High-resolution monitoring of parsec-scale jets in the *Fermi* era

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I review here the present observational efforts to study parsec-scale radio jets in active galactic nuclei with very-long-baseline interferometry (VLBI) as related to the new window to the Universe opened by the LAT instrument on-board the *Fermi* Gamma-Ray Space Telescope. I describe the goals and achievements of those radio studies, which aim to probe the emission properties, morphological changes and related kinematics, magnetic fields from the linear and circular polarization, etc., and I put those in the context of the radio-gamma-ray connection. Both statistical studies based on radio surveys and individual studies on selected sources are reported. Those should shed some light in the open questions about the nature of emission in blazars.

1. INTRODUCTION

Since the measurements from CGRO/EGRET we know that the γ-sky is dominated by the Galactic plane diffuse emission, pulsars, and blazars. This has been confirmed with the outstanding findings of *Fermi* and its LAT detector, launched in June 2008 and operative since August 2008. The 2nd *Fermi* LAT catalog (2LAC) includes all extragalactic sources with a significant detection over the first two years of scientific operation. The so-called ‘clean sample’ of the 2LAC contains 886 sources, from which 310 are flat-spectrum radio quasars (FSRQ), 395 are BL Lac objects, 157 candidate blazars of unknown type, 8 misaligned active galactic nuclei (AGN), 4 narrow-line Seyfert 1 (NLS1), 10 AGN of other types, and 2 starburst galaxies. Notice that sources with only sporadic activity were missing, since they don’t reach the test statistic threshold of 25 (TS > 25).1

*Fermi*/LAT has shown that BL Lacs are the most common γ-emitters, more frequently than FSRQ. One should be aware of the strong biases introduced by Doppler boosting on the observed flux from AGN, which biases the brightest extra-galactic γ-ray objects and high frequency radio sources towards fast jets with a small viewing angle, that is, close to the line of sight (e.g., 2, 3). The picture is completed by observations of the *AGILE* γ-mission (2008-) the rapid AGN results provided by the X-ray and γ-ray mission *Swift* (2005-) and the ground-based very-high-energy (VHE) γ-ray Cherenkov telescopes such as HESS (2003-), MAGIC (2004-), CANGAROO-III (2004-), or VERITAS (2006-).

Among the big questions raised in earlier editions of this workshop, it is open if γ-ray flares originate in relativistic shocks, what is the distance of the main energy dissipation site from the central engine, what are the emission mechanisms at stake, and what relates the brightness in the radio with the γ-rays. The observational tools to address the *Fermi* era are VLBI campaigns to be related with the continuous all-sky γ-ray observations by *Fermi*/LAT, complemented with multi-band campaigns including as well IR, optical, UV, and X-rays. The information achieved by intensive flux density monitoring campaigns are being addressed by other authors at this conference.

To review this topic, I will first introduce the observables measured directly and indirectly by VLBI and the other parameters to be compared with from the γ-ray monitoring and from the spectral energy distribution (SED) studies of AGN. I will continue describing the main survey campaigns and some of their highlights so far. To complement this, I will present a (necessarily incomplete) selection of studies on individual sources combining VLBI and γ-observations.

2. WHAT IS MEASURED BY VLBI?

2.1. VLBI targets

Blazars display powerful jets oriented towards the observer, and show high brightness temperatures in the radio regime, which allow them to be observed by VLBI. VLBI is a technique that provides resolutions of the order of the milliarcsecond ( parsecs at cosmological distances), working regularly from 3 mm up to 1 m wavelengths. At the longest wavelengths the presence of the ionosphere as a dispersive propagation medium distorts the waves and limits VLBI performance. At the shortest wavelengths, where the highest resolution is achieved, atmospheric turbulence, and especially water vapour, disturb the observations, causing coherence loss and limiting the integration time and therefore its detection threshold. Wavelengths from 7 mm up to 18 cm are the most commonly used.

One of the main targets of VLBI are AGN, given their high brightness temperatures $T_b$, of up to $10^{12}$ K in the core, dropping to $10^{10}$ K or lower values in the jet (see below for the definition of $T_b$).

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1 Remarkably, sources like 3C 120 or 3C 111, which were present in earlier catalogs, are not listed at the 2LAC.
Distinct features or ‘blobs’ in the jet can be identified with shocks or instabilities in the jet. The magnetic field orientation can be estimated by the linear and circular polarisation, if observing in this mode. The structural changes observed by combining several epochs can be associated with helical jets (e.g., [2]) or binary black holes (e.g., [7]). Identifying ‘moving’ features from different observing times, the kinematics of those components are established, and even the ejection times of the features at the base of the jet could be related to the outburst observed at the single-dish light curves of the sources [8]. At the base of the jet, the emission is self-absorbed by synchrotron, so that the peak of brightness (also labeled as jet ‘core’) corresponds to different physical locations at different frequencies. The absolute position of the source can be recovered by astrometric methods [9]. If this is not possible, images at different frequencies can be registered by aligning the optically thin regions either by model fitting with Gaussian functions [10], by cross-correlation of the jet features [11, 12], or by a combination of astrometry and jet alignment [13, 14]. After the core-shift correction, the synchrotron turnover frequency and flux density can be computed all over the jet, and from those, physical parameters in the jet are estimated, such as the magnetic field, and pressure gradients [13].

2.2. Extracting information from VLBI images

So, from one single VLBI image, or combining them in time (kinematics) or frequency (spectral studies), we can measure directly several physical quantities in AGN, most of them affected the observed flux by Doppler beaming, caused by relativistic effects and the small viewing angle of the jet, pointed almost towards the observer. Given a region of the jet moving downstream with a speed \( v \equiv c \) in the rest frame \( c \) is the light speed), with an angle \( \theta \) between the jet, the Lorentz factor will be \( \Gamma \equiv (1 - \beta^2)^{-1/2} \) and the Doppler factor will be \( \delta \equiv (\Gamma(1 - \beta \cos \theta))^{-1} \). Beaming will affect several magnitudes, and the relativistic effects and the small viewing angle will affect several parameters being measured by VLBI. I summarize those in Table II and describe them in the following paragraphs.

2.2.1. Directly measured parameters by VLBI

After identifying features between different observing epochs, we can determine the sky motion of those and compute the apparent speed \( \beta_{app} = \beta \sin \theta / (1 - \beta \cos \theta) \). For a given \( \beta \), the maximum speed \( \beta_{app,max} = \beta \Gamma \) is reached when \( \cos \theta_{max} = \beta \).

After hybrid mapping or Gaussian model fitting, we can measure for each feature the value of the flux density \( S \), usually expressed in Jy \((10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1})\).

### Table I Summary of observable VLBI, SED, and \( \gamma \)-ray parameters

| Parameter                      | Units       |
|-------------------------------|-------------|
| **Radio**                     |             |
| Radio detection               |             |
| Apparent speed                | \( \beta_{app} \) | c |
| Flux density                  | \( S \)     | Jy |
| Brightness temperature        | \( T_b \)   | K  |
| Apparent opening angle        | \( \psi \)  | deg |
| Luminosity                    | \( L_R \)   | W Hz\(^{-1} \) |
| Jet-to-counterj. ratio        | \( R \)     | –  |
| P.A. misalignment*            | \( \Delta \phi \) | deg |
| Spectral index                | \( \alpha \) | –  |
| Polarisation angle            | \( \chi \)  | deg |
| Polarisation level            | \( m \)     | %  |
| Faraday rotation              | \( RM \)    | rad m\(^{-2} \) |
| Viewing angle                 | \( \theta \) | deg |
| Lorentz factor                | \( \Gamma \) | –  |
| Doppler factor                | \( \delta \) | –  |
| Ejection epoch                | \( t_0 \)   | yr |
| **SED**                       |             |
| Sync. frequency peak          | \( \nu_{\text{max,sync}} \) | Hz |
| Lum. at sync. peak            | \( L(\nu_{\text{max,sync}}) \) | W Hz\(^{-1} \) |
| Inv. Compton frequency peak  | \( \nu_{\text{max,IC}} \) | Hz |
| Lum. at inv. Compton peak     | \( L(\nu_{\text{max,IC}}) \) | W Hz\(^{-1} \) |
| **Gamma**                     |             |
| \( \gamma \)-detection       |             |
| Flare epoch                   | \( t_{\gamma-\text{flare}} \) | yr |
| Flux                          | \( S_\gamma \) | Jy |
| Flux variability              | \( \Delta S_\gamma / S_\gamma \) | –  |
| Luminosity                    | \( L_\gamma \) | W Hz\(^{-1} \) |
| Photon index                  | \( \Gamma_\gamma \) | –  |
| Gamma-ray to radio flux ratio | \( G_\gamma \) | –  |

* Kiloparsec- and parsec-scale misalignment

The luminosity \( L \) can be obtained directly from the flux density: \( L = 4\pi D_L^2 S \) where \( D_L \) is the luminosity distance (to be computed from the redshift \( z \) measured in the optical). The intrinsic and observed luminosity are also affected by the K-correction and Doppler boosting (and the spectral index \( \alpha \), from \( S \propto \nu^{+\alpha} \)) as follows: \( L_{\text{obs}} = L_{\text{int}} \times \delta^{\alpha - \alpha} \times (1 + z)^{-(1 - \alpha)} \) \((n = 2, 3)\).

Having the flux density \( S \) and the interferometer resolution (beam), we compute the brightness temperature \( T_b = 1.222 \times 10^{12} S(1 + z)/\nu^2 ab \) where \( T_b \) is given in K, \( \nu \) is the observing frequency in Hz, \( S \) is the flux density in Jy, and \( a \) and \( b \) are the major and minor beam axes, respectively, in milliarcseconds. The intrinsic and observed brightness temperatures are related with the beaming Doppler factor \( \delta \) by \( T_{b,\text{obs}} = T_{b,\text{int}} \times \delta \).
We can also measure the difference in position angle of the jet in parsec- and kiloparsec-scales (the latter from connected interferometers such as the VLA or MERLIN), and get the jet misalignment angle $\Delta \phi$.

For images with a high dynamic range we can obtain the jet-to-counterjet ratio, which is $R = [(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]^{-2} = (\beta_{\text{app}}^2 + \delta^2)^{-2}$. By measuring how the jet gets broader (see e.g., [16, 17]), we measure the apparent opening angle $\psi$. Since the jets are not precisely in the plane of the sky, the apparent and the intrinsic opening angle are related by $\psi_{\text{int}} = \psi_{\text{obs}} \sin \theta$.

Finally, if we observe in polarisation mode, we can measure the polarisation level $m$ (as the ratio of linearly polarised and total intensity) as well as the polarisation angle $\chi$ (also known as electric vector position angle or EVPV). If we have several frequencies, we can compute the change of the EVPV as a function of the squared wavelength and determine the Faraday rotation measurement $\varphi$.

### 2.2.2. Indirectly measured parameters

From the parameters measured above we can see that the intrinsic parameters $\beta$, $\theta$, or $\delta$ are degenerate and several solutions are possible for a given value of $R$, $\beta_{\text{app}}$, etc.

We can measure $\delta$ independently of the VLBI kinematical analysis by computing the flux density variations measured by a densely sampled single-dish or VLBI monitoring campaign [19]. The variability time can be defined from the variations of the fluctuation density $S$ by decomposing a density fluctuation into exponential flares as $\Delta S(t) = S_{\text{max}} e^{(t-t_{\text{max}})/\tau}$, where $S_{\text{max}}$ is the maximum amplitude of the flare in Jy, $t_{\text{max}}$ is the epoch of the flare maximum and $\tau$ is the rise time of the flare. $\epsilon = 1$ for $t < t_{\text{max}}$ and $\epsilon = 1.3$ for $t > t_{\text{max}}$. In this way, $T_{\text{obs}}(\text{var}) = 1.474 \times 10^{13} S_{\text{max}} D_L^2 \nu^{-2} \tau^{-2} (1 + z)^{-1}$ where $D_L$ is the luminosity distance in Mpc and $\nu$ the frequency in Hz. From here the variability Doppler factor is $\delta_{\text{var}} = (T_{\text{obs}}(\text{var})/T_{\text{obs}}(\text{int}))^{1/3}$, where $T_{\text{obs}}(\text{int})$ is assumed to be $5 \times 10^{10} \text{K}$.

With the apparent speed $\beta_{\text{app}}$ and $\delta_{\text{var}}$, we also obtain the bulk Lorentz factor $\Gamma = (\beta_{\text{app}}^2 + \delta_{\text{var}}^2 + 1)/(2 \delta_{\text{var}})$ and the viewing angle $\theta = \tan(2 \beta_{\text{app}}^2 \beta_{\text{app}}^2 + \delta_{\text{var}}^2 - 1)$. Alternatively, an upper bound for the viewing angle can be obtained from the jet-to-counterjet ratio as $\theta < \beta^{-1} \arccos(R^{1/2} - 1/R^{1/2} - \alpha + 1)$.

Last but not least, knowing the apparent speed $\beta_{\text{app}}$ we can compute the ejection time $t_0$ simply by extrapolating the time for which the distance of the feature to the core is zero. If jet features are related to plasma injections at the base of the jet, this should be seen at high frequencies, as it has been observed in X-rays for 3C120 [20] or NGC1052 [21].

### 2.3. SED properties

AGN SED (representation of intensity as a function of frequency) show usually two bumps, caused by non-thermal synchrotron emission at the low energies and (most probably) by inverse Compton up-scattering of ambient optical-UV photons, although the contribution of energetic hadrons cannot be ruled out (e.g., [22]). Therefore, the positions and luminosities of SED peaks of both bumps are also used for correlation studies: $(\nu_{\text{max,synch}}, L(\nu = \nu_{\text{max,synch}}))$ and $(\nu_{\text{max,1C}}, L(\nu = \nu_{\text{max,1C}}))$. From this, additional parameters such as the gamma-radio loudness $G_r = L_{\gamma}/L_r$ has been defined [23].

### 2.4. Correlating VLBI measurements and $\gamma$-properties

Most of the statistical studies with radio surveys are based in relating the above mentioned parameters with the $\gamma$-measurements. The first check to be performed are cross-correlating catalogs (radio with the Fermi ones–three-month list [24], one-year AGN catalog [25], or the two-year AGN catalog [1]), and comparing $\gamma$-detection with radio properties. After that, the values of the radio parameters can be plotted against the high-energy parameters, and correlations are searched by using different statistical methods.

I have listed the parameters from $\gamma$-ray observations in Table I as well. In principle, those high-energy parameters are the $\gamma$-flux $S_\gamma$ and its $\gamma$-flux variability $\delta S_\gamma/S_\gamma$, the $\gamma$-luminosity $L_\gamma$, and the $\gamma$ photon index $\Gamma_\gamma$, since the number of photons per unit time per unit area in a frequency bandwidth is $dN/d\nu = (F_\gamma/h\nu)\nu_0$, where $\nu_0 = h/E_0$, where $E_0 = 1\text{keV}$ and $h$ is Planck’s constant, from the radio astronomy convention, $S = F_\nu \propto \nu^{\alpha}$, $dN/d\nu \propto \nu^{\Gamma_\gamma} \propto \nu^{\alpha-1}$. So, $\Gamma_\gamma = \alpha - 1$ if we want to compare the radio spectral index and the high energy photon index. We can also add the flaring activity, including $\delta S_\gamma$, $\gamma$-fluxes $t_\gamma$, etc.

A na"ive approach is to check the relationship between the different observables both in VLBI and in $\gamma$-rays, and draw physical conclusions of them. Having a sample of objects at one band, the properties at the other band can be divided between detections

2Notice that computing the luminosity in the $\gamma$-regime is more problematic than in the (almost monochromatic) radio regime, given the fact that photons with frequencies different in several orders of magnitude are being used. An expression for the $\gamma$-luminosity is given in [23] as $L_\gamma = 4\pi D_L^2 S_{\gamma 1}(1+z)^2-1\gamma^2$, where $S_{\gamma 1} = C_1 E_1 F_0(\Gamma_\gamma - 1/\Gamma_\gamma - 2)(1 - (E_1/E_2)^{2\gamma-2})$, being $F_0$ the upper limit on photon flux above a given energy $E_1 = 0.1\text{GeV}$, the upper energy $E_2 = 100\text{GeV}$, and $C_1 = 1.602 \times 10^{-3}\text{erg/GeV} = 1\text{J}/\text{J as conversion factor. The authors fixed } \Gamma_\gamma = 2.1.$
Table II VLBI surveys complementing $\gamma$-observations

| Program                  | $\lambda$ | $N_{\text{sources}}$ | $N_{\text{epochs}}^a$ | Time   | Ref. |
|-------------------------|-----------|----------------------|------------------------|--------|------|
| GMVA 3mm                | 3 mm      | 121                  | 2                      | 2004-  | 27   |
| Boston Univ.            | 7 mm      | 35                   | 50                     | 2007-  | 26   |
| TeV Sample              | 7 mm$^b$  | 7                    | 5                      | 2006-  | 29   |
| MOJAVE/2 cm Survey      | 2 cm      | 300                  | 20                     | 1994-  | 30   |
| Bologna low-z           | 2/3.6 cm  | 42                   | 2                      | 2010-  | 31   |
| TANAMI                  | 1.3/3.6 cm| 80                   | 5                      | 2008-  | 32   |
| VIPS                    | 6 cm      | 1127                 | 1                      | 2007   | 32   |
| VIPS subsample          | 6 cm      | 100                  | 2                      | 2010-  | 33   |
| CJF                     | 6 cm      | 293                  | 3                      | 1990s  | 34   |
| ICRF                    | 3.6/13 cm | 500                  | 10                     | 1990s  | 35   |
| VCS                     | 3.6/13 cm | 3400                 | 1                      | 1990s  | 35   |

$^a$ Typical number of epochs per source

$^b$ Also including $\lambda$1.3 cm & $\lambda$3.6 cm

and non-detections in histograms, and usually the sources are then divided into their optical classification (FSRQ, BL Lac, Radio Galaxy, etc.) or into their high-energy peak classification (HSP, ISP, LSP). This was especially the approach on the first VLBI-related publications of the Fermi era. When more data have been available, plots of properties at one band versus the other band provide some hints of the nature of radio-loud/quiet and $\gamma$-loud/quiet objects.

3. VLBI SURVEYS

VLBI has been performed since the early 1970s, and more intensively since the construction of the Very Long Baseline Array (VLBA$^3$) in the early 1990s. Regular observations with open calls are being performed by the European VLBI Network (EVN$^4$) and the Long Baseline Array (LBA$^5$; expanded with the addition of telescopes outside Australia) operate regularly. Several big surveys have monitored the brightest objects for calibration purposes, and for determining properties of sources detected in $\gamma$-rays, following [51]. Reaching both hemispheres, the geodetic networks, at present under the umbrella of the International VLBI Service, collected data of hundreds of sources for calibration purposes, and for determining tectonic motions, Earth Orientation Parameters, the length of the day, and other geophysical parameters.

3.1. VIPS

The VLBA Imaging and Polarimetry Survey$^6$ is a one epoch survey including polarimetry at 5 GHz performed in the mid 2000s. The first stage of the observations was described in [32]. Results on the radio properties of sources detected by Fermi/LAT showed no correlation between $S$ and $S_\gamma$. Furthermore, from this study radio-bright BL Lac objects detected by Fermi/LAT were similar to the non-LAT ones, but for FSRQ there is a difference on the emission related to Doppler boosting: not surprisingly, only the FSRQ with higher $\delta$ are $\gamma$-loud. Polarisation at the base of the jet is a signature as well for $\gamma$-ray loud AGN.

$^3$The VLBA is operated by the US National Radio Astronomy Observatory, a facility of the US National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

$^4$The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils.

$^5$The Long Baseline Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

$^6$http://www.phys.unm.edu/~gbtaylor/VIPS/
3.2. Boston University Blazar Program

The Boston University (BU) blazar group has been performing a monitoring campaign with VLBA images sampled monthly at 43 GHz since 2007 (continuing the monitoring performed on some sources on the early 2000s), whose calibrated data are publicly available\(^7\). Due to the nature of the survey (reduced number of sources, intensively monitored), the published results are focused on multi-band studies of individual sources (see below). A description of the overall project is given in \([28]\). In general it is interpreted that a high γ-state is related to an outburst at the millimetre regime. The outburst is associated to the passing of a traveling shock through a recollimation shock in the base of jet \([15]\). Other explanations are possible, e.g., a pinch instability in a helical jet.

3.3. MOJAVE

The 2 cm Survey project \([46]\) was started in 1994, short after VLBA completion, with the aim of monitoring a sample of bright and representative AGN at sub-parsec scales. It was continued from 2002 onwards and until now under the name ‘Monitoring Of Jets in Active galactic nuclei with VLBA Experiments’ (MOJAVE\(^8\)). The project studies a complete sample of 135 objects above \(-30^\circ\) observed at 15 GHz including dual polarisation, and its database contains images of up to 300 sources. It consists of continuous long-term monitoring including source-specific observing cadences, yielding high-quality jet motions. The well-defined sample enables solid statistics of the parent population (e.g., \([47, 48]\)). The high-quality imaging and monitoring results have also made possible numerous individual source studies performed by the MOJAVE group or by others, since all calibrated data are made publicly available.

Studies based on the Fermi three-month bright source list \([24]\) show that the sources being more compact, brighter in radio, with higher radio activity, and with higher δ values, are favorably detected by Fermi \([49]\). The γ-ray bright sources tend to have faster jets, especially in the case of quasars \([50]\). Concerning the apparent opening angles, jets detected in γ-rays tend to be broader than the non-detected ones, but the intrinsic opening angles are similar for detected and non-detected ones, connecting beaming and γ-detection \([16]\). A later study shows that LAT-detected blazars have higher δ values than the non-detected ones, and the viewing angle distribution is different for the γ-ray bright and weak sources; the comoving frame viewing angle distribution is narrower for γ-bright sources \([51]\). Furthermore, a correlation analysis showed a delay between the VLBI core brightness and the γ-ray emission (γ leads 15-GHz radio \([52]\)). Results on a joint γ-ray and radio-selected sample show that the γ-ray loudness \(G_γ\) increases with the SED \(ν_{IC}\), and that the high-synchrotron-peaked (HSP\(^9\)) BL Lac objects have lower radio core \(T_b\) values \([28]\). To finish with the recently published results, positive correlation was found between \(L_R\) and \(L_γ\) \([18]\). A study on the relationship of RM in the MOJAVE images with γ-ray is presented in \([18]\) and in a future publication. After including optical properties, a positive correlation is present between \(L_R\) and the γ-ray-optical loudness for quasars, and a negative correlation between \(L_{opt}\) and the γ-ray-radio loudness \([48]\). A preliminary study on the relationship between the SED properties of the MOJAVE sources and the radio properties has been also first presented in \([52]\), and will be published elsewhere.

3.4. TANAMI

The TANAMI project (Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry\(^10\)) uses the Australian Long Baseline Array with additional telescopes to study sources at declination below \(-30^\circ\). With a different approach, it complements the regions of the sky not covered by MOJAVE. The project was started in November 2007 and observes at 8.4 GHz and 22 GHz. First images at 8.4 GHz have been published, and a preliminary analysis shows that Fermi/LAT-detected sources have larger opening angles \(ψ\) \([17]\). 22 GHz and spectral index images and jet kinematics will be published in a near future.

3.5. Other studies and samples

Some of the TeV blazars have been studied systematically with VLBI. One of the γ-related studies studies the properties of six blazars in \([29]\), and additional ones are included in \([54]\). A VLBI-γ study based on the Bologna Complete Sample aims to observe a sample of 94 nearby (\(z < 0.1\)) sources, from which 76 are being processed now \([55]\). A study comparing the CJF sample with the 1LAC shows a tentative correlation between \(L_γ\) and \(β_{app}\), especially for BL Lac objects and γ-variable sources \([56]\): the apparent speed distribution seems to be the same for γ-detected and non-detected sources. Another interesting study is

\(^7\)http://www.bu.edu/blazars/VLBAproject.html
\(^8\)http://www.physics.purdue.edu/astro/MOJAVE/
\(^9\)HSP show a peak in high-energy bump of the spectral energy distribution above \(10^{15}\) Hz, whereas intermediate- (ISP) and low- (LSP) synchrotron-peaked have peaks between \(10^{14}\) Hz and \(10^{15}\) Hz, and below \(10^{14}\) Hz, respectively.
\(^10\)http://pulsar.sternwarte.uni-erlangen.de/tanami/
of the γ-ray emission is located at the VLBI cores.

4. INDIVIDUAL SOURCE STUDIES

Table IV shows a selection of sources of special interest. I have tabulated sources with published combined VLBI-γ results, and added some sources with more than one flare reported in ATels (to keep the list short). For a list of the sources detected at TeV, see http://tevcat.uchicago.edu/. A very useful list compiled by the MOJAVE team listing all sources being observed by the different surveys can be found at http://www.physics.purdue.edu/astro/MOJAVE/blazarlist.html.

Here we describe in detail a selection sources sorted by right ascension in B1950.0 coordinates, where γ-VLBI data have been reported.

AO 0235+164 This source has been studied in the framework of a multi-band campaign, and multi-band light curve correlations at different bands is presented together with VLBI analysis from the BU program 60. These results show hints of a new feature in the jet associated to the γ-outburst observed by Fermi, which is interpreted as the propagation of an extended moving perturbation through a re-collimation structure at the end of the region where the jet is collimated and accelerated.

IC 310 The galaxy 0313+411 in the Perseus Cluster has been recently detected in γ-rays with an extremely hard γ-spectrum. Sub-parsec-scale VLBA images at 8.4 GHz detect a one-sided core-jet structure with blazar-like radio emission oriented at the same position angle than the kiloparsec radio structure 41. Those findings suggest this object to have of blazar nature rather than being a head-tail radio galaxy as it was classified in the past.

3C 84 The Fermi-detection of 0316+413 in the Perseus Cluster was reported in 41, including MOJAVE data, where a brightening of the central sub-parsec-scale region is reported, especially by comparing images from August 2008 and September 2007. Results from 14 epochs in the 2010s carried out with the Japanese VLBI Network show an outburst associated with the central parsec near the core. A jet component with β_app ∼ 0.23c is getting brighter during the γ-ray flare, which suggests a connection between both events 62.

PKS 0528+134 Multi-band results during the 2nd half of 2009 show a quiescent high-energy behavior, and the BU program images presented a stable state in its parsec-scale radio jet at 43 GHz 63.

PKS 0537–441 First images from TANAMI are discussed by 44. Those results include monitoring and spectral information between 8.4 GHz and 22 GHz as compared to Fermi/LAT light curves in γ-rays.

OJ 287 Multi-epoch, multi-waveband flux and linear polarization observations of 0851+202 have been presented by 64 in the framework of the BU blazar monitoring program. Those observational results suggest that the γ-ray emission is caused by a prominent feature in the jet > 14 pc away from the central engine. The parsec-scale structure of this source has apparently changed its direction since 2005, and the kinematic analysis of the VLBI structure shows that two γ-flares happen while a feature passes through a quasi-stationary shock in the jet. Detailed results of intensive monitoring from 1995 to 2011 at 43 GHz are presented in 42, showing erratic wobbling in its sub-parsec jet structure.

PMN J0948+0022 The narrow-line Seyfert 1 source 0946+006 has been studied with a multi-band cam-

Table IV Individual source studies (γ & VLBI)

| ID (B1950.0) | Alt. ID | ATel No. | Program† Ref |
|-------------|---------|----------|-------------|
| 0219+428    | 3C66A   | 1753     | M12+B       |
| 0237−164    | 1744, 1784 | 2510 | M12+B       |
| 0313+411    | 3C310  | 2737     | M12+B       |
| 0316−413    | 3C84    | 2124, 2591 | T           |
| 0922−362    | 2413, 2484, 3554, 3655, 3648 | 1998, 3703 | M12+B       |
| 0951+260    | 4312    | M12+B    |
| 0957−441    | 2124, 2545, 2591 | T |
| 0958+624    | 1500, 3487, 3780 | M12+B       |
| 0957−115    | 1919, 2860 | M12       |
| 0958+027    | 2256, 3680 | M12+B       |
| 0958+066    | 2408, 2136 | M12+B       |
| 0958+020    | 2322, 2326, 2328, 2534, 2733, 3429, 3448 | M2          |
| 1101+304    | 3233, 3831 | M12+B       |
| 1122+216    | 2921, 2348, 2349, 2564, 2641, 2684, 2687 | M12+B       |
| 1126+123    | 1707, 2099, 2368, 2200, 2376 | M12          |
| 1128+126    | 2437    | M12       |
| 1213+409    | 1888, 3429 | M2          |
| 1213+423    | 1964, 2154, 2886 | M12+B       |
| 1232−426    | 2728, 2829 | M2          |
| 1302+049    | 2217, 3793 | M2          |
| 1304+451    | 2104, 2583, 3329 | M2          |
| 1304−095    | 1900    | M12+B     |
| 1310−089    | 1743, 1897, 1968, 1975, 2033, 2385, 3470, 3473, 3694 | M12+B       |
| 1319−128    | 1860−128 | M2          |
| 1319−128    | 2231, 2531, 3424 | M2          |
| 1333−382    | 2136, 2546, 3333 | M12+B       |
| 1641+099    | 3C345   | 2316     | M12+B       |
| 1652+307    | 2586, 3322 | M2          |
| 1652+307    | 2345, 3393 | M2          |
| 1803−174    | 1628, 1634, 2089, 2200, 2322, 2326, 2328, 2554, 2995, 3041, 3043 | M12+B       |
| 2245−167    | 2408, 2727 | M12       |

Note: Table updated as of February 1st, 2012
Note: ATel IDs on the gravitational lens PKS 1830−211 are not listed
† Key: M1/2 MOJAVE 1/2; T: TANAMI; B: Boston U.
‡ The ATel 2437 reports on post-VHE-flare eEVN observations.
A relationship between a high state in the VLBI core and a γ-ray by present in the jet, four of them related to ionisation regions [88]. Observations of 1226+023 by the e-EVN data show a relationship between a location distance of 4–11 pc between both emission regions [68], but no robust kinematics was possible with four epochs at the time of publication. The results from the eEVN yield a value of \( T_b = 3.4 \times 10^{11} \text{K} \), confirming that this object is similar to FSRQ [68].

**Mrk 421** A multi-band campaign on the TeV source 1101+384 [69] including VLBI data shows a partially resolved pc-scale radio core; the radio source showed a low activity at all wavebands during the campaign.

**Centaurus A** Detailed results from a multi-band campaign on 1322–428 is presented in [38], including TANAMI observations where the VLBI core size is used to calculate an upper limit on the size of the γ-ray emitting central region (<0.017 pc), whereas the slow \( \beta_{\text{app}} \) measured do not impose constrains in the value of \( \Gamma \). More detailed VLBI imaging is presented in [74] where some regions near the core have an inverted radio spectrum, which are suggested as possible production sites for the high energy photons, since they have high \( T_b \) and compact structure. Note that this is the only source known so far with detectable γ-emission beyond parsec-scales.

**4C +21.35** The BU program study on 1222+236 combined with multi-waveband observations has produced interesting results on the correlation of light curves [72]. VLBI morphological results are interpreted in [80] as showing a superluminal feature crossing at \( \beta_{\text{app}} \sim 14c \) a stationary jet feature simultaneously with a γ-ray high state [89].

**M 87** The nearby galaxy 1228+126 was detected by Fermi/LAT and multi-band results are presented in [72] including MOJAVE data. The source has been intensively monitored in the mid 2000s to track the location and nature of the high-energy and radio emission of the component HST-1 (see [41] and references therein). The relationship between the 43 GHz VLBI brightening of the core in 2008 and a TeV emission was presented in [71]. In this context, further monitoring has been performed including the eEVN [73], and the possibility that the γ-ray emission observed by Fermi comes from HST1 is still unclear.

**3C 273** A relationship between a high state in the VLBI core and a γ-ray flare has been reported, implying a location distance of 4–11 pc between both emission regions [88]. Observations of 1226+023 by the BU blazar program report that seven new features are present in the jet, four of them related to γ-emission with \( \beta_{\text{app}} \sim 7–12c \), and a value of 0.7 knots ejected per year is reported [80].

**3C 279** The BU blazar program reports on two knots appearing in the jet of 1253–055, and the time of their passage through the parsec-scale mm-wave radio core coincide with two prominent γ-ray events in the light curve [80]. This is so far the most distant source where TeV emission has been detected.

**PKS 1502+106** A multi-band campaign including Fermi/LAT and MOJAVE data has shown the connection between γ activity and a rotation in the EVPA at this source [75].

**PKS 1510–089** The source had a flare detected by AGILE in March 2009 [43], also reported by Fermi/LAT [76]. The radio structure, spectra, and polarisation of this source are presented in [77], including results from MOJAVE and from [57, 58]. The BU blazar monitoring results are interpreted as being caused by a bright knot of emission passing to the stationary VLBI ‘core’, which produces a long radio and X-ray outburst lasting months after the flare [77]. Newer γ-flares are interpreted as well in this picture. An analysis of earlier MOJAVE archival data reveals that emission at γ and radio energies has origin in the same region [78].

**4C +38.41** The source 1633+382 has been studied by [70, 51]. The BU observations report that a high γ-ray state in September 2009 is simultaneous with a high state in the VLBI core. The changes polarisation vectors from VLBI and the optical support the idea of the γ-rays are connected with processes near the mm-VLBI core.

**3C 345** The source 1641+399 was identified as the source of γ-ray emission reported from the 3C 345–NRAO 512 region [82]. The combination of 20-month data from Fermi/LAT and 43 GHz VLBA monitoring observations of 3C 345 shows that the quiescent and flaring components of γ-ray emission are produced in a region of the jet of up to \( \sim 23 \) pc (deprojected), favouring the synchrotron self-Compton mechanism for γ-ray production [83].

**Mrk 501** The source 1652+389 has emitted a mildly variable γ-flux over the period 2008–2011. A multi-band campaign of this source shows multi-frequency VLBA data from the projects BK150, BP143, and MOJAVE; its VLBI core is used for the SED analysis of the source [84].

**BL Lac** The source 2200+420 has registered several major γ-ray ﬂares detected by Fermi and is observed intensively in VLBI since the 1980s. Results on a multi-band campaign are presented in [57], including VLBI images from the Fermi-related multi-wavelength campaign reported in [57, 58]. Multi-band and spectral index VLBI images reveal a curved jet with a core region with inhomogeneous structure and changing spectral properties rather than being a single, uniform, self-absorbed feature. A turnover by synchrotron self-absorption in the core takes place at \( \sim 12 \) GHz; and assuming \( \delta = 7.3 \) from [19], a limit is set to the core magnetic field of \( B < 3 \) G.
The Fermi/LAT detection of 2251+158 is reported in [39]. The source has registered several major $\gamma$-flares (see e.g., the AGILE observations in [40]), as it seen in the amount of ATels in table IV. The source has been intensively studied with VLBI. The results from the BU blazar program [58, 59] report on the coincidence of $\gamma$-ray peaks with jet features crossing the jet location at superluminal speeds. This phenomenon has occurred three times, coinciding with the three major flares in December 2009, April and November 2010.

5. CONCLUSION

An enormous observational VLBI effort is being performed on AGN to address their nature under the new light of $\gamma$-emission. Extensive studies on AGN samples and intensive multi-band campaigns on individual sources are underway. As of writing this review, new publications are in the process of submission or revision, including newer correlations and observational data. One of the next challenges is to establish a (statistically robust) connection between ejection of features in VLBI jets and $\gamma$-flares and hardness changes at the high spectrum, once enough data have been collected during the Fermi era. The new windows opened to the Southern sky or to extreme regions in the parameter space such as mm-VLBI will provide new results. We look forward to the next $\gamma$-radio meeting and bigger symposia for new, exciting findings.

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