The jet detections in radio-loud narrow-line Seyfert 1 galaxies

(Gu et al. 2015, ApJS, 221, 3; Gu et al. 2016, AN)

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Shining from the heart of darkness: Black hole accretion and jets
Outline

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  radio-loud AGNs
  narrow line Seyfert 1 galaxies (NLS1s)
• The radio structure of radio-loud NLS1s
  VLBA observations
  comparison with other AGNs
  scenarios
• Ongoing and future work
• Summary
AGN structure and radio-loud AGNs

• Radio loudness: \( R \equiv \frac{L_{\nu 5}}{L_{\nu 4400}} \),
  \( R > 10 \) radio-loud; \( <1 \) radio-quiet;
  \( 1 < R < 10 \) radio intermediate
  (Kellermann et al. 1994)

• Radio luminosity: \( P_{6\text{ cm}} \approx 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1} \)
  (Miller et al. 1990)

Only 10%–20% were qualified as radio-loud objects in optically selected samples (e.g., Kellermann et al. 1989; Hooper et al. 1995).

Urry & Padovani (1995)
Narrow Line Seyfert 1 galaxies (NLS1s)

- Balmer lines broader than forbidden lines but narrower than normal type 1 AGNs (FWHM < 2000km/s)
- Peculiar properties: softer X-ray spectra, fast X-ray variability, strong optical Fe IIs
- Relatively small black hole mass $10^{6-8} \, M_\odot$ (e.g. Collin & Kawaguchi 2004), however still controversial: viewing angle, radiation pressure ...
- High accretion rate $L_{bol} > 0.1 \, L_{Edd}$ (up to $L_{bol}/L_{Edd} \sim 1$)
- Accretion possible via slim disk (e.g. Abramowicz et al. 1988; Mineshige et al. 2000)
Radio-loud NLS1s (RLNLS1s)

- NLS1s were long thought to be radio-quiet. Radio-loud NLS1s are rare, but they do exist (Siebert et al. 1999; Grupe et al. 2000; Zhou & Wang 2002; Zhou et al. 2003; Whalen et al. 2006; Komossa et al. 2006; Yuan et al. 2008).

- RL NLS1s sample from SDSS: >100 out of ~2000 NLS1s (Zhou et al. 2006) – RL (R>10) fraction = 7%; very radio-loud (R>100) NLS1s: very rare – 23 from SDSS DR5 (Yuan et al. 2008).

- Komossa et al. (2006): the radio loud NLS1 galaxies are generally compact, steep spectrum sources.

- Several of the radio loudest NLS1 galaxies display blazar characteristics and harbor relativistic jets (Doi et al. 2007; Zhou et al. 2007; Yuan et al. 2008)

- Flat radio spectra, large-amplitude flux and spectral variability, compact radio cores, very high variability brightness temperatures, enhanced optical continuum emission, flat X-ray spectra, and blazar-like SEDs.
Compact at arcsec scale

- Arcsecond-resolution observations have resolved the structures of only a few NLS1s because they are generally quite compact (e.g. Ulvestad et al. 1995, Moran et al. 2000, Stepanian et al. 2003, Doi et al. 2012).
Host galaxies

- Almost all the low redshift NLS1s are hosted by spiral galaxies (Crenshaw et al. 2003, Deo et al. 2006)
Host galaxies of RLNLS1s: unclear
RLNLS1s in overall AGNs

- Relatively smaller $M_{BH}$, and larger accretion rate.
- Two sequences on R - Eddington ratio plane (Sikora et al. 2007).

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**Fig. 1.**—Total 5 GHz luminosity vs. $B$-band nuclear luminosity. BLRGs are marked by filled circles, radio-loud quasars by open circles, Seyfert galaxies, and LINERs by crosses, FR I radio galaxies by open triangles, and PG quasars by filled stars.

**Fig. 3.**—Radio loudness $\mathcal{R}$ vs. Eddington ratio $\lambda$. BLRGs are marked by filled circles, radio loud quasars by open circles, Seyfert galaxies and LINERs by crosses, FR I radio galaxies by open triangles, and PG quasars by filled stars.
Jet formation

- Jets in BHBs and AGNs: similar?
- Jet-production related parameters: black hole mass, spin, host galaxy, accretion rate, environments ...

Fender et al. (2004)  
Yuan & Narayan (2014)
VLBI observations

- Morphologies: core & components - flux density, position angle, angular size, flux variability, proper motion and polarization

- Brightness temperature (Ghisellini et al. 1993)

\[
T_B = \frac{S_\nu \lambda^2}{2k\Omega_s} = 1.77 \times 10^{12} \left(\frac{S_\nu}{Jy}\right)(\frac{\nu}{\text{GHz}})^{-2}(\frac{\theta_d}{\text{mas}})^{-2}, \theta_d = \sqrt{\alpha \theta}
\]

\[T_B' = T_B(1 + z)/\delta\]

- Variability brightness temperature: (e.g. Yuan et al. 2008)

\[
T_{B,\text{var}} \gtrsim \frac{\Delta P_{B,e}}{2\pi k v^2 (\Delta t)^2} = \frac{2D_1^2 \Delta S_\nu}{(1 + z)\pi kv^2 (\Delta t)^2}
\]

\[T_{B,\text{var}}' = T_{B,\text{var}}/\delta^3\]

- Constraints on Doppler factor: equipartition brightness temperature

\[T_{\text{eq}} = 5 \times 10^{10} \text{ K} \text{ (Readhead 1994)}; \text{ Inverse Compton limit } T_{b,\text{int}} \sim 10^{12} \text{ K} \text{ (Kellermann & Pauliny-Toth 1969)}\]
Status of VLBI observations

• Radio-loud NLS1s: RXS J16290+4007, RXS J16333+4718, and B3 1702+457 (VLBA Gu & Chen 2010, Doi et al. 2011, JVN Doi et al. 2007), RX J0806.6+7248 (JVN Doi et al. 2007, VLBA Doi et al. 2011), B2 1111+32 (EVN, VLBA Chen & Gu in prep.).


• In total, only about 11 RLNLS1s (out of 117) have published VLBI images before Gu et al. (2015, ApJS).
Results of our VLBA observations
(Gu et al. 2015, ApJS, 221, 3)

• The largest sample of 117 RLNLS1s (R>10) has been constructed by combining various samples available so far, which are mostly from our own work.
• Fourteen RLNLS1s with FIRST 1.4 GHz flux >10 mJy were observed with a total of 15 hours at 5 GHz using VLBA on Oct. and Nov., 2013.

• This is the first and largest systematic high resolution radio study of RLNLS1s.

• The jet physics: the jet formation in these accretion systems.
• The accretion – jet relation: early stages in both activities?
• Feedback: jet – cloud interactions?
Table 1: Sample of Radio-loud NLS1 Galaxies

<table>
<thead>
<tr>
<th>Name</th>
<th>z</th>
<th>$f_{1.4\text{GHz}}$ (mJy)</th>
<th>$f_{5\text{GHz}}$ (mJy)</th>
<th>$\alpha$</th>
<th>$\log R$</th>
<th>$a$ (arcsec)</th>
<th>LS (kpc)</th>
<th>r.s.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS J081432.11+560956.6</td>
<td>0.509</td>
<td>69/60</td>
<td>43</td>
<td>-0.33</td>
<td>2.53</td>
<td>2.84</td>
<td>17.4</td>
<td>F</td>
</tr>
<tr>
<td>SDSS J085001.17+462600.5</td>
<td>0.523</td>
<td>21/16</td>
<td>43</td>
<td>-0.33</td>
<td>2.53</td>
<td>2.84</td>
<td>7.8</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J090227.16+044309.6</td>
<td>0.532</td>
<td>153/157</td>
<td>106</td>
<td>-0.30</td>
<td>3.02</td>
<td>1.00</td>
<td>6.3</td>
<td>F</td>
</tr>
<tr>
<td>SDSS J095317.09+283601.5</td>
<td>0.657</td>
<td>45/43</td>
<td>404</td>
<td>-0.51</td>
<td>3.87</td>
<td>1.16</td>
<td>8.7</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J103727.45+003635.6</td>
<td>0.595</td>
<td>27/28</td>
<td>40</td>
<td>-0.51</td>
<td>2.84</td>
<td>3.42</td>
<td>14.2</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J104732.68+472532.1</td>
<td>0.798</td>
<td>734/789</td>
<td>404</td>
<td>-0.51</td>
<td>3.87</td>
<td>1.16</td>
<td>8.7</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J111005.03+365336.3</td>
<td>0.630</td>
<td>19/23</td>
<td>46</td>
<td>-0.50</td>
<td>2.34</td>
<td>0.43</td>
<td>2.1</td>
<td>S</td>
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<tr>
<td>SDSS J113824.54+365327.1</td>
<td>0.356</td>
<td>13/12</td>
<td>46</td>
<td>-0.50</td>
<td>2.34</td>
<td>0.43</td>
<td>2.1</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J124634.65+023809.0</td>
<td>0.362</td>
<td>37/36</td>
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<td>2.38</td>
<td>1.12</td>
<td>5.6</td>
<td>F</td>
</tr>
<tr>
<td>SDSS J130522.75+511640.3</td>
<td>0.785</td>
<td>84/87</td>
<td>46</td>
<td>-0.50</td>
<td>2.34</td>
<td>0.43</td>
<td>2.1</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J142114.05+282452.8</td>
<td>0.538</td>
<td>48.7/45.4</td>
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<td>1.28</td>
<td>8.1</td>
<td>F</td>
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<tr>
<td>SDSS J144318.56+472556.7</td>
<td>0.703</td>
<td>165/166</td>
<td>72</td>
<td>-0.67</td>
<td>3.07</td>
<td>1.18</td>
<td>8.4</td>
<td>S</td>
</tr>
<tr>
<td>SDSS J154817.92+351128.0</td>
<td>0.478</td>
<td>141/141</td>
<td>107</td>
<td>-0.22</td>
<td>2.84</td>
<td>0.51</td>
<td>3.0</td>
<td>F</td>
</tr>
<tr>
<td>SDSS J163401.94+480940.2</td>
<td>0.494</td>
<td>8/14</td>
<td>46</td>
<td>-0.50</td>
<td>2.34</td>
<td>0.43</td>
<td>2.1</td>
<td>S</td>
</tr>
</tbody>
</table>

Notes. — Col. (1): source name; Col. (2): redshift; Col. (3): the FIRST and NVSS flux densities at 1.4 GHz (in the format of FIRST/NVSS); Col. (4): the flux density at 5 GHz from the literature; Col. (5): the spectral index between 1.4 and 5 GHz when available ($f_{\nu} \propto \nu^{\alpha}$); Col. (6): the radio loudness defined as $f_{\nu}(1.4\text{GHz})/f_{\nu}(4400\text{Å})$; Col. (7): the major axis from FIRST; Col. (8): the upper limit on the source linear size calculated from the FIRST major axis; Col. (9): the radio spectrum based on low-resolution NED data (see Section 4.3): F - flat spectrum, S - steep spectrum, $^a$ - uncertain (see text for details).
Morphology

- Generally compact: seven sources show compact core only, and other seven objects have core-jet structure.
Core-jet
Radio spectra

- From the multi-band radio data, seven sources show flat or even inverted spectra, while steep spectra are found in rest objects.

Steep radio spectrum – resemble to Compact Steep Spectrum sources
• Fermi detected? (Foschini 2011): SDSS J124634.65+023809.0 (TS=15)
• Core only, different from others

Flat radio spectrum – blazar like (see also Orienti et al. 2015 for VLBA images)
Brightness temperature

• The core brightness temperature ranges from $10^{8.4}$ to $10^{11.4}$ K with a median value of $10^{10.1}$ K.
• The radio emission is from non-thermal jets, and the beaming effect is generally not significant.
• Typical blazars have $10^{11} - 10^{13}$ K with a median value near $10^{12}$ K (Kovalev et al. 2005, 2009).
• The bulk jet speed may likely be low in our sources (see also Angelakis et al. 2015, Richards & Lister 2015).

Kovalev et al. 2009
Comparisons to typical CSSs: VLBI morphology

• Most high-power CSSs show double or triple morphologies (O’Dea 1998, Dallacasa et al. 2013)
Core and core-jet in low-power CSSs

- The compact core only, or core-jet structure have been detected in relatively low-power CSS sources (Kunert-Bajraszewska et al. 2006; Kunert-Bajraszewska & Marecki 2007)
Evolu)on

• Our sources occupy the space below the main evolutionary path of radio objects (An & Baan 2012).
• However, the difference is that our sources have small black hole mass and high accretion rate.
Scenario: low jet speed

- a) The outflows/jets accelerated from the hot corona above the disk by the magnetic field and radiation force, with high mass loss rate but low speed (Cao 2014).

- The \( M_{\text{BH}} - \Gamma \) correlation: the faster moving jets are magnetically accelerated by the magnetic fields threading the horizon of more rapidly rotating black holes (Chai, Cao & Gu 2012).

- b) The low jet speed could be due to the low spin, supported by low/intermediate average spins (\( a < 0.84 \)) from composite broad Fe K line (Liu et al. 2015).
Ongoing work (I)
Gu et al. in prep.

- The additional 19 RLNLS1s with FIRST flux density $\geq$6 mJy have been observed with VLBA in a total of 24 hours in Nov. and Dec. 2014, yielding the biggest VLBI sample of 33 sources.
- Five core-jet, and fourteen core-only; low brightness temperature compared to blazars; steep-spectrum and flat-spectrum sources.

Komossa et al. 2015
Ongoing work (II)

• To constrain the jet bulk velocity, 10 sources with core-jet structure have been observed with VLBA for 14 hours in Apr. 2016, and Oct. 2015, to detect the jet proper motion.

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>$f_{\text{GHz}}$ (mJy)</th>
<th>archive</th>
<th>Fermi</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS J081432.11 + 560956.6</td>
<td>0.509</td>
<td>43</td>
<td>2006-May, 2013-Nov., 2014-May</td>
<td>No</td>
</tr>
<tr>
<td>SDSS J090227.16 + 044309.6</td>
<td>0.532</td>
<td>295</td>
<td>2000-Apr., 2013-Mar., 2014-Jan.</td>
<td>No</td>
</tr>
<tr>
<td>SDSS J094857.31 + 002252.4</td>
<td>0.798</td>
<td>404</td>
<td>2006-May, 2013-Nov.</td>
<td>No</td>
</tr>
</tbody>
</table>

Notes. — Col. (1): source name; Col. (2): redshift; Col. (3): the flux density at 5 GHz; Col. (4): the previous VLBA 5 GHz observations; Col. (5): whether the source is detected by Fermi LAT.
Ongoing work (III)

SDSS J1433+4725: a gamma-ray detected NLS1 galaxy with CSS-like property

Abstract:

SDSS J1443+4725 \((z=0.703)\) is a radio-loud narrow line Seyfert 1 galaxy (NLS1) with radio properties similar to compact steep spectrum (CSS) sources. We recently found gamma-ray emission at high significance from Fermi/LAT. Its uniqueness makes it precious in studying the accretion process, jet activity and high energy emission. Our previous VLBA 5 GHz observation shows a likely core-jet structure with seven components in central regions and diffuse extended emission at outer regions. As continuation of our systematical study on the jet properties of radio-loud NLS1s, we propose multi-frequency polarimetry observations on SDSS J1443+4725 with VLBA at 2.3, 5.0, 8.4, 15.3, and 22 GHz, for a total observing time of 10.5 hours. We aim to study the jet physics in details, including identification of radio core, core-shift effect, variability, proper motion, and polarization. All these information will be crucial in understanding the gamma-ray emission, in terms of its origin (jets or/and core), and the role of beaming effect etc..

Liao et al. arXiv: 1510.05584
Summary

• Powerful jets may present in systems with small $M_{\text{BH}}$ and high accretion rate, e.g. NLS1s.

• The jet properties of radio-loud NLS1s are diverse on mas scale, in terms of the morphology and spectral shape.

• The jet speed in these sources is likely low, which is due to either the jet acceleration by the magnetic field and radiation force, or low spin in BZ mechanism.

• The slow jet speed or mildly relativistic jet, in combination with the low kinetic/radio power, could be responsible for the compact VLBA radio structure in most sources.
Thanks for your attention!
Polarization

- The higher fractional polarization in jets: the strong Faraday rotation in nuclei region due to the high plasma density, and/or depolarization due to the complex core structure.

- The gradient of fractional polarization along the direction perpendicular to the jet elongation: the jet-ISM interaction at the locations of high fractional polarization because of the jet bulk motion.