RADIO VIEW ON AGN

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AGN

- Seyfert (1943): Star-like nuclei + peculiar emission-line spectra in spirals (NGC 1068, NGC 4151)
- Baade & Minkowski (1954): Cygnus A radio source has Seyfert-like spectra
- Schmidt (1963): Quasar 3C 273 at z=0.158 discovered
The AGN zoo: list of AGN classes.

<table>
<thead>
<tr>
<th>Class/Acronym</th>
<th>Meaning</th>
<th>Main properties/reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sey1</td>
<td>Seyfert 1</td>
<td>FWHM \geq 1,000 \text{ km s}^{-1}</td>
</tr>
<tr>
<td>Sey2</td>
<td>Seyfert 2</td>
<td>FWHM \leq 1,000 \text{ km s}^{-1}</td>
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<tr>
<td>QSO</td>
<td>Quasar-like, non-radio source</td>
<td></td>
</tr>
<tr>
<td>QSO2</td>
<td>High power Sey2</td>
<td></td>
</tr>
<tr>
<td>RJ AGN</td>
<td>Radio-quiet AGN</td>
<td>see ref. 1</td>
</tr>
<tr>
<td>RL AGN</td>
<td>Radio-loud AGN</td>
<td>see ref. 1</td>
</tr>
<tr>
<td>Jetted AGN</td>
<td>with strong relativistic jets; see ref. 1</td>
<td></td>
</tr>
<tr>
<td>Non-jetted AGN</td>
<td>without strong relativistic jets; see ref. 1</td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>Sey1 and quasars</td>
<td></td>
</tr>
<tr>
<td>Type 2</td>
<td>Sey2 and QSO2</td>
<td></td>
</tr>
<tr>
<td>FR I</td>
<td>Fanaroff-Riley class I radio source</td>
<td>radio core-brightened (ref. 2)</td>
</tr>
<tr>
<td>FR II</td>
<td>Fanaroff-Riley class II radio source</td>
<td>radio edge-brightened (ref. 2)</td>
</tr>
<tr>
<td>BL Lac</td>
<td>BL Lacertian object</td>
<td>see ref. 3</td>
</tr>
<tr>
<td>Blazar</td>
<td>BL Lac and quasar</td>
<td></td>
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<tr>
<td>BAL</td>
<td>Broad absorption line (quasar)</td>
<td>ref. 4</td>
</tr>
<tr>
<td>BLO</td>
<td>Broad-line object</td>
<td>FWHM \geq 1,000 \text{ km s}^{-1}</td>
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<tr>
<td>BLAGN</td>
<td>Broad-line AGN</td>
<td>FWHM \geq 1,000 \text{ km s}^{-1}</td>
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<tr>
<td>BLRG</td>
<td>Broad-line radio galaxy</td>
<td>RL Sey1</td>
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<tr>
<td>CDQ</td>
<td>Core-dominated quasar</td>
<td>RL AGN, $f_{\text{core}} \geq f_{\text{rel}}$ (same as FSRQ)</td>
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<tr>
<td>CSS</td>
<td>Compact steep spectrum radio source</td>
<td>core dominated, $\alpha_r &gt; 0.5$</td>
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<tr>
<td>CT</td>
<td>Compton-thick</td>
<td>$N_H \geq 1.5 \times 10^{24} \text{ cm}^{-2}$</td>
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<tr>
<td>FR 0</td>
<td>Fanaroff-Riley class 0 radio source</td>
<td>ref. 5</td>
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<tr>
<td>FSRQ</td>
<td>Flat-spectrum radio quasar</td>
<td>RL AGN, $\alpha_r \leq 0.5$</td>
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<tr>
<td>GPS</td>
<td>Gigahertz-peaked radio source</td>
<td>see ref. 6</td>
</tr>
<tr>
<td>HBL/HISP</td>
<td>High-energy cutoff BL Lac/blazar</td>
<td>$\nu_{\text{sync peak}} \geq 10^{15} \text{ Hz}$ (ref. 7)</td>
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<tr>
<td>HEG</td>
<td>High-excitation galaxy</td>
<td>ref. 8</td>
</tr>
<tr>
<td>HPQ</td>
<td>High polarization quasar</td>
<td>$P_{\text{opt}} \geq 3%$ (same as FSRQ)</td>
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<tr>
<td>Jet-mode</td>
<td></td>
<td>$L_{\text{kin}} \gg L_{\text{ext}}$ (same as LERG); see ref. 9</td>
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<tr>
<td>BRL/ISP</td>
<td>Intermediate-energy cutoff BL Lac/blazar</td>
<td>$10^{14} \leq \nu_{\text{sync peak}} \leq 10^{15} \text{ Hz}$ (ref. 7)</td>
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<tr>
<td>LINER</td>
<td>Low-ionization nuclear emission-line regions</td>
<td>see ref. 9</td>
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<tr>
<td>LLAGN</td>
<td>Low-luminosity AGN</td>
<td>see ref. 10</td>
</tr>
<tr>
<td>LBL/LSP</td>
<td>Low-energy cutoff BL Lac/blazar</td>
<td>$\nu_{\text{sync peak}} &lt; 10^{14} \text{ Hz}$ (ref. 7)</td>
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<td>LDQ</td>
<td>Lobe-dominated quasar</td>
<td>RL AGN, $f_{\text{core}} &lt; f_{\text{rel}}$ (ref. 7)</td>
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<tr>
<td>LEG</td>
<td>Low-excitation galaxy</td>
<td>ref. 8</td>
</tr>
<tr>
<td>LPQ</td>
<td>Low polarization quasar</td>
<td>$P_{\text{opt}} &lt; 3%$</td>
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<tr>
<td>NLAGN</td>
<td>Narrow-line AGN</td>
<td>FWHM \leq 1,000 \text{ km s}^{-1}</td>
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<tr>
<td>NLRG</td>
<td>Narrow-line radio galaxy</td>
<td>RL Sey2</td>
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<tr>
<td>NLS1</td>
<td>Narrow-line Seyfert 1</td>
<td>ref. 11</td>
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<tr>
<td>OVV</td>
<td>Optically violently variable (quasar)</td>
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<tr>
<td>Population A</td>
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<tr>
<td>Population B</td>
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<tr>
<td>Radiative-mode</td>
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<tr>
<td>RBL</td>
<td>Radio-selected BL Lac</td>
<td>Seyferts and quasars; see ref. 9</td>
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<tr>
<td>Sey1.5</td>
<td>Seyfert 1.5</td>
<td>ref. 13</td>
</tr>
<tr>
<td>Sey1.8</td>
<td>Seyfert 1.8</td>
<td>ref. 13</td>
</tr>
<tr>
<td>Sey1.9</td>
<td>Seyfert 1.9</td>
<td>ref. 13</td>
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<tr>
<td>SSRQ</td>
<td>Steep-spectrum radio quasar</td>
<td>RL AGN, $\alpha_r &gt; 0.5$</td>
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<tr>
<td>USS</td>
<td>Ultra-steep spectrum source</td>
<td>RL AGN, $\alpha_r &gt; 1.0$</td>
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<tr>
<td>XBL</td>
<td>X-ray-selected BL Lac</td>
<td>BL Lac selected in the X-ray band</td>
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<tr>
<td>XBONG</td>
<td>X-ray bright optically normal galaxy</td>
<td>AGN only in the X-ray band/weak lined AGN</td>
</tr>
</tbody>
</table>
THE RL-RQ DICHOTOMY

Palomar Bright Quasar Survey
Kellermann+ 1989

Radio-loud / Radio-quiet AGN
$$R = \frac{S_{5\, \text{GHz}}}{S_{\text{B-band}}} \geq 10$$

Bimodality observed

Quasars      $$M_B < -23$$
“AGNs”      $$M_B > -23$$

~15% sources “radio-loud”

Jetted (<1%) versus Non-jetted
Radio-Loud AGN typically reside in elliptical galaxies, Radio-Quiet AGN typically in spiral galaxies.
Supermassive black hole (SMBH) 
$\sim 10^6 - 10^9 \, M_\odot$

Broad-line region (BLR) line widths 
$\sim 1000 - 10,000 \, \text{km/s}, \, n_e > 10^9 \, \text{cm}^{-3}$

Narrow-line region (NLR) line widths 
$\leq 500 \, \text{km/s}, \, n_e \sim 10^3 \, \text{cm}^{-3}$

Dusty torus shields the BLR from some lines of sight

Jets launched from Accretion disk-SMBH interface

Type 1s & 2s differ by orientation

Unification (Antonucci 1993)
RADIO-LOUD AGN: FANAROFF-RILEY DICHTOTOMY

Fanaroff-Riley type I (FRI) & type II (FRII)

$L_{178} \approx 2 \times 10^{25}$ W/Hz
(Fanaroff & Riley, 1974)

Break depends on host galaxy magnitude
(Owen & Ledlow, 1994)

Hybrid radio morphology sources
(Gopal-Krishna & Wiita, 2000)
RADIO-LOUD UNIFICATION

Pole-on FRIs = BL Lac objects

Pole-on FRIIs = Quasars

(Urry & Padovani 1995)

- Formation, collimation and propagation of jets?
- Jet composition?
- Jet stability: is there a large-scale magnetic field?
- Interaction with the surrounding medium?
JET FORMATION IN AGN

Blandford & Znajek (1977)

Energy & angular momentum extraction from a spinning black hole.

Strong poloidal magnetic field needed

Power extracted is proportional to $B^2 \& \omega^2$

$B =$ magnetic field strength
$\omega =$ angular velocity
VERY LONG BASELINE INTERFEROMETRY (VLBI)

- Widely separated antennas not connected by cables (Unlike VLA, GMRT)
- Data recorded on magnetic tapes
- Recorded data is time-stamped by atomic clocks (e.g., hydrogen maser)
- Later, the tapes are played back with accurate time-stamps and correlated in a central location
Synchrotron emission is highly linearly polarized (as much as 75% for optically thin radio emission and highly ordered magnetic field)

Electric vectors ($\chi$) - Plane of polarisation

Magnetic field orientation is perpendicular to $\chi$ vectors for optically thin emission

“Spine-Sheath” (Marscher+ 2002, Gabuzda 2003)

Helical magnetic fields (Lyutikov+ 2005)
**ROTATION MEASURE GRADIENTS**

\[ \text{RM} = \frac{e^3}{2\pi m_e c^4} \int n_e B \cdot ds \]

\[ \chi(\lambda^2) = \chi_0 + \lambda^2 \text{RM}, \]

Signature of helical magnetic fields wrapping the jets (Blandford 1993)

**3C78 – VLBI @ 5, 8, 15 GHz (Kharb+ 2009)**

**3C120 – VLBA @ 15, 22, 43 GHz (Gómez+ 2008)**
Monitoring of Jets in AGN with VLBA Experiments (MOJAVE)

>50% of MOJAVE BL Lacs have “hot spots” like FRIIs
Faster parsec-scale jets have more radio-powerful lobes

(Spearman rank correlation test results:
\[ p = 5 \times 10^{-7} \]
Partial regression w/ effects of luminosity
distance removed: \[ p = 0.0028 \]
Partial regression w/ effects of core
luminosity removed: \[ p = 0.0075 \]

Undermines the role of the environment on jet/lobe emission

Continuum in properties between BL Lacs and Quasars

Kharb, Lister, Cooper, 2010
JET DIRECTION CHANGES

X-shaped, Z-shaped Radio Galaxies

Jet Realignment due to Binary Black Holes?
NGC 7674

- Seyfert 2 at $z=0.0289$
- Z-shaped 0.7 kpc radio jet with the VLA (Momjian+ 2003)
- Core not detected at 1.4 GHz
NGC 7674

- VLBA at 2, 5, 8, 15 GHz
- $T_B > 5 \times 10^6$ K. Inverted spectral indices.
- Core projected separation = 0.65 mas = 0.35 parsec. **Closest SMBH binary!**
KILOPARSEC RADIO STRUCTURES

- Systematic studies w/ VLA and Westerbork at 5 & 1.4 GHz
- Diffuse radio emission by starburst-driven winds (Wilson 1988; Baum+ 1993)
- Colbert et al. 1996 suggested AGN-driven based on non-spherical morphology and skewed orientations w.r.t. galactic disks
UGC 3695: FRI radio galaxy with lowest “R” in sample of Seyferts & FRIs (Kharb+ 2014)

Radio Lobe Extent ≥10 kpc, E-S0 galaxy

VLBI image from Kharb+ 2012

FRI - Jetted Seyferts/LINERs (Baldi+ 2018)
Giant radio galaxies $\geq 1$ Mpc

Double-double radio galaxies

AGN activity is episodic

“Relic” steep-spectrum (synchrotron ageing) lobes
RELIC LOBES

3C388; Roettiger+ 1994

- Seyfert 1 NGC 4235: GMRT 325 - 610 MHz spectral index, Lobe: -0.6+/-0.2, Relic: -1.8+/-0.2 (Kharb+ 2016)
- Myers & Spangler (1985) formalism: Relic lobe 2 times older
Jetted Seyfert galaxy Mrk 6

1.4 & 5 GHz - VLA A, B, C, D arrays

North-South ~12 kpc, East-West ~3 kpc, N-S ~1 kpc jet

SFR ~33 M⊙/yr required (Kharb+ 2006)

Herschel (L250µm) SFR < 0.8 M⊙/yr (Kharb+ 2014)
Eddington rates = $\lambda = \frac{L_{\text{bol}}}{L_{\text{Edd}}}$

when $\lambda < 0.01$ Radiatively Inefficient Accretion Flow
else “standard” geometrically thin, optical thick disk


\[
L_{\text{Edd}} = \frac{4\pi G m_p c}{\sigma_T}
\approx 1.26 \times 10^{31} \left(\frac{M}{M_\odot}\right) W = 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot
\]
SUMMARY

- Magnetic fields (helical?) instrumental in jet launching, collimation, propagation
- Role of environment unsettled; also Jet composition
- Continuum in properties between FRIIs and FRIs
- Continuum in properties between FRIs and Jetted Seyferts/LINERs
- AGN classification may depend only on a few parameters: Orientation, Accretion-rate, Presence (or absence) of strong jets, Host galaxy and its environment
- SKA with large frequency coverage (50 MHz - 20 GHz) and nanoJy sensitivity will revolutionize the study of Radio AGN