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# The TANAMI Program: Southern-Hemisphere AGN on (Sub-)parsec Scales

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The Southern Hemisphere VLBI monitoring program TANAMI provides dual-frequency (8 GHz and 22 GHz), milliarcsecond monitoring of extragalactic jets south of $-30^\circ$ declination. The TANAMI sample consists of a combined radio and $\gamma$-ray selected subsample of currently $\sim 80$ AGN jets, with new $\gamma$-ray bright sources being added upon detections by *Fermi*/LAT. Supporting programs provide simultaneous multiwavelength coverage of all sources, in order to construct broadband spectral energy distributions (SEDs) of flaring and quiescence source states, as well as a rapid follow-up of high-energy flares. This combined setup allows us to continuously study the spectral and structural evolution of highly energetic extragalactic jets and test correlations in different wavebands, providing crucial information on underlying physical mechanisms. Here, we present jet kinematics of Centaurus A and show preliminary VLBI results on PKS 0625–354 and the time-dependent spectral index image of PKS 0537–441.

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## 1. Introduction

The basic concept of the TANAMI[1] program [1] consists of a frequent (with every source observed approximately every three months) Very Long Baseline Interferometry (VLBI) monitoring of a combined radio- and $\gamma$-ray selected sample of $\sim 80$ southern extragalactic jets. Simultaneous 8 GHz and 22 GHz observations are performed using the Australian Long Baseline Array (LBA) and associated telescopes in Antarctica, Chile, New Zealand and South Africa. TANAMI is the only large VLBI monitoring program with such a simultaneous dual-frequency approach, allowing us to study the evolution of the jet morphology and, in addition, the variation of the spectral index along the jet at highest spatial resolution. For about a third of the source sample, TANAMI provides the first ever VLBI images [2]. This is completed with contemporaneous multiwavelength observations from an intense radio monitoring campaign with ATCA and single dish observations with Ceduna, X-ray coverage with *Swift* and *XMM-Newton*, and continuously observing by *Fermi*/LAT in $\gamma$-rays (see [3] for more information).

With this setup, TANAMI aims to study the broadband emission behavior of jets at different source states. Our dual-frequency VLBI observations provide insight into structural and spectral changes of the jets at milliarcsecond (mas) resolution. In order to investigate the jet emission mechanism producing highly energetic photons and the putative link to the structural changes seen at parsec scales (also known as the 'radio-gamma-connection in jets'), we perform a combined multiwavelength study of the spectral energy distributions (SEDs) and the VLBI morphology of TANAMI sources since the end of 2007. We report on recent results of the VLBI analysis, showing first jet kinematics and time evolution of the spectral index. The multiwavelength analysis is described in detail in [3].

## 2. Jet Kinematics

Since the end of 2007, TANAMI is frequently performing dual-frequency observations of all sources in order to study changes in the jet structure, like jet component ejections. The $(u,v)$-coverage of the TANAMI array is considerably better than that of former Southern Hemisphere VLBI measurements with long baselines to the IVS antennas GARS/O'Higgins (Antarctica) and TIGO (Chile) and to the contribution of the new Warkworth antenna (New Zealand) since 2011. As of 2012, for almost the whole TANAMI sample the minimum required number of 8 GHz observations became available to perform first kinematics analysis. In order to build up a consistent and reliable kinematic model of the jet flow, experiences of other VLBI monitoring programs (e.g., MOJAVE [4]) show, that at least five observation epochs should be considered. Therefore, the TANAMI monitoring allows us to start now with the jet kinematic analysis of the initial source sample [1] for which sufficient time coverage is available.

Here, we present first results of the ongoing analysis on the jet kinematics of the jets of Centaurus A and PKS 0625–354 at milliarcsecond scales.

*Speaker.

[1] http://pulsar.sternwarte.uni-erlangen.de/tanami/



PoS(11th EVN Symposium)020

### 2.1 Centaurus A's Jet Kinematics at Sub-parsec Scales

At a distance of only 3.8 Mpc [5], Centaurus A is the closest radio-loud AGN. The TANAMI array provides an angular resolution of less than 1 mas (which translates into 0.018 pc), resulting in the highest resolved image of an extragalactic jet-counterjet system resolving the jet down to sub-parsec scales [6]. The detailed spectral index map shows multiple possible regions of $\gamma$-ray emission detected by *Fermi*/LAT [6, 7] challenging single-zone broadband emission models.

The analysis of the jet evolution over time (see Fig. 1, Müller et al., in prep.) gives a very complex jet morphology with varying jet speeds for individual identified components. By fitting Gaussian model components to the $(u,v)$-data, we can identify and track up to eight bright, distinct jet features resulting in apparent speeds ranging from $v_{\rm app} \propto 1$mas/yr to $v_{\rm app} \propto 4$mas/yr.

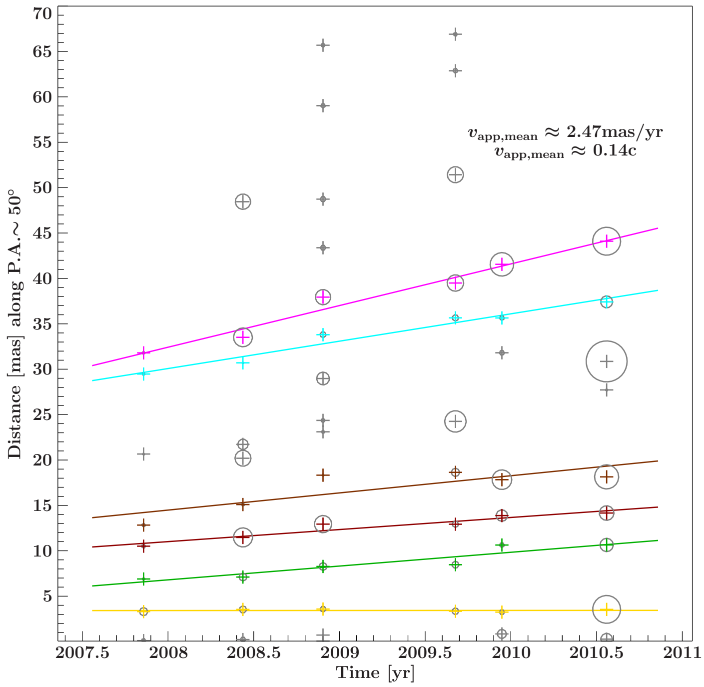


**Figure 1:** Jet kinematic analysis of Centaurus A. Separation of individual, associated jet components along the jet axis at a jet position angle of 50° with time for the first six TANAMI observations. Crosses mark the central position of every component with the FWHM of the Gaussian model components shown as gray circles. Straight lines indicate the corresponding linear regression fits to the distance giving in a mean apparent jet speed of $v_{\rm app} \propto 2.47$mas/yr $\propto 1.4\,c$ (yellow indicates the stationary component at ∼3.5 mas).

A stationary component, potentially a standing shock, is found downstream at a distance of ∼3.5 mas next to the jet core. This bright component has a flat spectrum [6] and possibly corresponds to the quasi-stationary core extension seen in previous VLBI observations [8]. Further downstream (∼25 mas) a jet widening is present, showing a substantial drop in surface brightness and subsequent collimation is detected at 8 GHz, co-spatial with an emission feature at 22 GHz [6]. Over three years of TANAMI observations, this peculiar feature appears to be stationary, while the speed of individual components ahead and after it shows no significant change.

The mean apparent speed of all moving components of $v_{\rm app} \propto 2.47$mas/yr $\propto 1.4\,c$ gives an estimate for an underlying, continuous jet flow and is consistent with previous results [8].

PoS(11th EVN Symposium)020

### 2.2 Superluminal Motion in PKS 0625–354

The misaligned radio galaxy PKS 0625–354 ($z = 0.55$) has a large scale FR I structure [12], but it is also classified as a LINER [9]. It has been detected by *Fermi*/LAT [10, 11] as a high luminosity and hard spectrum source, supporting a BL Lac classification [13]. Our TANAMI observations revealed a single-sided, parsec-scale jet morphology (Fig. 2). We identify the jet core as the optically thick and brightest component and use it as the reference point to determine the separation of each component from the core over time. The preliminary kinematic analysis results in a superluminal motion of $v_{\rm app} \propto 3.0 \pm 0.5c$ (Trüstedt et al., in prep.) .

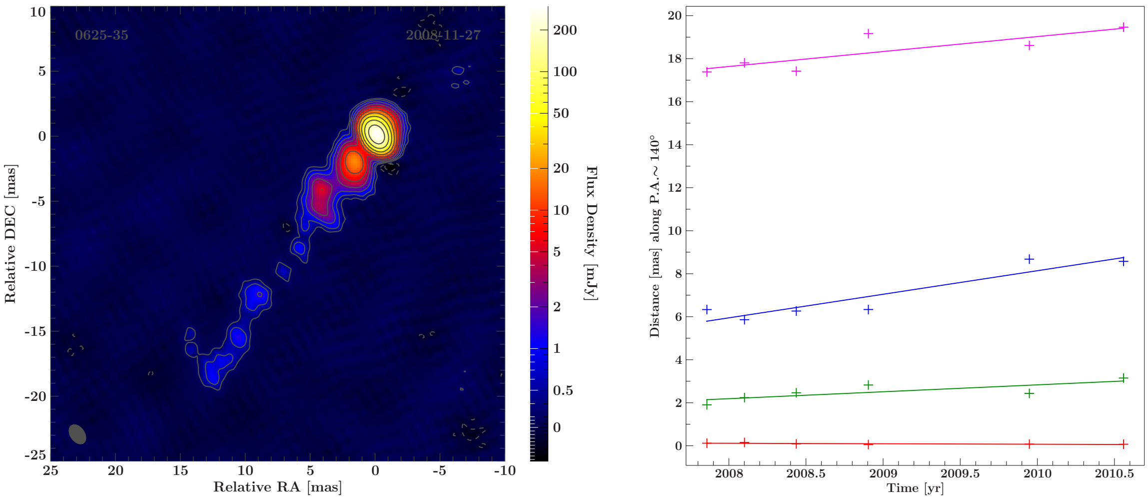


**Figure 2:** *Left:* TANAMI image of PKS 0625–354 at 8 GHz (2008 November). Contours are logarithmic, separated by a factor 2, with the lowest level set to the 3$\sigma$-noise-level. *Right:* Preliminary kinematic analysis of the inner pc-scale jet of PKS 0625–354 revealing a mean apparent speed of $v_{\rm app} \propto 0.7$ mas/yr $\propto 3c$. The plot shows the jet component separation over time of three identified jet components of the first six TANAMI observations at 8 GHz. The innermost component (red) was identified as the core and was taken as the reference point for component position. Linear regression fits were performed to derive component speeds.

## 3. Parsec-scale Spectral Index Imaging

The quasi-simultaneous dual-frequency VLBI monitoring at 8 GHz and 22 GHz enables us to construct images of the spectral distribution (with spectral index $\alpha$ defined as $F_\nu \propto \nu^{+\alpha}$) along the jet with high angular resolution. This can be used to identify possible $\gamma$-ray production sites (e.g., [6]) as the high energy emission is expected to originate from the optically thick regions within the jet. The time-dependent study of the spectral index maps provides insight into the spectral changes of individual features along the jets resolving possible active regions. Combined with multiwavelength investigations at different source states (flaring, quiescence) this spectral monitoring at very high angular resolution is a powerful tool to test different jet emission models [3]. As a representative example for such spectral index maps, Fig. 3 shows the 8 GHz, 22 GHz and corresponding spectral index map for two simultaneous TANAMI observations of the TeV-blazar PKS 0537–441.



PoS(11th EVN Symposium)020

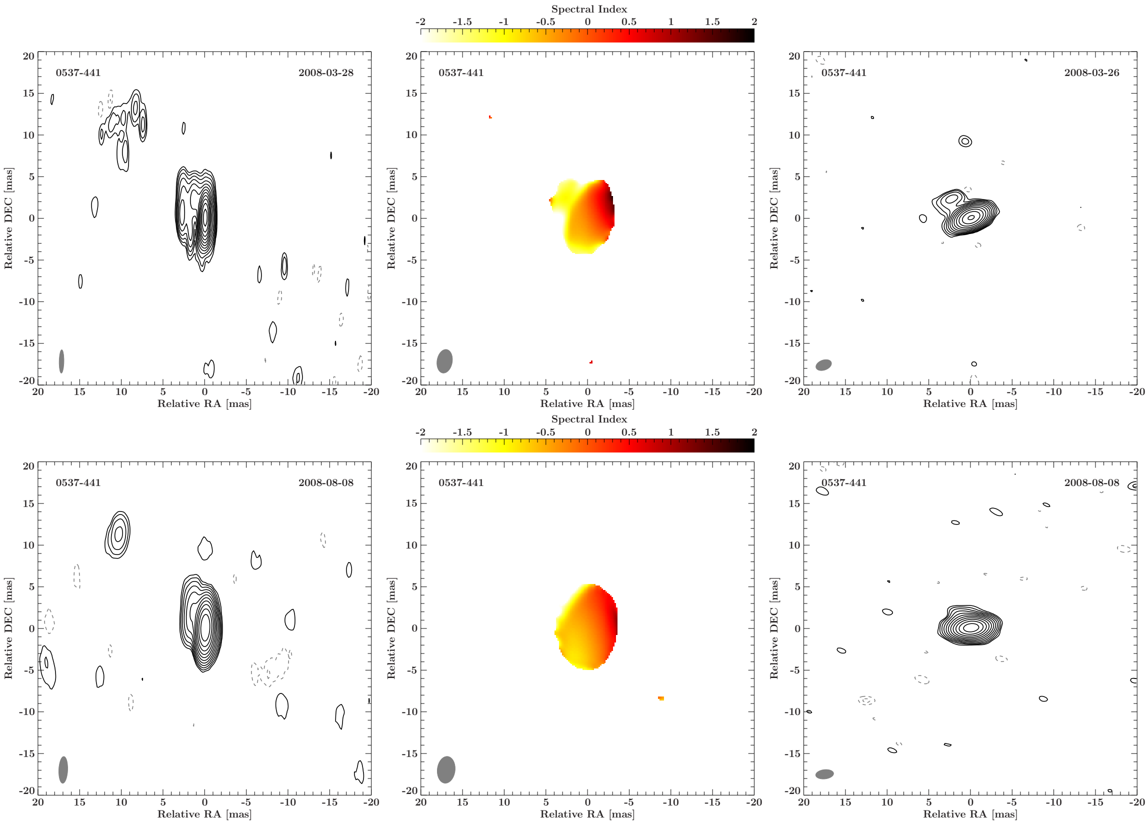


**Figure 3:** Two simultaneous dual-frequency observations of PKS 0537–441 in March 2008 (top) and August 2008 (bottom). The left and right panels show the 8 GHz and 22 GHz images, respectively, with the corresponding spectral index map in the middle panel. The color scale indicates the spectral index distribution: optically thick regions appear darker. Contours in the left and right panels are logarithmic, separated by a factor 2, with the lowest level set to the $3\sigma$-noise-level. The spectral index is derived where the flux densities at 8 GHz and 22 GHz exceed both the $3\sigma$-noise-level. To construct the spectral index map both images have been restored with a common beam represented by the gray ellipse in the lower left corner.

As described in more detail in [3], the broadband SED of PKS 0537–441 shows significant differences for different source states. The highly resolved dual-frequency images and spectral index maps provided by TANAMI observations will play an important role in distinguishing between possible broadband emission models.

## 4. Conclusion and Outlook

TANAMI is an ongoing VLBI monitoring program studying the kinematic and spectral changes of Southern extragalactic jets with mas resolution. Jet component ejection events and (radio) spectral changes are being determined in order to investigate possible correlations with high-energy flares and to study the broadband SEDs of the $\gamma$-ray bright subsample at different source states.

We started intense combined VLBI and multiwavelength studies on individual sources, testing different theoretical emission models for blazar SEDs. These try to explain the broadband emission seen from radio-loud AGN with leptonic or hadronic (or a combination of both) processes. As an important factor, the high resolution TANAMI observations allow us to distinguish between core and total jet emission. Quasi-simultaneous multiwavelength monitoring of flaring and quiescence states of the whole source sample will help us to observationally determine which model is most likely to be correct.

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