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VLBI STUDIES OF TANAMI RADIO GALAXIES

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Radio galaxies are relatively faint at γ-ray energies, where they make up only 1–2% of all AGN detected by *Fermi*-LAT. However, they offer a unique perspective to study the intrinsic properties of AGN jets. For this reason, the combination of γ-ray and multi-wavelength data with high-resolution VLBI monitoring is a powerful tool to tackle the basic unanswered questions about AGN jets. Here we present preliminary results from a sample study of radio galaxies in the Southern hemisphere observed by the TANAMI VLBI monitoring program. We obtain high-resolution maps at 8.4 and 22.3 GHz, and study the jet kinematics using multi-epoch data. We present a preliminary kinematic analysis for the peculiar γ-ray AGN PKS 0521−36.

Keywords: VLBI, AGN, γ-rays, Radio galaxies.

1 Introduction

AGN dominate the extragalactic high-energy γ-ray sky, as revealed by the Third *Fermi*-LAT Gamma-ray source List (3FGL, [2]). The great majority of the sources are blazars, i.e. radio-loud AGN with relativistic jets oriented at small angles to the observer's line-of-sight. Their radiation is strongly Doppler boosted and shows fast variability. Blazars are among the brightest sources of radiation in the universe, spanning the whole electromagnetic spectrum, from radio to γ-rays. Relativistic jets have been studied for half a century, but their fundamental inner workings are still not well understood, e.g. their acceleration and collimation mechanisms, or the location of the γ-ray emission region.

Radio galaxies are believed to be the parent population of blazars, with jets oriented at larger angles [23]. Because of their misaligned orientation, their radiation is much less Doppler boosted with respect to blazars. Therefore, radio galaxies are typically orders of magnitude fainter than their aligned counterpart, across the whole spectrum. Because of the limited sensitivity of γ-ray instruments, this has particularly evident implications at high-energies. Indeed, *Fermi*-LAT has detected less than 20 radio galaxies so far, while the 3FGL includes more than 1000 associated blazars [3]. In spite of the small sample size and lower fluxes, which complicate radio galaxy studies at high-energies, they provide us with a view on γ-rays from AGN jets which is less biased by relativistic effects, and is complementary to blazar studies [1].

The combination of γ-ray data with high-resolution radio observations can be a powerful tool in investigating these questions. *Fermi*-LAT has an energy-dependent angular resolution of the order of $\sim 0.1^{\circ}$, therefore almost all AGN observed in γ-rays appear as point sources, and it is not possible to directly associate the high-energy emission to a specific morphological component. VLBI observations, on the other hand, are able to achieve milliarcsecond resolutions. Since AGN are variable sources, it is possible to identify the γ-ray emission region on VLBI scales by looking for correlated variability in radio morphology or flux, and high-energy emission (e.g. [4, 9]). Additionally, multi-epoch VLBI observations provide the only direct measure of relativistic jet motion, allowing us to derive relevant jet parameters such as apparent speed and jet orientation angle.

2 The TANAMI monitoring program of Southern-hemisphere AGN

TANAMI (Tracking Active galactic Nuclei with Austral Milliarcsecond Interferometry) is a multi-wavelength monitoring program of AGN jets south of -30° declination, including almost ~ 100 sources. The sample was defined as a hybrid radio flux-limited sample combined with sources detected in γ-rays or reported as likely high-energy emitters [18].

The core of the program is VLBI monitoring at 8.4 GHz and 22.3 GHz, since 2007. The array is based on the Australian Long Baseline Array (LBA), supported by associated antennas in South Africa, New Zealand, Antarctica and Chile (a full list of the participating antennas can be found in [15]). First-epoch 8.4 GHz images at milliarcsecond resolution were presented for an initial sample of 43 sources by [18]. The sample was constantly expanded with new γ-ray detections or other interesting new sources, and first-epoch images of the first-ever high-resolution observations, for most sources, will be presented in a forthcoming paper (Müller et al. in prep.). The radio VLBI monitoring is complemented by an excellent multi-wavelength coverage, including NIR, optical, UV, X-ray and γ-ray data, providing a quasi-simultaneous broadband view of the sources, as is required for detailed studies of variable sources such as AGN. An overview of the multi-wavelength program and selected TANAMI results can be found in [8].

3 Radio galaxies in TANAMI

Since the TANAMI sample was selected based on current or expected γ-ray detections, the majority of the sources are blazars, but several well-known radio galaxies are also monitored. An example is the closest radio-loud AGN, Centaurus A, for which TANAMI data revealed the complex dynamics of the jet's inner parsec, indicating downstream jet acceleration [15] and a spectral morphology [12] that can be explained within the spine-sheath scenario [20].

The TANAMI sample includes fifteen additional radio galaxies, including several notable sources for which TANAMI is able to provide the highest resolution data available: the classic FR II Pictor A, whose jet has been detected and resolved in X-rays [24] and optical [7] as well as radio bands [21]; the FR I PKS 0625−35, which is the most recent addition to the elusive group of only 5 radio galaxies to be detected in the TeV band by Cherenkov telescopes [6], and shows evidence of superluminal motion in a preliminary kinematic analysis of TANAMI data [13]; the nearby FR I Centaurus B, detected in γ-rays by *Fermi*-LAT with a notably flat spectral index [3]; the peculiar object PKS 0521−36, showing γ-ray variability and originally classified as a BL Lac but later shown to have properties consistent with a larger viewing angle [5]. The full list of TANAMI radio galaxies is given in Table 1.

The multi-wavelength properties of these sources are currently under study within the TANAMI collaboration (Angioni et al. in prep.), including images, kinematic analysis and spectral index maps.

4 The peculiar γ-ray AGN PKS 0521−36

Here we present preliminary results on one γ-ray bright TANAMI radio galaxy, PKS 0521−36. This is a nearby ($z = 0.0565$) AGN with uncertain classification. Leon et al. 2016 [11] classify it as a BL Lac, and derive limits on the jet viewing angle, speed, and Doppler factor using the Atacama Large Millimeter Array (ALMA). Their results suggest a jet viewing angle in the range $16° \leq \theta \leq 38°$. D'Ammando et al. 2015 [5] constrain the same parameters using SED modeling including γ-ray data, obtaining a more aligned jet viewing angle of $6° \leq \theta \leq 15°$. These results point to an intermediate jet viewing angle between a blazar and a steep spectrum radio quasar (SSRQ) or radio galaxy.

Previous VLBI observations performed with the VLBA and with the Southern Hemisphere VLBI Experiment (SHEVE) at 4.9 GHz and 8.4 GHz provided an upper limit on the apparent speed of jet components $\beta_{app} < 1.2$ [22]. This is also consistent with the hypothesis that the jet of PKS 0521−36 is not strongly beamed. The authors mentioned that future more sensitive VLBI data would be able to provide more stringent constraints on the nature of this source.

The TANAMI 8.4 GHz full-resolution image presented in the left panel of Fig. 1 achieves an order of magnitude improvement in sensitivity with respect to previous VLBI data [22], allowing to reveal a more extended jet[1]. TANAMI monitoring provided 9 epochs for this source between 2007 and 2013, an excellent data set for kinematic analysis. Preliminary results from this analysis are shown in the right panel of Fig. 1, where the distance of jet components from the core is plotted as a function of time. The data shown include all TANAMI epochs and the previous VLBI data from [22], providing kinematic information across a ∼20 years time span. A linear regression fit is applied to the components, with two of them being cross-identified between the two data sets, yielding an estimate of their apparent speed.

This preliminary analysis confirms the absence of fast jet apparent motions in PKS 0521−36, with the largest possible apparent speed (for the components that can be reliably identified and fitted) being $\beta_{app} \sim 0.36$ for component C7 (see right panel of Fig. 1). This, together with estimates of the jet-to-counterjet ratio, constrains the intrinsic jet speed and viewing angle to a narrower region of the parameter space with respect to previous studies, namely $\beta > 0.56$ and $\theta < 16^\circ$. This viewing angle estimate agrees with the estimate provided by [5], supporting the hypothesis that the jet of PKS 0521−36 is oriented at an intermediate angle to the line-of-sight.

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Table 1. Radio galaxies in the TANAMI sample.

Source	Catalog	Class	z	*Fermi*-LAT det.
0518−458	Pictor A	FR II	0.035	yes
0521−365	PKS 0521−36	RG/SSRQ	0.0565	yes
0625−354	PKS 0625−35	FR I/BLL	0.0546	yes
1258−321	PKS 1258−321	FR I	0.017	no
1322−428	Centaurus A	FR I	0.0018	yes
1333−337	IC 4296	FR I	0.0125	no
1343−601	Centaurus B	FR I	0.0129	yes
1549−790	PKS 1549−79	RG/CFS	0.150	no
1600−489	PMN J1603−4904	MSO[a]	0.18	yes
1718−649	NGC 6328	GPS/CSO	0.0144	yes
1733−565	PKS 1733−56	FR II	0.098	no
1814−637	PKS 1814−63	CSS/CSO	0.0627	no
1934−638	PKS 1934−63	GPS	0.18	no
2004−447	PKS 2004−447	NLSy1/CSS[b]	0.24	yes
2027−308	PKS 2027−308	RG	0.539	no
2152−699	PKS 2153−69	FR II	0.0283	no

[a] Classified as a young radio galaxy based on multi-wavelength studies [14, 16, 17].
[b] Evidence for classification as young radio galaxy [10, 19].

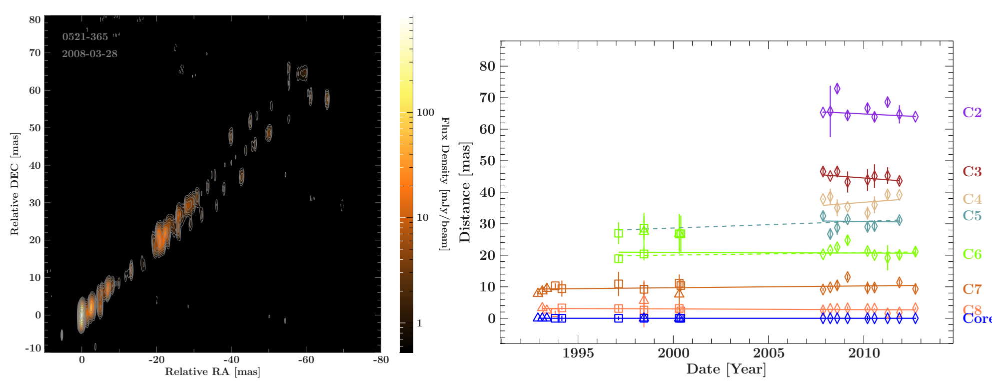

Fig. 1. *Left panel*: TANAMI full-resolution 8.4 GHz images of PKS 0521−36. The contours start at 3 times the rms level. The beam size is indicated in grey in the lower left corner. *Right panel*: Results of the preliminary kinematic analysis for PKS 0521−36, including TANAMI data and previous VLBI data from [22]. The plot shows the distance of jet component relative to the core as a function of time. Triangles and squares indicate 4.9 GHz data and 8.4 GHz data from [22], respectively. Diamonds indicate TANAMI 8.4 GHz data. The errors are estimated as half the component major axis.

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