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# The $\gamma$ -ray properties of radio-selected extragalactic jets

M. Böck<sup>1</sup>, M. Kadler<sup>1,2,3</sup>, G. Tosti<sup>4,5</sup>, T. H. Burnett<sup>6</sup>, C. Müller<sup>1</sup>, R. Ojha<sup>7,8</sup> on behalf of the LAT collaboration, and J. Wilms<sup>1</sup>

<sup>1</sup> Dr. Karl Remeis-Observatory & ECAP, Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

<sup>2</sup> CRESST/NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>3</sup> Universities Space Research Association, 10211 Wincopin Circle, Suite 500 Columbia, MD 21044, USA

<sup>4</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy

<sup>5</sup> Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy

<sup>6</sup> Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

<sup>7</sup> U.S. Naval Observatory, 3450 Massachusetts Ave. NW, Washington DC 20392, USA

<sup>8</sup> NVI, Inc., 7257 Hanover Parkway, Greenbelt, MD 20770, USA

**Abstract.** Most extragalactic jets in radio-loud Active Galactic Nuclei are bright and variable  $\gamma$ -ray sources, which are continuously monitored with *Fermi*/LAT. We present the  $\gamma$ -ray properties of the MOJAVE and TANAMI AGN samples of radio-loud AGN. Both programs provide properties of the parsec-scale radio jets using Very Long Baseline Interferometry (VLBI) techniques. This information is important to understand the broad-band emission mechanism of these sources. In this work we compare the radio and  $\gamma$ -ray properties of the two samples and present upper limits on the  $\gamma$ -ray flux of the radio-brightest jet sources not yet detected by *Fermi*/LAT.

## 1. Introduction

Most extragalactic jets in radio-loud Active Galactic Nuclei (AGN) are bright and variable  $\gamma$ -ray sources. The high luminosity and variability of blazars is explained by a jet orientated close to the line of sight, in which charged particles are moving with relativistic speed, thus the emission is Doppler boosted (Blandford & Rees, 1978; Maraschi et al., 1992). This model is supported by the apparent superluminal motion which is typically found in the inner radio-jets of blazars (Lister et al., 2009b, , and therein).

Since 2008 August 11, the sky is monitored at  $\gamma$ -ray energies in the range from  $\sim 20$  MeV to  $>300$  GeV with the Large Area Telescope (LAT), which is a pair conversion detector on board the *Fermi Gamma-Ray Space Telescope* (Atwood et al., 2009). *Fermi*/LAT scans the whole sky every three hours and its sky-survey mode is optimized to obtain a uniform exposure on longer time scales ( $>$  weeks). A large number of AGN were detected and monitored with *Fermi*/LAT (709 AGN during the first year of operation, Abdo et al., 2010b).

In this work, we present the  $\gamma$ -ray properties of two samples from the two largest ongoing Very Long Baseline Interferometry (VLBI) AGN monitoring survey programs: Tracking Active Galactic Nuclei with Austral Milliarsecond Interferometry (TANAMI; Ojha et al., 2010) and Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE; Lister et al., 2009a). The two samples are described in Sec. 2. For our analysis we use data obtained during the first year of *Fermi* operations.

The combined analysis of radio and  $\gamma$ -ray properties is still in progress. The detailed presentation of the upper limit analysis, a discussion of tentative new detections and individual sources is in work and will be published in an upcoming paper (Abdo et al., 2010, in prep.).

## 2. Sample

In our study, we investigate the  $\gamma$ -ray properties of two samples of extragalactic jets: the MOJAVE1 and the TANAMI samples. MOJAVE1 is a purely radio-selected sample of all AGN at declinations  $\delta > -20^\circ$ , whose 15 GHz radio flux density has exceeded 1.5 Jy (2 Jy for sources with  $\delta < 0^\circ$ ) at any epoch between 1994 and 2004 (Lister et al., 2009a). In total, the MOJAVE1 sample is comprised of 135 AGN: 101 quasars, 22 BL Lac objects, 8 galaxies, and 4 unclassified objects. About two thirds of the sources in the MOJAVE1 sample have been monitored since 1994 as part of the VLBA 2 cm Survey (Kellermann et al., 1998) with the Very Long Baseline Array (VLBA; Napier et al., 1994). Since 2002, the MOJAVE1 sample has been observed with the VLBA as part of the MOJAVE program<sup>1</sup> (see also Lister et al., these proc.).

TANAMI is a radio VLBI monitoring program of currently 75 extragalactic jets south of  $-30^\circ$  declination. The observations are performed approximately every two months with the telescopes of the Australian Long Baseline Array (LBA; Norris, 1988) in combination with telescopes in South Africa, Antarctica and Chile. A detailed discussion of the TANAMI program including a

<sup>1</sup> <http://www.physics.purdue.edu/astro/MOJAVE/>

**Table 1.** Total number  $N$  of the MOJAVE1 and TANAMI sources and the number of those detected with *Fermi*/LAT.

Class	MOJAVE1		TANAMI	
	$N$	detected	$N$	detected
Quasar	101	61	32	24
BL Lac	22	19	10	10
Galaxy	8	3	11	2
Unclassified	4	2	22	17

description of the initial source sample, explanations of the observation and data reduction procedures, and brief notes on the individual sources are given by Ojha et al. (2010). TANAMI contains a radio-selected and a  $\gamma$ -ray selected sub-sample (see Ojha et al., 2010, for details). The radio selected sub-sample supplements the MOJAVE1 sample south of  $-30^\circ$  declination. TANAMI observations are made at 8.4 GHz and 22 GHz yielding spectral indices of parsec-scale jet features (Müller et al., these proc.).

### 3. Analysis

To find associations of the AGN in the MOJAVE1 and TANAMI sample with *Fermi*/LAT-detected  $\gamma$ -ray sources we performed a positional-association analysis. For each radio position of the sources in the sample we selected the closest sources in the “Fermi Large Area Telescope First Source Catalog” (Abdo et al., 2010a) inside the position uncertainty region of the  $\gamma$ -ray source. This approach yielded unique results for the majority of sources. A comparison with the results of the automatic source association pipeline of the LAT team (Abdo et al., 2009), in which the class and physical expectations of the association is taken into account, confirmed these results.

We used a maximum likelihood analysis (Cash, 1979; Mattox et al., 1996) to analyze those AGN which could not be associated with  $\gamma$ -ray catalog sources. For the calculation of upper limits on the  $\gamma$ -ray flux and the test statistic (TS) measuring the significance we used data in the range 100 MeV to 100 GeV obtained in the first year of *Fermi*/LAT.

We used the standard *Fermi*/LAT *ScienceTools* and the methods described by Böck et al. (2009) to obtain the flux, photon index, and test statistic of each unassociated source. For sources with  $TS < 25$  we calculated upper limits on the flux. Sources with  $TS \geq 25$  were considered as tentative new detections and in this case we modeled the flux and the spectral index. For the sources with  $TS < 1$  the upper limits can be underestimated, thus we do not consider these sources in this work. Results for a Bayesian approach following Abdo et al. (2010a) will be presented in a following paper.

### 4. Results

Table 4 shows the number of quasars, BL Lacs, and galaxies in the MOJAVE1 and TANAMI sample which are

associated with  $\gamma$ -ray sources in the *Fermi*/LAT 1-year source list (Abdo et al., 2010a). 85 out of the 135 AGN in the MOJAVE1 sample are detected with *Fermi*/LAT during its first year of operation. With a detection rate of 19/22 most BL Lac objects in the sample are detected. 61/101 quasars are detected and 2/4 unclassified objects. At 3/8, the detection rate of the galaxies is the lowest. In the TANAMI sample 24 out of 32 quasars are detected with *Fermi*/LAT. The detection rates of unclassified sources is substantially higher in the TANAMI sample than in the MOJAVE1 sample. This is most likely due to the inclusion of a  $\gamma$ -ray selected sub-sample and the addition of sources detected by *Fermi*/LAT after three months (Abdo et al., 2009). The detection rates for the radio-selected TANAMI sub-sample consisting of 21 AGN are: 9/13 Quasars, 3/3 BL Lac objects and 2/5 Galaxies, which is comparable to the MOJAVE1 sample.

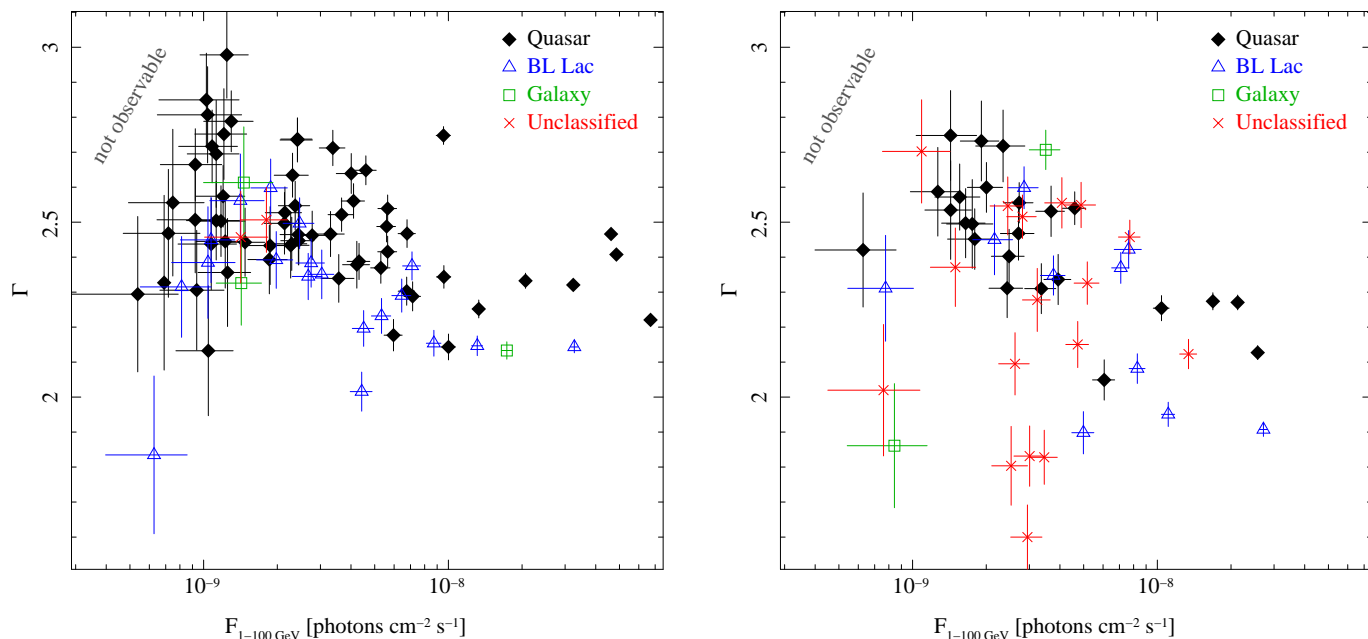
For the analysis of the associated sources we used the photon spectral indices from the *Fermi*/LAT first source catalog calculated in the range of 0.1–100 GeV, since this value can be obtained even for relatively weak sources (Abdo et al., 2010b). Figure 1 shows the distribution of flux and photon spectral index averaged over 11 months. In addition to the catalog values we present the values we obtained for the tentative new detections.

Figure 1 indicates a difference between the MOJAVE1 and the TANAMI sample which is caused by the different selection criteria. The  $\gamma$ -ray selected TANAMI sub-sample contains several hard sources, i.e., sources with relatively small  $\gamma$ -ray photon spectral index, including many BL Lac objects and unassociated sources. BL Lac objects tend to have on average harder  $\gamma$ -ray spectra than the quasars (Abdo et al., 2009, 2010b).

Hard sources can be better localized with *Fermi*/LAT. Thus the limiting photon flux for a  $TS > 25$  detection is significantly lower for BL Lac objects than for quasars with softer spectra (Abdo et al., 2010b, Fig. 10). In Fig. 2 this effect is not visible as the hardest sources in the sample do not reach a photon spectral index of  $\Gamma < 1.5$  as it is the case for the sources discussed by Abdo et al. (2010b). In addition, they consider the photon flux above 100 MeV instead of 0.1–100 GeV, which increases the photon flux for soft sources significantly.

The distribution of spectral indices (Fig. 3) confirms that BL Lac objects exhibit harder  $\gamma$ -ray spectra than quasars and shows that the majority of the spectral indices of the tentatively new detected sources is softer than that of the associated sources, which is consistent with the difficulty to detect soft weak sources with *Fermi*/LAT.

It is worth noting that all three BL Lac objects in the radio-selected TANAMI sub-sample and the majority of BL Lac objects in the MOJAVE1 sample have  $\gamma$ -ray spectral indices  $\Gamma > 2.2$ . Abdo et al. (2010c) found that BL Lacs with  $\Gamma > 2.2$  are mostly low synchrotron peaked (LSP) BL Lacs (see also Abdo et al., 2010b, Fig. 14). It might be expected that a radio-selected sample contains more LSP BL Lacs than high synchrotron peaked ones, as



**Fig. 1.** Distribution of flux and photon spectral indices of the associated sources in the MOJAVE 1 (left) and TANAMI (right) samples. The flux is given in units of photons  $\text{cm}^{-2} \text{s}^{-1}$  in the energy range 1–100 GeV. In the top left corners *Fermi*/LAT cannot detect sources.

the LSP type is brighter at the radio frequencies used for the selection.

## 5. Summary

The  $\gamma$ -ray properties of the MOJAVE 1 and TANAMI AGN samples were analyzed. The detection rates with *Fermi*/LAT depend on the source class. For the radio-selected MOJAVE 1 sample and the radio-selected TANAMI sub-sample BL Lac objects have the highest detection rates, followed by the quasars, whereas only a small fraction of the radio galaxies in the samples are seen by *Fermi*/LAT. With a maximum likelihood analysis on sources which were not associated with  $\gamma$ -ray sources in the *Fermi*/LAT First Source Catalog, we obtained upper limits on the  $\gamma$ -ray flux of these sources and found tentative new detections.

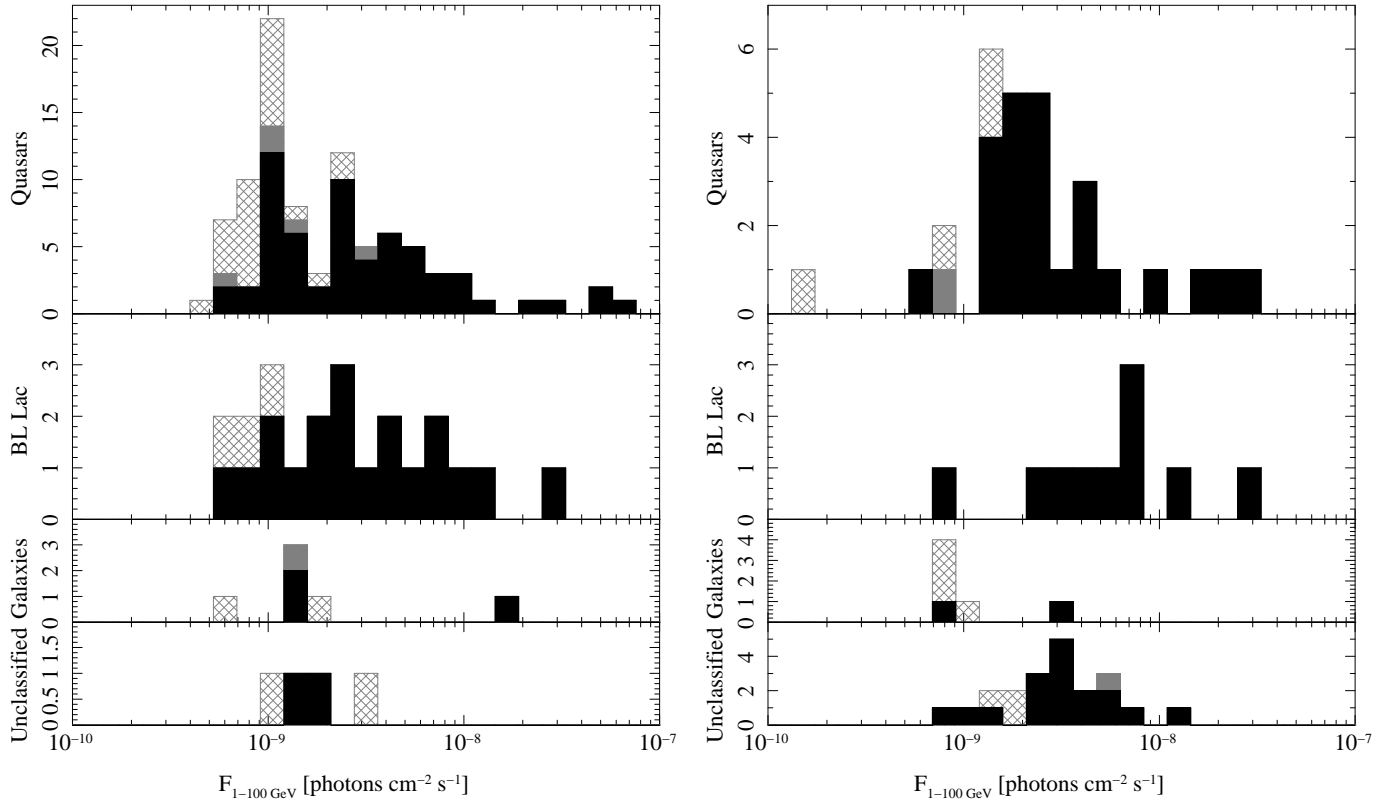
The analysis of the upper limits and the tentative new detections will be discussed in an upcoming paper.

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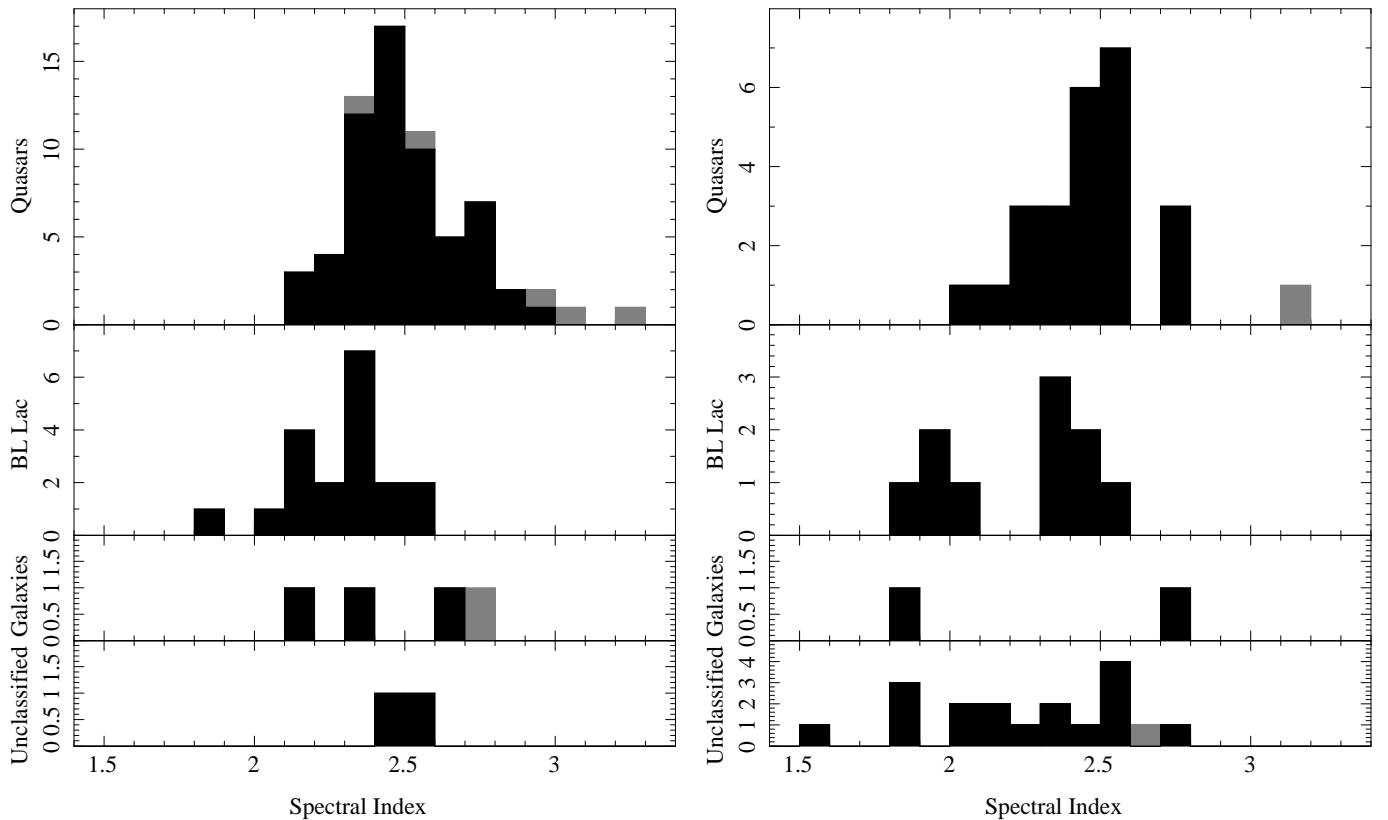
Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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**Fig. 2.** Distribution of the flux of the associated sources in the MOJAVE 1 (left) and TANAMI (right) samples. Sources associated with catalog sources are shown in black, the tentative new detections in gray and the upper limits are shown cross hatched.



**Fig. 3.** Distribution of the spectral index of the associated sources in the MOJAVE 1 (left) and TANAMI (right) samples. The tentative new detections are shown in gray.

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