Millimeter-VLBI observations of blazars

Marcello Giroletti
INAF Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
E-mail: giroletti@ira.inaf.it

Abstract. High angular resolution observations of blazars are a key step to understand the properties of relativistic jets emerging from Active Galactic Nuclei (AGN). Space-VLBI and mm-VLBI are complementary approaches to obtain an extraordinary resolution, with the latter being more suitable in the case of the most compact self-absorbed regions at the base of the jet. In this contribution, I present the results of mm-VLBI observations of a TeV active blazar (Mrk 501), successfully detected with a flux density of \( \sim 110 \, \text{mJy} \) and a resolution of \( 110 \, \mu \text{as} \times 40 \, \mu \text{as} \). A limb-brightened structure seems to be present even on the smallest scales. The need for new observations of Mrk 501 and of four more EGRET blazars is discussed, with an outlook to the main questions in the era of gamma-ray satellites.

1. Introduction

It is now commonly accepted that most or even all galaxies host a super-massive black hole (BH, \( M_{\text{BH}} = 10^7 - 10^9 M_\odot \)) at their center, and that a substantial fraction of these black holes is responsible for some level of multi-wavelength activity, from \( \sim 10^{39} \, \text{erg s}^{-1} \) in low-luminosity AGN (LLAGN) to \( 10^{45} \, \text{erg s}^{-1} \) in the brightest quasars. In a smaller fraction of galaxies, the central black hole is also capable of creating relativistic jets of plasma, which travel through the inter-stellar medium (ISM) and eventually form large structures (as large as hundreds of kiloparsecs), which are revealed thanks to their synchrotron radiation. When the jet is closely aligned to our line of sight, the radiation on the approaching side is strongly enhanced by relativistic effects, and the beamed emission from the jet base dominates the overall spectral energy distribution (SED). This happens in the objects named blazars, which include flat spectrum radio quasars (FSRQ) and BL Lacs. Blazar SEDs are two-peak, with the low-frequency peak due to synchrotron radiation, and the high-frequency one to inverse Compton scattering. The scattered photons can be external (EC scenario, favoured in FSRQ), or the jet’s own synchrotron photons (synchrotron self-Compton, SSC, in BL Lacs).

Because of the broad range of energies covered by blazar SEDs, it is clear that multi-wavelength studies are of great importance in constraining the jet physical properties (Kataoka et al., 1999). However, since the very presence of the highest energy emission and the short variability timescales indicate that the emission takes place on extremely small scales, a primary requirement for our study is the highest possible angular resolution (Ghisellini & Tavecchio, 2008).

In this contribution, we discuss the status of the current observational capabilities available in this field. We will focus on a particular astrophysical laboratory, i.e., the jet of the blazar Markarian 501, and present high angular resolution observations obtained in the radio band with the technique of Very-Long-Baseline Interferometry (VLBI). Mrk 501 is a well known BL Lac
Figure 1. Total intensity contours of the inner part of the jet in Mrk 501. Left: space VLBI observations at 1.6 GHz, with contours traced at (1, 1.5, 2, 3, 4, 6, 8, 10, 30, 50, 100, 200, 400) × 1.0 mJy beam⁻¹; right: VLBA image at 22 GHz, with contours at (1, 1.5, 3, 5, 7, 10, 15, 20, 30, 50, 70, 100, 200, 300) × 1.0 mJy beam⁻¹. The convolving beam is shown in the bottom left corner of each panel.

object, nearby (z = 0.034) and bright in the radio (S_{5\text{GHz}} = 1 \text{Jy}). It is also highly active and variable at high energy; it has been detected both by EGRET and by TeV Cherenkov telescopes (Kataoka et al., 1999; Bradbury et al., 1997). The short time scale variability and high energy emission indicate that high Doppler factors (δ > 10) are present in the innermost jet region of Markarian 501 (Tavecchio et al., 2001).

As the subject of this conference is high angular resolution, the reader shall already be familiar with the following formula:

$$\theta = \frac{\lambda}{d},$$

where $\theta$ is the angular resolution of an instrument, $\lambda$ and $d$ its observing wavelength and dimension, respectively. In the case of an interferometer, $d$ actually is replaced by the size of its (longest) baseline. For VLBI, $\lambda \sim 10$ cm, and $d \sim 1000$ km; therefore, $\theta \sim 20$ mas. This result can then be improved by increasing $d$ with more distant telescopes or decreasing $\lambda$ with the use of mm-wavelength receivers.

In this contribution, we will explore both the above mentioned ways, describing Space VLBI observations in §2 and mm-VLBI observations in §3. Since Space VLBI observations have already been presented in detail elsewhere (Giroletti et al., 2004, 2008a), we will concentrate here mainly on the use of shorter wavelengths (in the millimeter range).

The results of the observations will be discussed in §4. A more thorough discussion and some high sensitivity centimeter-wavelength data will also be presented in a forthcoming paper (Giroletti et al., 2008b). Finally, we will discuss in §5 some future prospects for this and other blazars, in the light of the developments in the instrumentation announced for the coming years across the electromagnetic spectrum.

2. Space VLBI observations

Radio images show a core-dominated symmetric structure on kpc scales (Cassaro et al., 1999); higher resolution VLBI images reveal a one-sided jet, suggesting that the parsec scale radio jet is in relativistic regime. Thanks to the VLBI Space Observatory Programme (VSOP), we
have for the first time been able to observe Mrk 501 with baselines as long as 180 MA at 18 cm wavelength, where the steep spectrum emission of the resolved jet is brighter (Giroletti et al., 2004). As a result, we have revealed a limb brightening of the jet in the region between 10 and 20 mas from the core. This limb brightening has then been confirmed both closer to the core and in the more extended jet. Figure 1 shows total intensity contours at 1.6 GHz with space VLBI (3 mas resolution, left panel) and at 22 GHz with the VLBA (0.6 mas resolution, right panel).

Under a small to moderate viewing angle, a transverse brightness structure can be due to different Doppler beaming of regions with different velocities. The issue of the presence of transverse velocity structures is hotly debated at the moment, in the light of analytical models and of numeric simulations (Mizuno et al., 2007; Perucho et al., 2007; Ghisellini et al., 2005). In this framework, the direct detection of limb brightening in Mrk 501 with the VSOP provides an observational evidence of great importance.

Another remarkable result coming from high resolution ground and space VLBI observations at centimeter wavelengths deals with the identification of jet components and their motion. From a study based on nine epochs, it turns out that compact components are resolved out in higher resolution images and that fast ballistic motions are not present in the jet of Mrk 501 (Giroletti et al., 2004).

Finally, there is also a rich polarization structure, with an electric vector polarization angle (EVPA) parallel to the jet axis in the inner spine and misaligned on the jet limbs. This behavior is detected on various scales, including the innermost jet (Pushkarev et al., 2005) and the region between 10 and 20 mas (Giroletti et al., 2008b).

3. Millimeter VLBI observations

3.1. Observations and data reduction

The Global mm-VLBI Array (GMVA\(^1\)) adds some large apertures (Effelsberg, Pico Veleta, Plateau de Bure Interferometer), plus Onsala and Metsähovi, to 8 VLBA stations, providing a resolution of \(\sim 0.05\) mas at 86 GHz and a baseline sensitivity (7\(\sigma\)) lower than 0.1 Jy for the largest telescopes and around 0.2–0.4 Jy for other baselines. Mrk 501 is therefore one of the weakest sources detectable to date.

We observed Mrk 501 on 14 Oct 2005 with the Global mm-VLBI Array, at a frequency of 86.2 GHz, for a total of \(\sim 9\) hours (the American telescopes joined in for the last \(\sim 6\) hours). The calibrator 3C 345 was readily detected with good signal-to-noise ratio. Mrk 501 itself was well detected not only between large European apertures but also on baselines to the smaller VLBA antennas. Our final image is shown in Fig. 2, and it is characterized by a resolution of 110 \(\times\) 40 \(\mu\)as and a final r.m.s. noise of 1.5 mJy.

3.2. Core and inner jet structure

Mrk 501 is dominated by a compact, prominent component, of \(\sim 45\) mJy beam\(^{-1}\) peak brightness. The visibility data suggest that there is a fair amount of extended emission, although the \((u,v)\) coverage is not ideal and it is extremely difficult to image it. In our clean image and with model fitting, we recover a total flux density of \(\sim 110\) mJy in the core region, including a jet-like feature in PA 144\(^\circ\) and some more diffuse emission in PA \(\sim -135\)\(^\circ\). A tentative jet knot (\(\sim 7\sigma\)) is also visible 0.73 mas south of the core (PA 172\(^\circ\)).

The brightest and most compact component, which we identify with the core visible at centimeter wavelengths, is unresolved at 86 GHz. We then use our deconvolved size of this component to give an upper limit to the dimension of the jet base, and a lower limit to its brightness temperature. At \(z = 0.034\), 1 mas = 0.67 pc, therefore the deconvolved angular size of the GMVA core corresponds to 0.021 \(\times\) 0.032 pc. The black hole mass for Mrk 501 is estimated

\(^1\) http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/
around $M_{\text{BH}} = 10^9 M_\odot$ (Rieger & Mannheim, 2003), which implies a Schwarzschild radius $R_S = 1.0 \times 10^{-4}$ parsecs. This means that the radio emission originates in a region that is smaller than $210 \times 320 R_S$.

We derive the brightness temperature of this region from the following formula:

$$T_B = \frac{B}{2k} \lambda^2,$$

and we derive $T_B \geq 6.8 \times 10^9 K$. If we assume that the size of the emitting region is actually smaller (e.g., less than 1/3 of the deconvolved size), we get $T_B \geq 6 \times 10^{10} K$.

The detection of a possible jet knot at $(r, \theta) = (0.72 \text{ mas}, 172^\circ)$ is in agreement with images at lower frequency. Comparing the GMVA data with model fits at 15 and 22 GHz (Edwards & Piner, 2002; Giroletti et al., 2004), the tentative jet knot can be identified with the region labelled as C4, which is found at the same distance and position angle. Edwards & Piner (2002) found this region to be apparently stationary between 1995 and 1999, and the positional coincidence lends support to this interpretation. At this resolution, the jet has therefore a still different orientation with respect to that seen at lower resolutions: the jet PA is $\sim 100^\circ$ at $2 < r < 20 \text{ mas}$ and $\sim 45^\circ$ at $r > 20 \text{ mas}.

3.3. Spectral index

We show in Fig. 3 a spectral plot for both the (average) total flux density on kiloparsec scale as measured by single dish telescopes, and for the VLBI core, including the data point at 86 GHz. The spectrum of the VLBI core between 1.6 and 22 GHz has been presented in Giroletti et al. (2004): the core has a turnover at about 8 GHz, and then the flux density falls as a power law of
Figure 3. Non-simultaneous radio spectra of Mrk 501. Filled squares represent average single dish measurements (see references in Giroletti et al., 2008b); empty squares show the VLBI core flux: data between 1.6 and 22 GHz are mean values taken from Giroletti et al. (2004); the datum at 86 GHz is from the present work. Solid lines connect the points simply to guide the eye. Error bars show the standard deviation of averages but for the 86 GHz VLBI datum (instrumental calibration uncertainty).

The new data point follows the optically thin part of the core spectrum. Note that as 86 GHz flux density we include the whole jet like structure and the diffuse component discussed above; this is because observations at lower frequency do not have the angular resolution to distinguish the different components. This implies that the turnover frequency at $\sim 8$ GHz is related to the whole structure and not to the 86 GHz core, whose self-absorption peak is probably located at higher frequency.

4. Discussion

4.1. The inner core

The nuclear region of Mrk 501 consists of (1) an unresolved component: the radio ‘core’, point-like at the resolution of present mm-VLBI (deconvolved size smaller than $\sim 30 \times 20 \mu$as or $0.020 \times 0.014$ pc or $200 \times 140R_S$), and (2) a faint resolved jet-like structure with a large opening angle, similar (taking into account the significant difference in flux density and linear resolution) to the inner structure of M 87 (Ly et al., 2007).

The unresolved component with a total flux density of about 45 mJy, is characterized by a relatively low $T_B$ in contrast with the higher $T_B$ of M 87. However, because of the different distance from us of the two sources, our ‘core’ includes the whole M 87 structure visible in images at 86 GHz (Krishbaum et al., 2006). Therefore, the $T_B$ of Mrk 501 is the average $T_B$ of a resolved structure where the jet velocity could be only mildly relativistic, as suggested by the detection of a counter-jet in the more misaligned M 87 (Ly et al., 2007; Kovalev et al., 2007).

The lack of a dominant unresolved component is in agreement with the spectrum shown in Fig. 3, where we can assume that the observational data refers to both regions (1) and (2) discussed above. Of course, uncertainties related to the variability are always present, but
because of the regularity of the spectrum we can use it to estimate the extension of the radio emitting region, by simply inverting the following formula (Marscher, 1987):

$$B = 3.2 \times 10^{-5} \theta^4 u^5 S_{m}^{-2} \delta (1 + z)^{-1}.$$ 

We assume a local average magnetic field $B = 0.02$ G and a Doppler factor $\delta = 10$ (as discussed by Tavecchio et al., 2001). The low ($\sim 8$ GHz) self-absorption frequency requires that the emitting region has a size of the order of 0.1 mas, in agreement with Fig. 2, and that a point-like source, if present, is not dominant. Note that the angular size is proportional to the magnetic field to the $1/4$th power, therefore a relatively small (even a factor 10) increase of the value of the magnetic field does not affect these conclusions.

4.2. Jet structure
Limb brightening in the jet of Mrk 501 seems to be present on scales as small as 0.1 mas, but also after the two main bends at $\sim 2$ and $\sim 20$ mas, where the jet has significantly expanded transversely. Under a given viewing angle, different Doppler factors can arise from different velocities; therefore, a common explanation for limb brightening in jets lies in the existence of a velocity structure transverse to the jet, with an inner spine and an outer shear.

Mrk 501 is unique in the fact that the limb brightened structure is visible on scales ranging over three orders of magnitude, and in sections of the jet that are differently oriented on the plane of the sky. In particular, the limb brightening in the mm-VLBI image indicates that a spine/shear structure could be present from the very inner part of the jet, close to the region where the higher frequency optical emission is produced. Our image provides support for the transverse dual velocity structure hypothesized on the basis of the correlation between the radio and the optical core luminosity in radio galaxies and BL Lacs (Chiaberge et al., 2000).

5. Summary and future prospects
We have presented the results of GMVA observations of Mrk 501 at $\lambda =3$ mm in October 2005. We detected a compact source and some extended flux. The source structure is dominated by a compact, prominent component, $\sim 45$ mJy beam$^{-1}$ bright, corresponding to a brightness temperature $T_B \sim 10^6 K$. A fair amount of extended emission is present in the visibility data, although the $(u, v)$ coverage is not excellent and it is extremely difficult to image it. We recover a total flux density of $\sim 100$ mJy in the core region, including a jet-like feature in P.A. $144^\circ$ and some more diffuse emission in P.A. $\sim 135^\circ$. A tentative jet knot ($\sim 7\sigma$) is also visible 0.95 mas south of the core (P.A. $172^\circ$). Despite their weakness and low-confidence, it interesting to note that these jet-like features seem to be in agreement with the direction of the innermost structure visible in 22 GHz images (Giroletti et al., 2004).

Better $(u, v)$—coverage and lower noise level are necessary to better understand the properties of this source in the region not accessible to centimeter VLBI. In particular, it would be important to (1) image the extended emission not well constrained by the previous observation and (2) to study possible variability and motion of the detected features. Clarification of these issues is important to discuss the jet properties at its base: velocity and orientation, the origin of the limb brightened structure, the connection to the parsec and large scale jet. We have then obtained new GMVA observations, which were performed during the meeting and that will be discussed in future papers. The results will also be relevant in order to test the current models for extragalactic jets, particularly in the light of the launch of the $\gamma$-ray missions AGILE (April 2007) and GLAST (June 2008, now the Fermi Gamma-ray Space Telescope).

Moreover, mm-VLBI observations of more $\gamma$-ray blazars can lead us to a better understanding of the physical processes in the region near the central black hole in blazars, and that is going to be particularly relevant during the lifetime of the space missions AGILE and Fermi. We
Figure 4. VLBI images at high frequency (43 or 22 GHz, Marscher, 2002) of the four targets for ongoing mm-VLBI observations by the GMVA. Noise levels and image peaks (mJy beam$^{-1}$) are as follows: 0219+428: 2.0, 700; 0235+164: 2.9, 400; 1101+384: 2.6, 290; 1219+285: 1.7, 300.

have then selected a small sample of four more blazars, characterized by the presence of high energy emission ($\gamma$-rays detected by EGRET) and of compact, dominant cores at centimeter wavelengths (including at $\lambda = 7$ mm). Centimeter-VLBI images of these blazars are shown in Fig. 4. With 8 hours observations at 512 Mbps, we expect to reach a dynamic range similar to these 1997 images in observations planned for October 2008. Among other goals, we plan to use mm-VLBI observations to pinpoint the location of the region where the $\gamma$-ray emission is produced, which is presently not well understood.
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