



The TANAMI Program

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Abstract. The TANAMI (Tracking AGN with Austral Milliarcsecond Interferometry) program provides comprehensive VLBI monitoring of extragalactic gamma-ray sources south of declination -30° . Operating at two radio frequencies (8 and 22 GHz), this program is a critical component of the joint quasi-simultaneous observations with the *Fermi* Gamma-Ray Space Telescope and ground based observatories to discriminate between competing theoretical blazar emission models. We describe the TANAMI program and present early results on the 75 sources currently being monitored.

1. Introduction

Very Long Baseline Interferometry (VLBI) observations play a unique role in unraveling the physics of active galactic nuclei (AGN). They provide the only direct measurements of relativistic motion in AGN, thus measuring jet speeds, Doppler factors, opening and inclination angles of jets. With their unmatched resolution, VLBI observations can allow us to associate γ -ray flaring activity with structural changes on milliarcsecond scales (such as jet-component ejections) helping to identify the location and extent of emission regions.

VLBI observations have acquired particular salience in the age of *Fermi*. Data from *Fermi*/LAT in combination with other space and ground-based telescopes have made possible the quasi-simultaneous observations across the electromagnetic spectrum that have long been considered essential to distinguish between different models of AGN emission. The close connection between VLBI and *Fermi* observations is impressively demonstrated by the large number of VLBI-*Fermi* papers published and submitted in the past year, including many from the *Fermi*/LAT collaboration, to which VLBI observations have contributed crucially needed data for the proper interpretation of γ -ray results. With VLBI data we have started to address some of the most crucial questions raised by the association of γ -ray emission with blazars.

2. The TANAMI Program

The indispensable role of parsec-scale monitoring of radio- and γ -ray bright AGN has led to the establishment of a

number of highly successful VLBI monitoring programs (see Lister et al. 2010 for a review) but all of these programs use northern hemisphere arrays that cannot observe much of the southern hemisphere. The TANAMI program is the only parsec scale monitoring program targeting AGN south of declination $\sim 30^\circ$. Further, uniquely among comparable VLBI programs, TANAMI observations are made at two frequencies (8.4 and 22 GHz). This lets us monitor the parsec-scale spectra of the cores and the brightest jet features, allowing us to contribute radio spectral indices of jet features to *Fermi* multi-wavelength studies (e.g., Abdo et al. 2010a, Chang et al. 2010) besides probing emission processes along AGN jets (e.g., Müller et al. 2010, Hungwe et al. 2010).

Since it covers that third of the sky not observed by other VLBI monitoring programs, TANAMI significantly improves the statistics for jet kinematics and flare-ejection studies. This region of the sky includes many interesting AGN (see below) and newly discovered γ -ray AGN can be followed up, often for the first time, with VLBI (e.g., Abdo et al. 2009). The TANAMI collaboration has also begun work with the ANTARES (Coyle 2010) and KM3NeT (Piatelli 2010) consortia, two neutrino telescopes that target the southern sky. *Fermi* γ -ray variability data and TANAMI-determined jet-ejection epochs will help develop data-filtering techniques to search for extragalactic neutrino point sources. This could usher us into an era of multi-messenger astronomy.

TANAMI observations are made using the telescopes of the Australian Long Baseline Array (LBA¹; e.g.,

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14. ABSTRACT The TANAMI (Tracking AGN with Austral Milliarcsecond Interferometry) program provides comprehensive VLBI monitoring of extragalactic gamma-ray sources south of declination -30 degrees. Operating at two radio frequencies (8 and 22 GHz), this program is a critical component of the joint quasi-simultaneous observations with the Fermi Gamma-ray Space Telescope and ground based observatories to discriminate between competing theoretical blazar emission models. We describe the TANAMI program and present early results on the 75 sources currently being monitored.					
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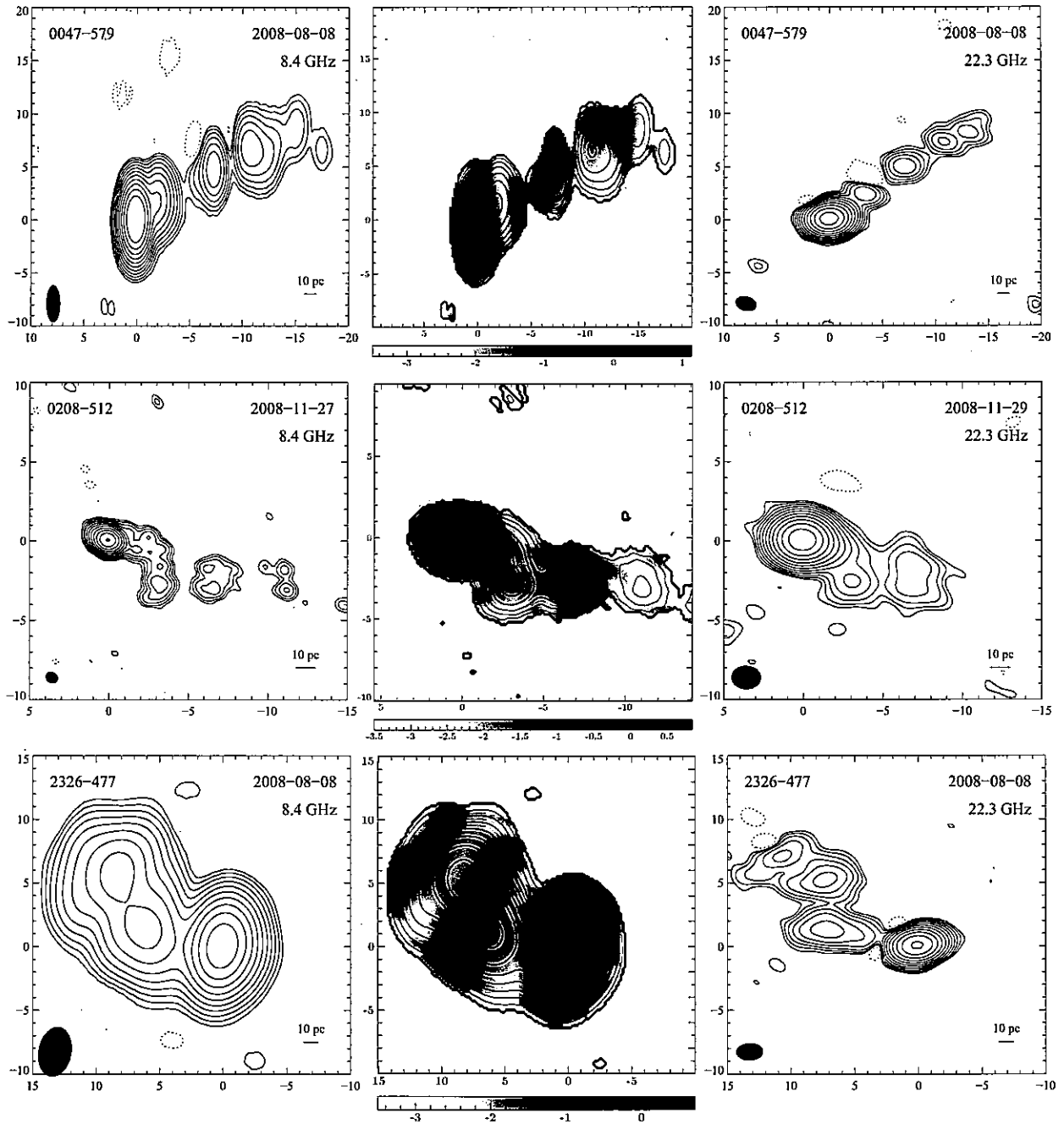


Fig. 1. TANAMI images of four *Fermi* sources. Starting from the top, the four rows show images of 0047-579, 0208-512, and 2326-477 respectively. In each row the left image shows the image at 8 GHz and the image on the right at 22 GHz at the same epoch. In the center of each row is the spectral index image made from the simultaneous images at these two frequencies. Both the axes in all plots are labeled in milliarcseconds from the center of the image. The hatched ellipse at the bottom left of each contour image represents the synthesized beam of the observing array. The color coding in the spectral index image represents the spectral index defined as $F_\nu \sim \nu^\alpha$.

Ojha et al. 2005) and affiliated telescopes. TANAMI was able to significantly improve the (u, v) -coverage of the LBA by obtaining access to International VLBI Service (IVS) telescopes in Antarctica and Chile as well as Deep Space Network telescopes in Tidbinbilla, Australia. All telescopes that participate in TANAMI observations are listed, along with their diameters, in Table 1. At each epoch and each frequency, every source is typically observed for 6 scans of about 10 minutes each. Typical (u, v) -coverage at both frequencies are shown in Müller et al. 2010. Our augmentation of the LBA has lead to the highest fidelity images for most of the sources observed by TANAMI.

The initial sample of 44 TANAMI sources were selected based on previous (EGRET) γ -ray detection and/or radio flux density and luminosity. Under an MoU (Memorandum of Understanding) with the *Fermi* collaboration TANAMI started monitoring observations of new *Fermi* sources through 2009 adding the new sources to our observing schedule while decreasing the observing cadence of sources showing limited radio-structural variability. The current TANAMI sample includes 75 sources of which 55 have been detected by *Fermi*. 53 TANAMI sources have 1FGL (Abdo et al. 2010c) associations while 2 are tentative new detections (Böck et al. 2010). To date, 12 epochs (most at both frequencies) have been observed. Correlation, processing and imaging are progressing smoothly. Images and other results are available at our website² as soon as they are finalized. For further details of the TANAMI program including details of calibration and imaging see Ojha et al. (2010).

3. Results

TANAMI is routinely producing VLBI images of high quality at 8 and 22 GHz (X and K-band respectively). We show examples for three sources in Fig. 1. For each source we show the 8.4 GHz image and the 22 GHz image from the same epoch (on the left and right respectively). In the center of each row is shown the corresponding two-frequency spectral index image. It is important to note that the resolution of the lower frequency image is often *better* than that of the higher frequency image because the trans-oceanic telescopes in Antarctica and Chile cannot observe at 22 GHz.

These spectral index images were made by aligning the brightest pixels in the X and K-band images from the same epoch. The images at both frequencies have been convolved with the larger of the two beams of the individual images. The larger beam has also been used to produce the overlaid contours on these images. The color coding depicts the spectral index defined as $F_\nu \sim \nu^\alpha$ i.e., a positive spectral indicates an inverted spectrum. Thus we are able to measure spectral indices of the cores and individual jet features and we are using these data to measure core shift, localize the central engine, calculate the opac-

Table 1. VLBI array for TANAMI observations.

Telescope	Diameter [m]
Parkes, NSW, Australia	64
Narrabri, NSW, Australia	5×22
Hobart, TAS, Australia	26
Ceduna, SA, Australia	30
Hartebeesthoek, S. Africa ^a	26
DSS43, ACT, Australia ^b	70
DSS45, ACT, Australia ^b	34
O’Higgins, Antarctica ^c	9
TIGO, Concepción, Chile ^c	6

^a Not available since Sept 2008. Likely return Sept 2010.

^b Operated by the Deep Space Network of the National Aeronautics and Space Administration, USA

^c Operated by the German Bundesamt für Kartographie und Geodäsie (BKG) http://www.bkg.bund.de/nn_147094/EN/Home/homepage__node.html__nnn=true

ity towards the central engine and identify the emission along the jet. In combination with data at other wavelengths we are modeling the SEDs of AGN. Note that the figures shown here are not corrected for coreshift.

For a growing number of sources in our sample we have enough epochs of data to study their kinematics. We are fitting Gaussian components to jet features to track jet trajectories, measure their speeds, and derive their intrinsic parameters. When combined with SED modeling, these kinematic data address the relationship between the Doppler-boosting parameters for the radio and γ -ray emitting regions of the jets.

TANAMI data have been and are being used in a number of studies that can broadly divided into two categories, individual source studies and statistical studies of the full sample or some subset, which are briefly described below.

3.1. Individual Source Studies

Studies of individual TANAMI sources include:

- One of the first *Fermi*/LAT publications addresses a bright γ -ray flare of the poorly studied source PKS 1454-354 (Abdo et al. 2009). TANAMI contributed the first deep 8.4 GHz VLBI image of this source revealing its core-jet structure.
- TANAMI data on nine *Fermi*/LAT sources were used to generate SEDs of the γ -ray selected LBAS blazars and investigate their broadband spectral properties (Abdo et al. 2010a).
- TANAMI data were used to construct the SED of PKS 2052-47 during a LAT multiwavelength campaign (Chang et al. 2010).
- TANAMI data are being used to study the highly variable BLLac 0537-441 which is one of the most luminous γ -ray blazars detected in the southern sky so far (Hungwe et al. 2010)

² <http://pulsar.sternwarte.uni-erlangen.de/tanami/>

• TANAMI data were used to constrain the size of the γ -ray emitting region and for SED modeling of the nearest galaxy Centaurus A (Abdo et al. 2010b). A multi-epoch, dual-frequency analysis of the innermost regions of this source is in progress (Müller et al. 2010)

3.2. First Epoch Results

First epoch 8.4 GHz results for the initial sample of 43 sources have been analyzed and presented in Ojha et al. (2010). Using the classification scheme of Kellermann et al. (1998), the initial sample has 33 single-sided (SS) and 5 double-sided (DS) sources with just one example each of the compact (C) and irregular (Irr) morphological types. Three sources do not have an optical identification. All of the quasars and BL Lacertae objects in the sample have an SS morphology while all 5 DS sources are galaxies. The lone C source is optically unidentified while the only Irr source is a GPS galaxy 1718–649.

The core and the total luminosity was calculated for all 38 initial TANAMI sources that had published redshifts, assuming isotropic emission. There is no significant difference in the distribution of luminosities of LBAS and non-LBAS sources. On the other hand, there is a clear relationship between luminosity and optical type with quasars dominating the high luminosity end of the distribution, galaxies dominating the low luminosity end while the BL Lacertae objects fall in between.

The redshift distribution of the quasars and BLLacs in the TANAMI sample is similar to those for the LBAS and EGRET blazars. There does not appear to be any significant difference between the radio- and γ -ray selected subsamples. The core brightness temperature (T_B) limit of all initial TANAMI sources was calculated. The high end of the distribution of calculated brightness temperatures is dominated by quasars and the low end by BL Lacertae objects and galaxies. Of the 43 sources in the sample, 14 have a maximum T_B below the equipartition value of 10^{11} K (Readhead 1994), 30 below the inverse Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969), putting about a third of the values above this limit. There is no significant difference in the brightness temperature distribution of LBAS and non-LBAS sources.

A link between γ -ray emission and the parsec scale morphology of AGN has been sought (e.g., Taylor et al. 2007). We fit circular Gaussians to the visibility data and measured the angle at which the innermost jet component appears relative to the position of the core i.e. the opening angle. Of the LAT AGN Bright Sample (LBAS) sources 78% have an opening angle > 30 degrees while only 27% of non-LBAS sources do. This result should be treated with great caution as the sample size for this analysis is currently small but Pushkarev et al. (2009) report similar results.

If confirmed, the above result presents two possibilities: either the LBAS jets have smaller Lorentz factors (since the width of the relativistic beaming cone

$\sim 1/\Gamma$) or LBAS jets are pointed closer to the line of sight than γ -ray faint jets. The former scenario appears unlikely, indeed the opposite effect is reported by Lister et al. (2009), Kovalev et al. (2009).

4. Conclusions

Fermi sources in the southern third of the sky are being monitored by the TANAMI program at about every two months. These high quality, dual frequency observations are producing spectral index images at milliarcsecond resolutions which are a crucial element in the multiwavelength study of AGN physics. For a subset of the TANAMI sample, the number of observed epochs is now sufficient for kinematic modeling to begin. When combined with jet-speed measurements, SED modeling across the electromagnetic spectrum will let us probe the relation between the Doppler-boosting parameters for the radio and γ -ray emitting regions of the jet.

Studies of several individual AGN detected by *Fermi* have been enriched by data from the TANAMI program and multiwavelength analysis of a number of interesting sources are in progress. Statistical analysis of the growing TANAMI sample is providing broader insight into the tie between the low- and high-energy radiation from AGN.

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