Properties of the radio jet emission of four gamma-ray Narrow Line Seyfert 1 galaxies

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Seyfert Galaxies

General: discovery, properties, characteristics
Seyfert 1943, ApJ...97...28 studied “6 extragalactic nebulae” that were showing:

- “high excitation nuclear emission lines superposed on a normal G-type spectrum”
- all lines were Doppler broadened up to 8500 km/s
- the max width of the Balmer emission increased with the absolute mag of the nucleus and the (light on nucleus)/(total light of nebula)

following Khachikian & Weedman 1974, ApJ...192...581, they are further classified:

- Seyfert 1: HI Balmer lines are broader than forbidden lines
- Seyfert 2: HI Balmer lines and forbidden lines are approximately same width

(typically FWHM for forbidden lines for both are 300-800 km/s while HI in Seyfert 1’s are 1000-6000 km/sec)
Seyfert galaxies then are characterized by:

- extremely bright nuclei
- very bright emission lines
- lines strong Doppler broadened,
- vary fast
- originating near an accretion disc:
  ‣ at the surface of the accretion disk, or
  ‣ at gas clouds illuminated by the central engine in an ionization cone
- narrow lines from the outer part of the AGN
- not varying
- in **Type 2** the broad component is obscured
  ‣ in cases it can be observed in polarized light which is BLR scattered by hot, gaseous halo surrounding the nucleus *(Antonucci & Miller 1985, ApJ...297...621).*
Davidson & Kinman 1978, ApJ...225...776 noticed that **MRK 359**:  
• was lying at the low-end of the line-width distribution  
• HI and forbidden lines showed FWHM ~ 300 km/s (similar to Seyfert 2)  
• and showed properties common for Seyfert 1’s but rare for Seyfert 2’s:  
  ‣ strong featureless continuum  
  ‣ strong high-ionisation lines (e.g. [Fe VII] and [Fe X])  
That is: shows a mixture of properties of type 1 and 2 implying a special category that of “**Narrow Line Seyfert 1**” (Osterbrock & Dahari 1983, ApJ...273...478)

Koski 1978, ApJ...223...56 and Philips 1978, APJL...38...187 noticed that **MRK 42** showed similar properties with all line-widths to be narrow like in Seyfert 2

HST image, Malkan, Gorjian & Tam, 1998, ApJ...117...25
Osterbrock & Pogge 1985, ApJ...297...166 then studied a number of such sources that showed:

- unusually narrow HI lines
- strong Fe II line
- normal luminosities
- Hβ was slightly weaker than typical Seyfert 1’s

Zhou et al 2007, ApJ...658...L13 summarize:

- a narrow width of the broad Balmer emission line: FWHM(Hβ) < 2000 km s⁻¹
- weak forbidden lines: [O III] λ5007/Hβ < 3).
Narrow Line Seyfert 1 galaxies
Radio Observations
Ulvestad, Antonucci & Goodrich 1995, AJ...109...81 studied 7 NLSY1s with VLA:

- the **radio power** at 5 GHz is moderate ($10^{20-23}$ W/Hz)
- the radio emission is **compact** (< 300 pc)

Moran 2000, NewA Rev....44...527 studied 24 NLSY1s with VLA:

- most of the sources are **unresolved**
- show relatively **steep spectra**

Stepanian et al. 2003, ApJ...588...746 studied 26 NLS1 galaxies and found:

- found 9 radio-detected (FIRST) all **radio-quiet**

Greene, Ho & Ulvestad 2006, ApJ...636...56 observed in radio 19 galaxies with low BH mass and NLS1 spectra and **found only 1**
Komossa et al 2006, AJ...132...531 studied a number of NLS1s and found:

- most radio-loud NLS1 are **compact, steep**-spectrum, accreting close to or **above** the $L_{\text{Edd}}$
- black hole masses are generally at the upper observed end for NLS1 but still **unusually small**
- index $R$ is distributed smoothly up to the critical value of $\sim 10$ and covers about 4 orders of magnitude
- $\sim 7\%$ of the NLS1 galaxies are formally radio-loud,
- only $2.5\%$ exceed a radio index $R > 100$
- morphology similar Compact Steep Spectrum sources (e.g. PKS 2004–447 by Galo et al. 2006, MNRAS... 370...245)

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![Diagram](image_url)

**Notes on Individual Objects**

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_{1.4}$</th>
<th>$f_{1.4}$</th>
<th>$f_{2.4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS 0204–304</td>
<td>0.67</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>PKS 0229+110</td>
<td>0.38</td>
<td>0.84</td>
<td>2.7</td>
</tr>
<tr>
<td>PKS 2004–447</td>
<td>0.46</td>
<td>0.51</td>
<td>1.4</td>
</tr>
<tr>
<td>PKS 0558–425</td>
<td>0.48</td>
<td>0.69</td>
<td>1.4</td>
</tr>
<tr>
<td>PKS 2235+145</td>
<td>0.56</td>
<td>0.33</td>
<td>1.4</td>
</tr>
<tr>
<td>PKS 2316–006</td>
<td>0.67</td>
<td>0.33</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Komossa et al 2006, AJ...132...531
RL Narrow Line Seyfert 1 galaxies
the *Fermi* / LAT discovery
Abdo et al. 2009, ApJ...699...976 reports the very first Fermi/LAT detection of PMNJ0948+0022

in the first year 4 RL NLSy1 galaxies are detected (Foschini et al. 2010, ASPC...427...243):

- 1H0323+342 (z = 0.061)
- PMNJ0948+0022 (z = 0.585)
- PKS1502+036 (z = 0.409)
- PKS2004-447 (z = 0.24)

after 30 months 7 are detected:

- SBS 0846+513 (z = 0.585) (F. D’Ammando et al. 2012, MNRAS...426...317)

currently ~dozen RL NLSy1s are detected in MeV - GeV at lower significance (Foschini et al. 2011, PoS...024 : http://tinyurl.com/gnls1s)
What is so special about RL NLSy1s:

*E.g. Foschini et al. 2013, PoS:*

- a new class of γ-ray AGN
- show jets similar to blazars although very different in:
  - mass $10^6-8M_\odot$
  - high accretion rate $0.1-1L_{\text{Edd}}$
  - host morphology (mostly in spirals)

- **What switches on the jet production?**
- allow us to study a rather unexplored range of low masses ($10^6-8M_\odot$):
  - breaking down of the mass requirement of the central accreting object to develop a jet in AGN (*Laor 2000, ApJ...543...L111*)

- RL NLSy1s maybe blazars in a early stage of their life

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**Fig. 3** Jet power vs mass of the central black hole (*top panel*) and the accretion luminosity in Eddington units (*bottom panel*). See the text for more details.

*Foschini 2011, RAA....11.1266F*
**F-GAMMA program** (*Furhmann et al. 2007, AIPCS... 921...249 ; Angelakis et al. 2010arXiv1006.5610A*):

- Effelsberg 100-m, IRAM 30-m and APEX 12-m
- monitoring ~60 Fermi blazars since January 2007
- at 2.6 - 345 GHz at 12 frequencies, optical and gamma-rays
- linear and circular polarization
- mean cadence 1.3 months

**RoboPol program** (*Pavlidou, Angelakis et al. in prep.*):

- optical polarimetry (first light spring 2013)
- ~100 sources (targets and “control” sample)
- cadence 1/3 days

**VLBI structural evolution:**

- J0324+3410 (*Karamanavis, Furhmann et al. in prep.*)

See talk by Prof. V. Pavlidou
J0324+3410

cm to sub-cm bands | light curves

- **mild variability** at low frequencies and intense at high
- short-lived events
- high frequency events absent at low frequencies! (events not energetic enough?...)
- extended jet apparent even at intermediate frequencies

![Diagram of J0324+3410 and 1H0323+342 SEDs and light curves](image.png)

**Table 3: Parameters Used to Model the SEDs**

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_{\text{diss}}$</th>
<th>$a$</th>
<th>$\log M_b$</th>
<th>$R_{\text{BLR}}$</th>
<th>$P'_i$</th>
<th>$\log L_d$</th>
<th>$B$</th>
<th>$\Gamma_b$</th>
<th>$\theta_v$</th>
<th>$\gamma_e$, break</th>
<th>$\gamma_e$, max</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1H 0323+342</td>
<td>1.9 (650)</td>
<td>7.0</td>
<td>116</td>
<td>1.0</td>
<td>1.4 (0.9)</td>
<td>30</td>
<td>12</td>
<td>3</td>
<td>60</td>
<td>6000</td>
<td>–1</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>PKS 1502+036</td>
<td>24 (4000)</td>
<td>7.3</td>
<td>155</td>
<td>21</td>
<td>2.4 (0.8)</td>
<td>1.6</td>
<td>13</td>
<td>3</td>
<td>50</td>
<td>3000</td>
<td>1</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>PKS 2004–447</td>
<td>6 (4000)</td>
<td>6.7</td>
<td>129</td>
<td>0.39</td>
<td>1.45 (0.2)</td>
<td>6.9</td>
<td>8</td>
<td>3</td>
<td>120</td>
<td>1500</td>
<td>0.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>PMN J0948+0022</td>
<td>72 (1600)</td>
<td>8.2</td>
<td>300</td>
<td>240</td>
<td>9 (0.4)</td>
<td>3.4</td>
<td>10</td>
<td>6</td>
<td>800</td>
<td>1600</td>
<td>1</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

**Notes.**

- $R_{\text{diss}}$ in units of $10^{15}$ cm and (in parenthesis) in units of the Schwarzschild radius.
- $M_b$ in units of $M_\odot$ (details and caveats about the mass estimation used in this work can be found in Ghisellini et al. 2009a; the error with this method is generally about 50%).
- $R_{\text{BLR}}$ in units of $10^{15}$ cm.
- $P'_i$ in units of $10^{41}$ erg s$^{-1}$.
- $L_d$ in units of $10^{45}$ erg s$^{-1}$ calculated by integrating the thermal component (black dotted line) of the SEDs in Figure 1 and (in parenthesis) in Eddington units.
- $B$ in Gauss.
- $\Gamma_b$ at $R_{\text{diss}}$.
- $\theta_v$ in degrees.
- $s_1$ and $s_2$ are the slopes of the injected electron distribution below and above $\gamma_e$, break.

**Abdo et al. 2009, ApJ...707...L142–L147**
J0324+3410
cm to sub-cm bands | radio SED

- prominent quiescence spectrum
  - optically thin extended jet: $\alpha_{2.6-8.4} \text{ min} \sim -0.5$
- spectral evolution at high frequencies $\alpha_{25-230} \text{ max} \sim +1.0$
  - very homogenous events
- rapid spectral variability (~month)
J0324+3410

• **highly radio polarized**: signature of a optically thin relic jet
• **highly variable polarization**: indicative of spectral events
• correlated with opacity evolution

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>&lt;PD&gt; (%)</th>
<th>StDev</th>
<th>&lt;PA&gt; (deg)</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.85</td>
<td>6.6</td>
<td>0.97</td>
<td>43</td>
<td>5</td>
</tr>
<tr>
<td>8.4</td>
<td>5.8</td>
<td>1.03</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>10.45</td>
<td>6</td>
<td>3.15</td>
<td>30</td>
<td>15</td>
</tr>
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**Analysis done by I. Myserlis**
**J0324+3410**

VLBI | structural evolution

- combine variability D and apparent speeds to extract
  - viewing angles
  - Lorenz factors
- super-c indicating relativistic jet

\[ u_{app} = \frac{u_{jet} \sin \theta}{1 - \frac{u_{jet}}{c} \cos \theta} \]

\[ \delta_{jet} = \gamma_{jet} \left(1 - \frac{u_{jet}}{c}\right)^{-1} \]

### Component ID | mass/ly | \( \beta_{jet} \) | Notes
--- | --- | --- | ---
J1 | 0.0037 | 0.0017 | The stationary feature
J2 | 0.164 | 0.658 |
J3 | 0.752 | 3.017 |
J4 | 1.676 | 6.723 |
J5 | 0.616 | 2.471 |
J0948+0022

cm to sub-cm bands | light curves

- **intense variability** (factors ~5)
- **short events** with spectral evolution
- events propagation in band-pass (energetic enough? ... )
J0948+0022
cm to sub-cm bands | radio SED

- absent (?) quiescence spectrum:
  $\alpha_{2.6-8.4}^{\text{min}} \sim -0.13$

- spectral evolution present at all frequencies:
  $\alpha_{2.6-8.4}^{\text{max}} \sim +1.3$

- variability transverses the band-pass
  $\alpha_{25-230}^{\text{max}} \sim +1.6$ and $\alpha_{25-230}^{\text{min}} \sim -1.7$
  - homogenous events

- rapid spectral variability

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2010arXiv1006.5610A and Angelakis et al. in prep.
J0948+0022

cm to sub-cm bands | radio polarization

- **radio un-polarised**: core dominated, optically thick unpolarised emission
- optical polarization **historical values** ~19%

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>&lt;PD&gt; (%)</th>
<th>StDev</th>
<th>&lt;PA&gt; (deg)</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.85</td>
<td>1.4</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
<td></td>
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<tr>
<td>10.45</td>
<td>3.3</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

J0948+0022

Polarization properties at 4.85 GHz (60mm)
J1505+0326

cm to sub-cm bands | light curves

- mild variability
- long events
- core dominated


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J1505+0326

cm to sub-cm bands | radio SED

- mostly convex spectrum
  - $\alpha_{2.6-8.4 \text{ min}} \sim -0.2$ and $\alpha_{2.6-8.4 \text{ min}} \sim +0.3$
  - $\alpha_{10-25 \text{ max}} \sim +0.2$ and $\alpha_{10-25 \text{ min}} \sim -0.5$
- mild spectral evolution
- variability self-similar: semi-achromatic

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2010arXiv1006.5610A and Angelakis et al. in prep.

11th Helic Astronomical Society Conference, September 2013
J1505+0326
radio and optical polarization

- radio rather un-polarized or very little or variable: core dominated, optically thick un-polarized emission
- optically: un-polarized

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>&lt;PD&gt; (%)</th>
<th>StDev</th>
<th>&lt;PA&gt; (deg)</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.85</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.45</td>
<td>2.9</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R band</td>
<td>5.7 +/- 5.3</td>
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</tbody>
</table>

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Putting it all together

variability mechanism | $T_B$ | Doppler factors | jet powers
Variability
TB and Doppler factors

Variability amplitude measures brightness temperature:

\[ T_B = 4.5 \cdot 10^{10} \cdot \Delta S_\lambda \left( \frac{\lambda \cdot d_\lambda}{\Delta t_\lambda \cdot (1 + z)^2} \right)^2 \]

Assuming Equipartition brightness temperature limit:

\[ T_B \approx 5 \cdot 10^{10} \cdot \left( \frac{\delta_{\text{var.}}}{1 + z} \right)^{3+\alpha} \]

Hence, Equipartition Doppler factor:

\[ \delta_{\text{var.}} = (1 + z)^{3+\alpha} \sqrt{T_B/5 \cdot 10^{10}} \]
Variability
TB and Doppler factors

• J0324+3410
  - time scales ~ 40 d
  - $T_{B,15\text{GHz}} \approx 4.1 \times 10^{10}$ °K (log=11.6)
    implying $D \approx 0.4$

• J0948+0022 (see also Foschini et al. 2012, 2012arXiv1209.5867F)
  - time scales ~180 d
  - $T_{B,15\text{GHz}} \approx 2.3 \times 10^{11}$ °K (log=13.4)
    implying $D \approx 2.1$

• J1505+0326
  - time scales ~120 d
  - $T_{B,15\text{GHz}} \approx 5.3 \times 10^{11}$ °K (log=12.7)
    implying $D \approx 1.1$
variability mechanism
intrinsic modulation indices

- shock model (Marscher & Gear 1985)
- study case CTA102:
  - a conical jet (p = 1)
  - a toroidal magnetic field (b = 1.2)
  - constant Doppler factor
- if all follow same pattern: increase - max: ~ 60-80 GHz - then plateau - decrease

\[ \mathcal{L}(\mathbf{m}) = \int_{\text{all } S_0} dS_0 S_0 \left\{ \left( \prod_{j=1}^{N} \frac{1}{\sqrt{2\pi (\bar{m}^2 S_0^2 + \sigma_j^2)}} \right) \times \exp \left[ -\frac{1}{2} \sum_{j=1}^{N} \frac{(S_j - S_0)^2}{\sigma_j^2 + m^2 S_0^2} \right] \right\} \]

Richards et al. 2011, ApJS...194...29R

calculations done by C. Fromm
variability mechanism
intrinsic modulation indices

Angelakis et al. in prep. | calculations done by V. Pavlidou

Nestoras et al. in prep.

Angelakis et al. in prep. | calculations done by V. Pavlidou

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11th Hellenic Astronomical Society Conference, September 2013
jet powers
radiative and kinetic

- jet power calculated according to the model by Ghisellini & Tavecchio 2009, MNRAS...397...985
- H0=70 km/s/Mpc
- the physical basis of the correlations are described by Blandford & Konigl 1979 (found that the radio flux is linked to the jet power)
- radiative and kinetic (electrons+protons +B) jet powers

\[
\log P_{\text{jet}} = (11 \pm 3) + (0.81 \pm 0.06) \log L_{15 \text{ GHz}}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>( \log(P_{\text{radiative}}) ) (log(erg/s))</th>
<th>( \log(P_{\text{kinetic}}) ) (log(erg/s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0324+3410</td>
<td>43.27</td>
<td>43.52</td>
</tr>
<tr>
<td>J0849+5108</td>
<td>44.80</td>
<td>45.36</td>
</tr>
<tr>
<td>J0948+0022</td>
<td>44.98</td>
<td>45.58</td>
</tr>
<tr>
<td>J1246+0038</td>
<td>43.48</td>
<td>43.78</td>
</tr>
<tr>
<td>J1505+0326</td>
<td>44.72</td>
<td>45.26</td>
</tr>
</tbody>
</table>
Conclusions
Conclusions

Light curves

- Light Curves
  - 0324 and 1505: **mild variability**
  - J0948: **intense variability** (factors of 5)
  - variability (intrinsic stdev) for J0324, J0948 imitates the “**shock-in-jet**”
    - exception: J1505 behaves otherwise

- Standard deviation vs Rest frequency
  - Red = BLLacs, Blue = FSRQs

- J0324+3410, 1H0323+342
  - Rest frequency (GHz): 4.85 GHz, 8.35 GHz, 10.45 GHz, 14.60 GHz, 23.05 GHz, 32.00 GHz, 42.00 GHz

- J0948+0022
  - Rest frequency (GHz): 3.64 GHz, 4.85 GHz, 8.35 GHz, 10.45 GHz, 14.60 GHz, 23.05 GHz, 32.00 GHz, 42.00 GHz

- J1505+0326, PKS1502+036
  - Rest frequency (GHz): 4.85 GHz, 8.35 GHz, 10.45 GHz, 14.60 GHz, 23.05 GHz, 32.00 GHz, 42.00 GHz, 86.00 GHz, 142.33 GHz
Conclusions

Radio SEDs

- not one flavour
- J0324: quiescent present, mild evolution, only high frequencies
- J0849: NO quiescent present, intense evolution, all frequencies
- J0948: NO quiescent present, intense evolution, all frequencies
- J1505: NO quiescent present, NO evolution - achromatic
Conclusions

Polarization

- J0324: **radio polarized** (indicative of opt. thin large scale jet.) - R-band unpolarized
- J0948: **radio unpolarized** - R-band (?)
- J1505: **radio unpolarized** - R-band unpolarized
Conclusions

- a new class of gamma ray AGNs
- low mass systems ($10^6$-$8$)
- high accretion $\sim L_{\text{edd}}$

- clear indications for presence of a relativistic jet with characteristics (e.g. variability mechanisms) as seen in all other blazars)
  - superluminal motions
  - SBS 0846+513 reaches observed isotropic $\gamma$-ray luminosity (0.1–300 GeV) of $1.0 \times 10^{48}$ erg s$^{-1}$ on daily timescales, comparable to that of luminous FSRQs
  - similar 0948 (Foschini et al 2012)
  - spectral evolution
    - High $T_B$
  - polarization

- **what is the key parameter for switching on the jet activity** if not the mass, spin?
- more sources needed
- longer cycle to be observed
Thank you!

E. Angelakis | Max-Planck-Institut für Radioastronomie
### Table 1: Sample characteristics

<table>
<thead>
<tr>
<th>Source</th>
<th>z</th>
<th>Var. Index*</th>
<th>Energy Flux (erg cm(^{-2}) s(^{-1}))</th>
<th>(\log(R))**</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0324+3410</td>
<td>0.061</td>
<td>90.6</td>
<td>1.42E-11</td>
<td>2.3 (at 5GHz)</td>
</tr>
<tr>
<td>J0849+5108</td>
<td>0.584</td>
<td>-</td>
<td>-</td>
<td>3.16</td>
</tr>
<tr>
<td>J0948+0022</td>
<td>0.585</td>
<td>326.5</td>
<td>3.89E-11</td>
<td>2.55</td>
</tr>
<tr>
<td>J1246+0238</td>
<td>0.363</td>
<td>-</td>
<td>-</td>
<td>2.38</td>
</tr>
<tr>
<td>J1505+0326</td>
<td>0.409</td>
<td>27.7</td>
<td>2.05E-11</td>
<td>3.19</td>
</tr>
</tbody>
</table>

* Var. Index: 41.6 => chance of being a steady source of less than 1%

\(R=\frac{1.4\text{GHz}}{f(4400\text{A})}\) from Yuan et al. 2008, ApJ...685...801