peacock 90, Condon+ 02,

Gendre, Best, Wall 10
High-z radio galaxies usually associated with Massive galaxies, (obscured) quasar, high star formation, (proto-) cluster (e.g., review from Miley & De Breuck 08)
FRI AT HIGH Z

• a few FRI in 7C sample (Heywood + 07) and two possible FRI in HDF (Snellen & Best 01)

• Chiaberge + 09 selected the first sizeable sample of 37 FRI candidates at $z \geq 1$ in the COSMOS field.

• 4-steps selection criteria: radio ($1 < F < 13 \text{ mJy}$), optical ($m_i > 21$), no FRII, independent of photo-z
FRI CANDIDATES

VLA-COSMOS

- Extended and compact radio sources
- $1 < z < 2$, Ilbert + 09, Mobasher + 07
- Host: no clear spirals and one QSO (Prescott + 06)

5'' -> ~40 kpc @ z=1.5 ~ 1.5'' resolution
COSMOS Survey

- COSMOS survey provides multi-wavelength imaging and spectroscopy from radio to X-ray, covering a 2 deg².
- It includes HST, Subaru, GALEX, Spitzer data

Capak+ 07, 08, Taniguchi+ 08, Koekemoer + 07, Sanders + 07
Counterpart identification: 29 correctly identified in $i$ band.

We perform our 3″-aperture photometry on the mis-identified counterparts.
Spectral Energy Distribution

- SEDs from FUV to MIR bands.
- Stellar Templates: Bruzual & Charlot 03, 09 and Maraston+ 05
- E(B-V)=0-3
composite stellar population with single SF history

Two stellar population (OSP and YSP) and dust component(s)
• The photo-z of the sample range from 0.7 to 3.
• Agreement with previous photo-z derivation and spectro-z (Ilbert+09, Lilly + 07, Trump + 07).
**RESULTS: RADIO DISTRIBUTION**

- K-corrected Radio distribution straddling the FRI/FRII break: LP and HP sources
- \( L_{\text{FIRST}} \approx 10^{40.7-42.3} \) erg/s

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**FRI/FRII break**

![Histograms showing LP and HP sources with K-corrected distribution across the FRI/FRII break.](image)

- LP
- HP

- Baldi+ 13, 14
RESULTS: STELLAR POP

- Stellar masses: $10^{10.5-11.5} \, M_\odot$.
- SEDs are red and dominated by OSPs.
- OSP: $1-3 \times 10^9 \, \text{yr}$.
- YSP: 1-30 Myr and $\lesssim 1\%$ mass contribution.
T range ~300-850 K; radio-IR relation: AGN origin

$L_{dust} \sim 10^{43.5-45.5} \text{ erg s}^{-1}$

$L_{UV} \sim 10^{42-44} \text{ erg s}^{-1}$

radio-UV no relation, IR-UV relation: SF or AGN?
- $\log R_x > -4.5$: radio loud
- X-ray- radio correlation: synchrotron nuclei?
- IRAC diagnostics: QSO?
- $M_{\text{BH}} > 10^8 M_\odot$?
HIGH-Z RADIO POPULATION

In COSMOS field

$F_{\text{FIRST}} > 13 \, \text{mJy}$

+ FRII

- FRI e FRII
- $0.7 < z < 3$
- SED: most are OSP
- UV and MIR excess are typically in FRII
COMPARISON WITH LOCAL RG

- Radio distribution: LP-HP/LEG-HEG
- Host mass: $\sim 10^{10.5} - 10^{11.5} \, M_\odot$
- Host color: LP red, HP bluer
- Accretion: QSO vs RIAF
- Environment (Castignani et al 14)
- MIR and UV excess in HP and not in LP

LP/HP = FRI/FRII? Possible progenitors?
COSMIC EVOLUTION

- Similar stellar masses
- Similar color vs radio power relation
- HP RG have a stronger evolution than LP RG

LP RG occur in most massive galaxies at z~1 and quench cold gas accretion
HP RG undergo gas-rich merger which induces strong BH and galaxy growth

Smolcic+ 09, Best+ 14
Heckman & Best 14
CONCLUSIONS

• LP and HP radio galaxies in local Universe appear to have typically similar behavior to those in distant Universe: accretion, host properties, environment.

• Future: study of the new population of FR0; optical spectra e radio morphology of distant radio galaxies.
THANK YOU