

TANAMI: Multiwavelength and multimessenger observations of active galaxies

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Extragalactic jets launched from the immediate vicinity of supermassive black holes in radio-loud active galactic nuclei (AGN) are key objects in modern astronomy and astroparticle physics. AGN jets carry a fraction of the total gravitational energy released during the accretion of matter onto supermassive black holes and are prime suspects as possible sources of ultrahigh-energy cosmic rays and the recently detected extraterrestrial neutrinos at PeV energies. TANAMI (Tracking Active galactic Nuclei with Austral Milliarcsecond Interferometry) is a multiwavelength program monitoring AGN jets of the southern sky. It combines high-resolution imaging and spectral monitoring at radio wavelengths with higher-frequency observations at IR, optical/UV, X-ray, and γ -ray energies. We review recent results of the TANAMI program, highlighting AGN candidate neutrino-emitters in the error circles of the IceCube PeV neutrino events.

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1 Introduction

Active Galactic Nuclei (AGN) are, by far, the largest category of *identified* sources in the *Fermi*/LAT Third Source Catalog (3FGL; Acero et al. 2015, 3LAC; Ackermann et al. 2015), with blazars being the dominant source type. This confirmed the strong link between the physics of blazars and γ -ray emission, first suggested based on data from the Compton Gamma Ray Observatory with its EGRET detector (Thompson et al. 1993; Doni & Ghisellini 1995). Blazars are copious emitters of highly variable emission in every waveband, forming the most *active* subset of AGN. High resolution observations of blazars show relativistic collimated outflows of plasma from a center of activity which is associated with a supermassive central object (Begelman et al. 1984). These jets emit brightly across the electromagnetic spectrum, often exhibit apparent superluminal motion (Cohen et al. 2007), and are involved in the regulation of star formation and galaxy evolution via AGN feedback (McNamara & Nulsen 2007).

Observations and modeling of blazar phenomena now span about half a century and impressive progress has been made in understanding many aspects of these mysterious objects. However, the fundamental questions regarding their composition, formation, collimation and dissipation are still open. There are several reasons for this of which the biggest is their variability. This creates three challenging demands on observations that seek to address blazar physics: they

must be (i) frequent, (ii) broadband, and (iii) simultaneous. The launch of the *Fermi* satellite (in June 2008), commissioning of large TeV telescopes, the availability of X-ray satellites, access to the 100 GHz through 1 THz band with ALMA, combined with a host of optical/NIR and radio facilities, have made it possible for the first time to make observations that are well constrained throughout the electromagnetic spectrum and can be made quasi-simultaneously (see, e.g., Ojha 2013).

High resolution radio observations have a unique role in unraveling the physics of blazars that goes beyond their important role in constraining the low energy end of the spectral energy distribution (SED) in at least two vital ways. First, VLBI (Very Long Baseline Interferometry) monitoring of AGN provides the only direct measure of relativistic motion in AGN jets, probing intrinsic jet parameters such as speed, Doppler factor, opening and inclination angles. Second, the unmatched resolution of VLBI makes identifying the location and extent of emission regions possible through observed changes in both VLBI morphology and flux, correlated with changes in the high energy emission.

In combination with observations at other wavelengths, VLBI observations are addressing some of the most fundamental questions posed by the detection of γ -ray emission from blazars: Where are the γ -rays produced in blazar jets and what is the extent of these emission regions? What are jets made of? Which physical processes regulate the high-energy emission of blazars? Are AGN also responsible for the production of ultrahigh-energy cosmic rays? Here, we describe a multiwavelength program monitoring AGN in the

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southern sky, which is also taking advantage of new opportunities in multimessenger astrophysics.

2 The TANAMI Multiwavelength program

It has long been apparent that broadband, quasi-simultaneous data on a large sample of AGN in different activity states are needed to address the key questions mentioned above. In anticipation of the launch of the Fermi Gamma-ray Space Telescope, TANAMI began observing an initial sample of 43 AGN in 2007. Addition of subsequent *Fermi*-LAT detections continues to expand the sample which currently contains more than 90 monitored sources. Starting as a radio program with its focus on high-resolution VLBI observations and flux-density monitoring, the program has developed into a multiwavelength program providing excellent NIR/optical/UV, X-ray and γ -ray coverage for a large sample of γ -ray loud AGN.

The unique role of parsec scale radio monitoring of γ -ray AGN is well appreciated (Jorstad et al. 2001; Lister et al. 2011). However, most monitoring programs use northern hemisphere arrays that cannot observe the far southern sky. Since the beginning of the *Fermi* mission, TANAMI is the only large VLBI monitoring program targeting AGN south of declination -30° (Ojha et al. 2010). Uniquely among large VLBI programs, TANAMI observes at two frequencies, 8.4 and 22.3 GHz, measuring spectral indices of jet features and their time evolution. TANAMI uses a southern-hemisphere VLBI network (Preston et al. 1989) consisting of the five telescopes that make up the Australian Long Baseline Array (LBA), an antenna at Hartebeesthoek, South Africa, and the 34 m and 70 m telescopes of the NASA Deep Space Network in Tidbinbilla. Through a program approved by the International VLBI Service, these are typically joined by two German antennas, GARS at O'Higgins, Antarctica and TIGO which was at Concepcion, Chile, but which has now been moved to La Plata, Argentina. Lately, the fidelity of the TANAMI array got an additional boost with access to two AuScope antennas in Yarragadee, Western Australia and Katherine, Northern Territory (Lovell et al. 2013) and both a telescope in Warkworth, New Zealand and a single ASKAP antenna also in Western Australia (Tzioumis et al. 2010).

A radio flux-density monitoring program with the ATCA (Australia Telescope Compact Array) at frequencies of 4.8, 8.6, 17/19, 38 and 40 GHz (Stevens et al. 2012) and a single-dish monitoring program using the University of Tasmania telescope at Ceduna at 6.7 GHz are supplementing the VLBI observations. A single-baseline interferometer, the Ceduna Hobart Interferometer (CHI) formed with the radio telescopes in Hobart, Tasmania, and Ceduna, South Australia, can respond to a *Fermi* trigger within half an hour (Blanchard et al. 2012a).

To cover the NIR/optical part of the spectrum, 22 TANAMI sources were monitored through 2011/2012 with the Rapid Eye Mount (REM) telescope in *J*, *H*, *K*, and *R*

bands (Nesci et al. 2013). Additional REM time was granted in 2014 and monitoring of another 6 sources is in progress. Many sources that did not have measured redshifts, or even an optical identification, were observed using Gemini South and are now being targeted using the TNG (Telescopio Nazionale Galileo) telescope on La Palma. Many TANAMI sources are being observed with the Nordic Optical Telescope, the SARA consortium telescope on CTIO, and ATOM (for some sources). We also take advantage of public data from the SMARTS program. Coverage in the UV band is provided by the UVOT instrument on board Swift (see below).

Over many years, the TANAMI sample has had an unusually uniform X-ray coverage. Due to the lack of a sensitive enough X-ray all-sky monitoring instrument, this has been obtained via many pointed observations via the guest-observer programs of various X-ray telescopes: 60 ks on RXTE, 260 ks on XMM-*Newton*, 125 ks with Swift, 800 ks with INTEGRAL, and 70 ks with Suzaku. In addition, a total of 300 ks of optical/UV and X-ray observing time comes from a dedicated Swift fill-in program.

The *Fermi* Large Area Telescope (LAT, Atwood et al. 2009) has been monitoring the sky at 30 MeV to 300 GeV since its launch in 2008. A large number of AGN were detected and monitored with *Fermi*/LAT (709 AGN during the first year of operation, Abdo et al. 2010b; 886 AGN after two years, Ackermann et al. 2011; 1563 AGN after four years, Ackermann et al. 2015).

In recent years, TANAMI has established a close liaison with the ANTARES collaboration. ANTARES is an under-sea neutrino telescope in the Mediterranean Sea off the coast of Toulon, France (Ageron et al. 2011), completed in 2008 (coincident with the launch of *Fermi*). 885 photomultiplier tubes mounted on twelve vertical lines are anchored to the seabed at a depth of 2475 m and register Cherenkov light induced by relativistic muons produced in charged-current interactions of high-energy neutrinos with matter around the detector. ANTARES is optimised for up-going muons produced by neutrinos from southern-hemisphere sources which have traversed the Earth, and achieves its highest sensitivity at declinations south of about -30° , coinciding with the TANAMI sky.

3 Selected results

3.1 The (sub-)parsec-scale structure and dynamics of AGN jets

First epoch VLBI images of the initial TANAMI sample of 43 objects at 8.4 GHz included many sources observed for the first time at milliarcsecond resolution (Ojha et al. 2010). These images revealed morphological differences between γ -ray bright and faint sources with the brighter jets having larger projected opening angles possibly indicative of smaller angles to the line of sight. This was also shown independently, based on data from the

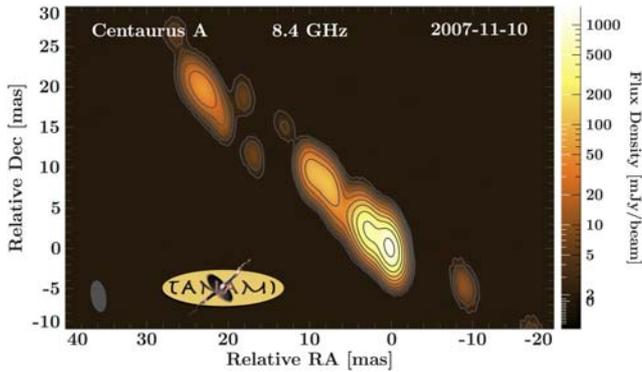


Fig. 1 First frame of a movie, available via <http://www.aip.de/AN/movies>, showing the structural evolution of the inner 60 mas of the Cen A jet-counterjet system. The movie is based on eight images obtained by TANAMI between 2007 and 2011, which were convolved with a common beam as indicated by the grey ellipse in the bottom left corner and interpolated between the individual observations. The color scale was fixed to the minimum and maximum flux density of the images. The contour lines start at three times the maximum noise level of the images and increase logarithmically by factors of two.

MOJAVE program (Pushkarev et al. 2009). VLBI images of the extended TANAMI sample have been published as part of several TANAMI studies (Müller et al. 2011; Blanchard et al. 2012a; Müller et al. 2013; Müller 2014; Müller et al. 2014a; Müller et al. 2014b; Krauß et al. 2014; Krauß et al. 2015) or as supplementary data in multiwavelength studies of the *Fermi*/LAT collaboration (Abdo et al. 2009a; Abdo et al. 2010c; Abdo et al. 2010d; Buson et al. 2014). Data from the TANAMI ATCA program were used in *Fermi*/LAT multiwavelength publications on the TANAMI sources PKS B 2123–463 and PKS B 2142–758 (D’Ammando et al. 2012; Dutka et al. 2013). VLBI images of both of these sources will be presented as part of a comprehensive catalog of 8.4 GHz VLBI images of all TANAMI sources observed with VLBI beyond the initial sample (Müller et al., in prep.).

The jet-counterjet system of the closest radio-loud active galaxy Centaurus A (Cen A), at a distance of only 3.8 Mpc, has been studied within the TANAMI VLBI program on unprecedented small linear scales (Müller et al. 2014b). The high linear-resolution observations provide a unique view of the inner parsec of an AGN jet. A 3.5 yr kinematic study showed the evolution of the central-parsec jet structure of Cen A, revealing complex dynamics indicative of a spine-sheath jet structure and downstream acceleration of jet plasma (see Fig. 1). Both moving and stationary jet features are found. A persistent local minimum in surface brightness suggests the presence of an obstacle interrupting the jet flow, which can be explained by the interaction of the jet with a star at a distance of ~ 0.4 pc from the central black hole.

3.2 High-energy emission of blazars and other classes of AGN

The TANAMI sample was originally defined as a hybrid radio and γ -ray selected sample that includes most radio-loud extragalactic jets south of -30° that had either been detected at γ -ray energies during the EGRET era or were considered candidates for γ -ray emission. Indeed, the majority of TANAMI sources have now been detected in γ -rays after more than six years of *Fermi*/LAT observations, either during flares or over long-time integration. The largest group of non-detected TANAMI sources are radio galaxies, but also some radio-bright quasars remain notoriously γ -quiet. Due to source variability, the best statistical results can be obtained from quasi-simultaneous data sets and relatively short time averages. We have performed a radio-gamma correlated analysis of TANAMI sources (Böck 2012; Böck et al. 2015) based on the 11-month 1FGL period (Abdo et al. 2010a). A large fraction (72 %) of all TANAMI sources is associated with γ -ray sources for this time range. Association rates differ for different optical classes with all BLLacs, 76 % of quasars and 17 % of the TANAMI galaxies being detected by *Fermi*/LAT. We also calculated upper limits on the γ -ray flux for γ -faint sources. We found a correlation between the γ -ray and radio luminosities with $L_\gamma \propto L_{\text{VLBI}}^{0.90 \pm 0.04}$ and showed that this correlation is not induced by the common distance-squared term in both quantities. Some of the upper limits are still statistically compatible with this correlation but we also find a group of apparently intrinsically γ -ray faint quasars. We calculated brightness temperatures of the radio cores during the 1FGL period and showed that they correlate with γ -ray luminosity. Brightness temperatures of several sources above the inverse Compton limit imply strong Doppler boosting, which is in general agreement with other studies (e.g., Kovalev et al. 2009; Linford et al. 2011).

The vast majority of AGN detected by *Fermi*/LAT are blazars. In addition to those, new classes of non-blazar γ -ray bright AGN have been discovered by the LAT. The elusive class of γ -ray detected *misaligned* radio-loud AGN has grown to a size of 29 sources (Abdo et al. 2010e; Ackermann et al. 2015). Apart from three radio galaxies (Cen A, Cen B, and Pic A), the source PKS B 0625–354 is in the TANAMI sample. While showing an extended FR I structure (Morganti et al. 1999), the optical spectrum of PKS B 0625–354 resembles that of a BL Lac object (Wills et al. 2004). TANAMI observations revealed a single-sided, parsec-scale jet morphology (Müller et al. 2013) with a high-brightness-temperature core, suggesting that the γ -ray emission of this object is produced in a similar way as in blazars.

A new class of γ -ray emitting AGN detected by *Fermi*/LAT are radio-loud Narrow-Line Seyfert 1 Galaxies (RLNL-Sy 1s, Abdo et al. 2009b; Abdo et al. 2009c). VLBI observations of PMN J0948+0022 (Abdo et al. 2009d; Giroletti et al. 2011) have demonstrated that this source has a high-brightness-temperature radio core, suggesting

that the γ -ray emission of *Fermi*/LAT-detected RLNL-Sy 1s is coupled to the presence of relativistically beamed jets as in blazars, but harboured in spiral rather than elliptical galaxies and originating from the environment of supermassive black holes with relatively low-masses (Foschini et al. 2013). Among the five γ -ray detected RLNL-Sy 1s, the radio-loudest one, PKS 2004–447, is located in the southern hemisphere and exhibits peculiar properties in this elusive sample. TANAMI VLBI images (Schulz et al., in prep.) show an extended, but diffuse one-sided jet with a dominating unresolved VLBI core. Along with its radio spectral classification as a CSS galaxy (Gallo et al. 2006) and its compact structure on arcsec scales, this might suggest that PKS 2004–447 is a young jet source pointed at a relatively small angle to the line of sight. This is also in agreement with new TANAMI X-ray observations with *XMM-Newton*, showing a blazar-like X-ray spectrum with only marginal evidence for the presence of the previously reported soft excess (Kreikenbohm et al. 2013; Kreikenbohm et al., in prep.).

An unusual γ -ray source detected by *Fermi*-LAT is PMN J 1603–4904 which was originally classified as a BL Lac object. Imaged at VLBI resolution for the first time by TANAMI, it shows a hard to classify morphology; it is either an atypical blazar or a γ -ray loud young radio galaxy (Müller et al. 2014a). If confirmed as the latter, this would be the first of this class of objects to be detected in γ -rays. Subsequently, near simultaneous observations with *XMM-Newton* and *Suzaku* detected a redshifted X-ray line (Müller et al. 2015a) making it unlikely to be a blazar and thus supporting the possibility that PMN J 1603–4904 is a young radio galaxy with a misaligned jet.

3.3 SED modeling

The SED of blazars have two maxima. Synchrotron emission from relativistic electrons in the jet produces the low energy peak in the radio-to-infrared band (Blandford & Königl 1979). The origin of the high energy component, which lies in the MeV to TeV bands, remains an open question. It could arise from inverse-Compton upscattering of synchrotron photons by the electrons which emitted them (Synchrotron Self Compton model; e.g., Königl 1981) or from the inverse-Compton scattering of photons external to the jet by the relativistic electrons within the jet (External Compton model; e.g., Sikora et al. 1994). Yet another class of models suggest this second component arises from hadronic processes involving high-energy protons which produce neutral and charged pions that decay into γ -ray photons and neutrinos (e.g., Mannheim 1993). Since blazar emission is variable at all wavelengths and the relationships between these variations is unclear, multi-epoch, quasi-simultaneous observations across the spectrum are essential to distinguish between these models.

TANAMI is playing a major role, with studies of a number of blazars in different states of γ -ray activity (Blanchard et al. 2012b; Buson et al. 2014; Dutka et al. 2013; Buson et

al. 2014; Carpenter et al. 2015). Flaring and quiescent states were modeled with a leptonic model (based on Finke et al. 2008 and Dermer et al. 2009) that includes the synchrotron, synchrotron self-Compton (SSC), and the external Compton (EC) processes. Fits to the SED were first attempted with a single seed photon source of EC and a broken power-law electron distribution but in some cases the data required more complicated models introducing more free parameters, e.g., changing the electron distribution from a broken power-law to a double broken power-law.

The resulting models show a wide variety in the fitted parameters even for different flares in the same blazar (Chatterjee et al. 2013), so at first glance each flare appears to be different. Fortunately, even with a modest (but increasing) number of modeled flares a tentative pattern is emerging with two types of flares apparent. Type I flares require changes in the electron distribution to explain the observed changes in their SED between active and quiescent γ -ray states, e.g., PKS 0537–441 (D’Ammando et al. 2013). On the other hand, Type II flares require changes in additional parameters such as the magnetic field or the size of the emitting region (or both), e.g., flare B in PKS 2142–758 (Dutka et al. 2013). Both Type I and Type II flares can be sub-divided into two types. In the case of Type Ia flares, the γ -ray flare is accompanied by an optical flare. For Type Ib flares the optical flare is either weak or absent. Type IIa γ -ray flares are accompanied by a weak or absent X-ray flare whereas Type IIb flares are accompanied by a strong X-ray flare. More observations over flaring and quiescent states are needed to establish or improve this tentative classification scheme which has the potential to bring order to our study of high energy blazar emission.

3.4 Neutrino Emission of Radio-Loud AGN

In SED analysis, an unambiguous separation of the emission components due to the relativistic electrons, positrons, protons, or ions is often not possible due to the superposition of a large number of emission zones within the jets. Even the superb broadband SEDs that can be collected since the beginning of the *Fermi*/LAT mission do not allow us to unambiguously discriminate between hadronic and leptonic emission processes, and to pin down the matter content of AGN jets, which have long been suspected as the origin of ultrahigh-energy cosmic rays (Hillas 1984). Secondary neutrino emission would then naturally explain a high-energy neutrino flux exceeding the atmospheric background above energies of 100 TeV (Mannheim, Stanev & Biermann 1992; Mannheim 1995). A tentative association of high-energy neutrinos with flaring blazars have been suggested (Halzen & Hooper 2005; Adrián-Martínez et al. 2012), but to date no unambiguous identification of an AGN as a neutrino source could be established.

The major challenge for neutrino telescopes is to detect a weak signal in the presence of a strong background of atmospheric muons and neutrinos, which are not directly associated with any cosmic sources. One way to in-

crease the significance is to search for time-clustered multiple events from the same direction and/or the search for correlations with flaring activity in the electromagnetic spectrum. ANTARES has performed a search for time-clustered neutrino events from eight TANAMI sources (Fritsch 2014). For the source PKS 0208–512, two events were found, for PKS 1954–388 one event, which however is not a significant signal. In another joint analysis, *Fermi*/LAT light curves are used to select suitable time windows during short flares for an ANTARES analysis (Müller 2014; Fehn 2015), which can enhance the sensitivity of the detector substantially (see also Adrián-Martínez et al. 2012).

Recently, the IceCube collaboration has reported the detection of three neutrinos at PeV energies and a larger number of sub-PeV events in excess of the atmospheric background (Aartsen et al. 2013; IceCube Collaboration 2013; Aartsen et al. 2014). Due to the steeply falling background towards higher energies, the PeV events are the most likely ones in this sample of events to be of extraterrestrial origin. Using contemporaneous TANAMI multiwavelength data, we investigated the six radio- and γ -ray brightest blazars located in the median angular resolution uncertainty circles reported by the IceCube collaboration for the first two PeV neutrino events, dubbed “Ernie” and “Bert” (Krauß et al. 2014). Our VLBI images revealed typical blazar morphologies for most candidate sources with high-brightness-temperature radio cores and typically one-sided jets indicative of strong differential Doppler boosting. PKS B0302–623 shows a highly peculiar halo-like morphology and PMN J1717–3342 is found to be affected by strong scatter broadening. Broadband SED analysis revealed prominent blue bumps of Swift J1656.3–3302 and PMN J1717–3342, suggesting that the latter’s earlier classification as a BL Lac object should be revised.

Interpreting the high-energy emission of the six candidate blazars in a hadronic scenario, in which accelerated protons give rise to photoproduction of pions and subsequent γ -ray and neutrino emission, the neutrino luminosity of these sources can be estimated from the observed flux of the high-energy bump in the SED. We could demonstrate that the integral energy output of the six TANAMI candidate blazars is high enough to explain the observed neutrino flux. No single blazar in the field, however, yields a high-enough calorimetric output for an unambiguous association with the highest predicted neutrino fluxes being ascribed to Swift J1656.3–3302 and PMN J1717–3342. Instead, we showed that the larger population of faint unresolved blazars can contribute a comparable fraction to the total neutrino flux in a field of several degrees in size (Krauß et al. 2015) so that a direct association with an individual source might currently only be possible in exceptional cases.

The ANTARES and TANAMI collaborations have followed up on these results by analysing the sub-PeV neutrino emission of the six TANAMI candidate blazars (ANTARES and TANAMI Collaborations 2015). Although much smaller in volume, ANTARES offers better sensitivity

below ~ 100 TeV at the given southern declinations. A standard point-source analysis revealed two signal-like events, one fitted to the position of Swift J1656.3–3302 and the second fitted to the position of PMN J1717–3342, the same two sources which showed the highest predicted neutrino output. Still, an atmospheric origin cannot be excluded. No ANTARES events are observed from any of the other four blazars, constraining at a 90 % confidence level the possible neutrino power-law spectral indices to be flatter than -2.4 .

An analysis of the TANAMI AGN in the field of the third PeV neutrino event detected by IceCube (dubbed “Big Bird”) is currently ongoing. The field holds two remarkable objects: the high-fluence outburst blazar PKS 1424–418 and the closest radio-loud AGN to Earth, Cen A. In the latter case, the possible jet-star interaction in the inner jet of Cen A (see above) provides an interesting scenario for a possible source of the neutrino emission. We investigated the possibility that neutrinos are produced in the interaction of protons accelerated at a bow shock surrounding a red giant star and its wind in the jet (Müller et al. 2015b) but found that an association with the Big Bird neutrino event is highly improbable due to the low predicted neutrino flux.

4 Outlook

Quasi-simultaneous, multiwavelength, multiepoch observations of the TANAMI program are providing answers to many conundrums about γ -ray loud AGN. With up to seven years of VLBI monitoring, most of the original 43 sources of the 2007 TANAMI pilot program have reached the stage at which robust studies of jet kinematics are now yielding a rich harvest of results. Further TANAMI epochs will allow us to determine basic kinematics for sources added more recently to the sample. Equally important, they are needed to determine component ejection epochs which can be correlated with γ -ray flares or neutrino emission.

To understand the energetics of blazars it is imperative to probe them in different states of activity by establishing a sample of sources with simultaneous observations in every waveband. This can only be achieved by long-term monitoring programs such as TANAMI lasting several years. The new availability of data from ALMA and NuSTAR, at previously inaccessible bands, increases the value of new observations. TANAMI observations will also image structural changes in high brightness sources targeted in snapshot observations by the RadioAstron radio satellite. TANAMI is uniquely well positioned to exploit multimessenger observations which have long been anticipated and are now a reality.

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