VLBI and $\gamma$-ray studies of TANAMI radio galaxies

Roberto Angioni, MPIfR Bonn
EVN symposium, 20-23 September 2016
St. Petersburg, Russia
Collaborators

Eduardo Ros – MPIfR Bonn, Uni. Valencia
Matthias Kadler – Uni. Würzburg
Roopesh Ojha – NASA Goddard Space Flight Center
Cornelia Müller – Radboud Uni. Nijmegen
Felicia Krauss – GRAPPA & API, Uni. Amsterdam
Anton Zensus – MPIfR Bonn

TANAMI collaboration

Fermi-LAT collaboration (graduate member)
Outline

• TANAMI program and science
  • VLBI monitoring
  • The highest-resolution view of the closest AGN: Centaurus A
• VLBI sample study of TANAMI radio galaxies: Pictor A
  • Dual frequency imaging
  • Spectral index mapping
  • Kinematics
• $\gamma$-ray studies of radio galaxies
The TANAMI program

Tracking Active Nuclei with Austral Milliarcsecond Interferometry

- ~90 jets at $\theta < -30^\circ$ declination at mas resolution since 2007
- Array: LBA + New Zealand, South Africa, Antarctica, Chile
- Dual frequency 8.4 GHz and 22.3 GHz, 3-4 epochs/yr
The TANAMI program

First-epoch images
Ojha et al. 2010
The TANAMI program

New sources Müller et al. in prep.
The TANAMI program

Centaurus A
Highest-resolution view of the closest AGN jet
Müller et al. 2011, 14

Comp. speeds 0.1 c to 0.3c, downstream acceleration

Intrinsic jet parameters
\[ \theta \sim 12^\circ - 45^\circ \]
\[ \beta \sim 0.24 - 0.37 \]

‘Tuning fork’ \sim 0.4 pc from core revealed by stacked images, most likely jet-start interaction
## TANAMI radio galaxies

<table>
<thead>
<tr>
<th>B1950 IAU</th>
<th>Alt. name</th>
<th>RA</th>
<th>Dec</th>
<th>Class</th>
<th>z</th>
<th>γ-ray det.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0518-458</td>
<td>Pictor A</td>
<td>79.96</td>
<td>-45.78</td>
<td>FR II</td>
<td>0.035</td>
<td>Y</td>
</tr>
<tr>
<td>0521-365</td>
<td>PKS 0521-36</td>
<td>80.74</td>
<td>-36.46</td>
<td>RG/SSRQ</td>
<td>0.057</td>
<td>Y</td>
</tr>
<tr>
<td>0625-354</td>
<td>PKS 0625-35</td>
<td>96.78</td>
<td>-35.49</td>
<td>FRI/BLL</td>
<td>0.055</td>
<td>Y</td>
</tr>
<tr>
<td>1258-321</td>
<td>PKS 1258-321</td>
<td>195.25</td>
<td>-32.44</td>
<td>FR I</td>
<td>0.017</td>
<td>N</td>
</tr>
<tr>
<td>1333-337</td>
<td>IC 4296</td>
<td>204.16</td>
<td>-33.97</td>
<td>FR I</td>
<td>0.013</td>
<td>N</td>
</tr>
<tr>
<td>1343-601</td>
<td>Centaurus B</td>
<td>206.70</td>
<td>-60.41</td>
<td>FR I</td>
<td>0.013</td>
<td>Y</td>
</tr>
<tr>
<td>1549-790</td>
<td>PKS 1549-79</td>
<td>239.25</td>
<td>-79.23</td>
<td>RG/CSO</td>
<td>0.15</td>
<td>N</td>
</tr>
<tr>
<td>1718-649</td>
<td>NGC 6328</td>
<td>260.92</td>
<td>-65.01</td>
<td>GPS/CSO</td>
<td>0.014</td>
<td>Y</td>
</tr>
<tr>
<td>1733-565</td>
<td>PKS 1733-56</td>
<td>264.40</td>
<td>-56.57</td>
<td>FR II</td>
<td>0.099</td>
<td>N</td>
</tr>
<tr>
<td>1814-637</td>
<td>PKS 1814-63</td>
<td>274.90</td>
<td>-63.76</td>
<td>CSS/CSO</td>
<td>0.065</td>
<td>N</td>
</tr>
<tr>
<td>1934-638</td>
<td>PKS 1934-63</td>
<td>294.85</td>
<td>-63.71</td>
<td>GPS</td>
<td>0.18</td>
<td>N</td>
</tr>
<tr>
<td>2027-308</td>
<td>PKS 2027-308</td>
<td>307.41</td>
<td>-30.66</td>
<td>RG</td>
<td>0.54</td>
<td>N</td>
</tr>
<tr>
<td>2152-699</td>
<td>PKS 2153-69</td>
<td>329.28</td>
<td>-69.69</td>
<td>FR II</td>
<td>0.028</td>
<td>N</td>
</tr>
</tbody>
</table>
VLBI dual frequency imaging

VLBI imaging of southern hemisphere radio galaxies (FR I, FR II, compact objects) at 3.6 cm and 1.3 cm

13 sources in total

Perley+ 1997, VLA 1.4 GHz

Angioni+ in prep., TANAMI 8.4 GHz
Spectral index mapping

No previous study on spectral morphology on VLBI scales

Pictor A

Pictor A

8.4 GHz

22 GHz

Preliminary map indicates inverted core
Jet kinematics

Previous VLBI study (Tingay et al. 2000)
- 2 epochs at 8.4 GHz (SHEVE 1993 + VLBA 1999)
- Jet bend at ~5 mas from core
- Subluminal motion of inner components $\beta \lesssim 1$

Preliminary TANAMI features
- 5 epochs at 8.4 GHz
- Jet bend looks persistent
- App. speed for innermost moving component $\beta = 1.8 \pm 0.4$

Angioni+ in prep.
TANAMI radio galaxies

Current progress on sample study:
- Imaging completed for 10/13 sources, ~80 maps in total
- 16 spix maps
- 3 preliminary kinematic analyses
Radio galaxies with *Fermi*-LAT

- Alternative high-energy view of relativistic jets (w.r.t. blazars)
  - Smaller bias from strong Doppler effects
  - Test for unified models, emission models, acceleration models
  - Simultaneous obs. of accretion and jet → origin of radio-loudness

- GeV $\gamma$-rays from RG lobes
  - Energetic particles far from central engine
  - Core/lobes and impact on variability

$\gamma$-ray RGs provide crucial information, but we have only few sources...new detections with Pass8 analysis?
Multi-wavelength and *Fermi*-LAT

- Pass8 *Fermi*-LAT data analysis for RGs and γ-ray undetected quasars: new detections or better ULs
- SEDs: why are these sources not detected by the LAT?
Thank you for your attention!
There is a strong connection between radio and $\gamma$-ray emission in radio-loud AGN...

Correlations (Arshakian+ 2012)

Variability behavior (e.g. Fuhrmann+ 2014, Casadio+ 2015, Rani+ 2014, 2015, Karamanavis+ 2015, 2016)

...but there are bright radio-loud sources without a $\gamma$-ray detection (Lister+ 2015)

Lower SED peak? Doppler factor?
Multi-wavelength and *Fermi*-LAT

- Analysis of Pass8 LAT data for $\gamma$-ray-faint TANAMI sources (radio galaxies and quasars)
**γ-ray-faint sample**

<table>
<thead>
<tr>
<th>Source</th>
<th>RA(J2000)</th>
<th>Dec(J2000)</th>
<th>Redshift</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS 0438-43</td>
<td>70.07167</td>
<td>-43.5525</td>
<td>2.863</td>
<td>Q</td>
</tr>
<tr>
<td>PMN J0529-3555</td>
<td>82.406958</td>
<td>-35.921222</td>
<td>*</td>
<td>U</td>
</tr>
<tr>
<td>PKS 1257-326</td>
<td>195.17678</td>
<td>-32.886697</td>
<td>1.256</td>
<td>Q</td>
</tr>
<tr>
<td>PKS 1258-321</td>
<td>195.25334</td>
<td>-32.441456</td>
<td>0.017042</td>
<td>G</td>
</tr>
<tr>
<td>IC 4296</td>
<td>204.1625</td>
<td>-33.96583</td>
<td>0.012465</td>
<td>G</td>
</tr>
<tr>
<td>PKS 1549-79</td>
<td>239.24542</td>
<td>-79.23444</td>
<td>0.1501</td>
<td>G</td>
</tr>
<tr>
<td>PKS 1716-771</td>
<td>260.96042</td>
<td>-77.23056</td>
<td>*</td>
<td>U</td>
</tr>
<tr>
<td>PKS 1733-56</td>
<td>264.39917</td>
<td>-56.5675</td>
<td>0.098</td>
<td>G</td>
</tr>
<tr>
<td>PKS 1814-63</td>
<td>274.89583</td>
<td>-63.76333</td>
<td>0.0627</td>
<td>G</td>
</tr>
<tr>
<td>PKS 1915-458</td>
<td>289.81950</td>
<td>-45.727389</td>
<td>2.47</td>
<td>Q</td>
</tr>
<tr>
<td>PKS 1934-63</td>
<td>294.85428</td>
<td>-63.71267</td>
<td>0.539</td>
<td>G</td>
</tr>
<tr>
<td>PKS 2027-308</td>
<td>307.74125</td>
<td>-30.65667</td>
<td>0.539</td>
<td>G</td>
</tr>
<tr>
<td>PKS 2106-413</td>
<td>317.38833</td>
<td>-41.1725</td>
<td>1.058</td>
<td>Q</td>
</tr>
<tr>
<td>PKS 2153-69</td>
<td>329.275</td>
<td>-69.69</td>
<td>0.028273</td>
<td>G</td>
</tr>
</tbody>
</table>
Multi-wavelength and *Fermi*-LAT

- Analysis of Pass8 LAT data for $\gamma$-ray-faint TANAMI sources (radio galaxies and quasars)
  - No detections yet, but significantly improved upper limits w.r.t. previously published work (TANAMI paper on 1st year of LAT data, Böck et al. 2016)

<table>
<thead>
<tr>
<th>B1950 IAU name</th>
<th>P7 UL (erg cm^-2 s^-1)</th>
<th>P8 UL (erg cm^-2 s^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0438-436</td>
<td>7.92e-12</td>
<td>2.34e-12</td>
</tr>
<tr>
<td>1257-326</td>
<td>1.55e-11</td>
<td>2.15e-12</td>
</tr>
<tr>
<td>1258-321</td>
<td>1.73e-11</td>
<td>3.43e-12</td>
</tr>
<tr>
<td>1333-337</td>
<td>6.48e-12</td>
<td>1.88e-13</td>
</tr>
<tr>
<td>1549-790</td>
<td>1.59e-11</td>
<td>1.54e-12</td>
</tr>
<tr>
<td>2106-413</td>
<td>4.32e-12</td>
<td>1.55e-12</td>
</tr>
<tr>
<td>2152-699</td>
<td>1.23e-11</td>
<td>1.61e-12</td>
</tr>
</tbody>
</table>
Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler\textsuperscript{1*}, F. Krauß\textsuperscript{1,2}, K. Mannheim\textsuperscript{1}, R. Ojha\textsuperscript{3,4,5}, C. Müller\textsuperscript{1,6}, R. Schulz\textsuperscript{1,2}, G. Anton\textsuperscript{7}, W. Baumgartner\textsuperscript{3}, T. Beuchert\textsuperscript{1,2}, S. Buson\textsuperscript{8,9}, B. Carpenter\textsuperscript{5}, T. Eberl\textsuperscript{7}, P. G. Edwards\textsuperscript{10}, D. Eisenacher Glawion\textsuperscript{1}, D. Elsässer\textsuperscript{1}, N. Gehrels\textsuperscript{3}, C. Gräfe\textsuperscript{1,2}, S. Gulyaev\textsuperscript{11}, H. Hase\textsuperscript{12}, S. Horiuchi\textsuperscript{13}, C. W. James\textsuperscript{7}, A. Kappes\textsuperscript{1}, A. Kappes\textsuperscript{7}, U. Katz\textsuperscript{7}, A. Kreikenbohm\textsuperscript{1,2}, M. Kreter\textsuperscript{1,7}, I. Kreykenbohm\textsuperscript{2}, M. Langejahn\textsuperscript{1,2}, K. Leiter\textsuperscript{1,2}, E. Litzinger\textsuperscript{1,2}, F. Longo\textsuperscript{14,15}, J. E. J. Lovell\textsuperscript{16}, J. McEnery\textsuperscript{3}, T. Natusch\textsuperscript{11}, C. Phillips\textsuperscript{10}, C. Plötz\textsuperscript{12}, J. Quick\textsuperscript{17}, E. Ros\textsuperscript{18,19,20}, F. W. Stecker\textsuperscript{3,21}, T. Steinbring\textsuperscript{1,2}, J. Stevens\textsuperscript{10}, D. J. Thompson\textsuperscript{3}, J. Trüstedt\textsuperscript{1,2}, A. K. Tzioumis\textsuperscript{10}, S. Weston\textsuperscript{11}, J. Wilms\textsuperscript{2} and J. A. Zensus\textsuperscript{18}
Long $\gamma$-ray outburst from blazar PKS B1424-418 coincident with highest energy IceCube neutrino event

TANAMI sees strongest outburst ever from VLBI core, starting before $\gamma$-ray flare (1.5 to 6 Jy)

Chance coincidence probability estimated in $\sim5\%$
TANAMI highlights: time resolved

Krauss et al. 2016
Dynamic SED catalog: 81 SEDs for 22 brightest TANAMI $\gamma$-ray blazars
TANAMI highlights: multi-wavelength

Identification of the peculiar γ-ray source PMN J1603-4904 with a MPS radio galaxy