Extragalactic Jets: Theory and Observation from Radio to Gamma Ray
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The jet of Markarian 501 from the sub-parsec to the kpc scale

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Abstract. We have observed the BL Lac object Markarian 501 at 1.4 GHz with the High Sensitivity Array and at 86 GHz with the global VLBI mm array. Thanks to the great resolution and sensitivity provided by these instruments, we probe regions of the radio jets never accessed before. The new data at 1.4 GHz allow us to map the one-sided jet at large distances from the core, and to constrain jet properties thanks to the high jet to counter-jet brightness ratio. The 86 GHz data give us a high resolution image of the nuclear region. Putting together these new results and available published data we discuss the properties of this source from sub-parsec to kiloparsec scales.

1. Introduction

The study of extragalactic radio jets is an important area in astrophysics. In radio loud sources, jets contribute a large fraction of the total radiated power, and provide energy to kiloparsec scale radio lobes. Jets are present in high and low power sources, with some common features: on the parsec scale they are relativistic regardless of power, and they are also intrinsically identical in beamed and misaligned sources. Giovannini et al. (2001), have shown that the Lorentz factor in the parsec scale jets of low power FRI radio galaxies as well as of more powerful FR IIs are both in the range $\Gamma = 3 - 10$. Giroletti et al. (2004b) have also shown that with these properties one can unify BL Lac objects and FRI radio galaxies, if the former have jet axis oriented at an average viewing angle of $\langle\theta\rangle = 18^\circ \pm 5^\circ$.

In this work we focus on the jet structure of the BL Lac source Markarian 501. This object is highly active and well-studied at all frequencies. In the radio band, centimeter VLBI observations have revealed a clear limb-brightened structure, beginning in the very inner jet, suggestive of a dual velocity structure (Giroletti et al. 2004a). The complex limb-brightened structure makes component identification problematic and multi-epoch attempts to measure pattern speed conclude that it is not well defined (Giroletti et al. 2004a) or in any case at most subliminal (Edwards & Piner 2002). These seem to be common features in TeV blazars (Piner & Edwards 2004; Giroletti et al. 2006), and theoretical

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models have been proposed to reconcile the low observed speeds with the very high energy emission observed (Ghisellini et al. 2005; Wang & Xue 2004).

However, the information available up to now has been restricted to the region between ~ 1 and ~ 100 milliarcseconds, with smaller and larger scale regions being precluded by inadequate resolution and sensitivity. Improvements in the technical and organizational issues are now offering to astronomers VLBI arrays of unprecedented resolution and sensitivity, such as the High Sensitivity Array (HSA, see http://www.nrao.edu/hsa), and the Global mm-VLBI Array (GMVA see http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm). Thanks to its proximity and brightness, Mrk 501 is an ideal laboratory for experiments using these advanced VLBI techniques: it is at $z = 0.034$ (1 mas = 0.67 pc, using $H_0 = 70$ km s^{-1} Mpc^{-1}). The total flux density at 5 GHz is $S_5 = 1.4$ Jy; the Schwarzschild radius for its central black hole is estimated about 10^{-4} pc (1.4 10^{-4} mas), if we adopt $M_{\rm BH} = 10^9 M_\odot$ (Rieger & Mannheim 2003). Using these new facilities, we now access region never studied previously: the jet base with the GMVA, and the faint, resolved jet region at > 100 mas with HSA.

2. Observations

We observed Mrk 501 on November 2004 with the HSA for 8 hours at 1.4 GHz. Thanks to the HSA facility we observed with the full VLBA (NRAO), the VLA phased array (NRAO), the Effelsberg (D) 100 m single dish and the Green Bank Telescope (NRAO). The final map thanks to the high sensitive and good uv-coverage, allows us to image the one sided low brightness jet at a much larger distance (250 mas) from the core than previous observations (Giroletti et al. 2004a), and to obtain significant upper limits to the jet brightness ratio because of the low noise level (0.05 mJy/beam with a HPBW = 9 $\times$ 5 mas).

We used the VLA phased array observations to produce also a VLA only image. During the observations the VLA was in the A configuration and we observed 3C 286 for absolute flux calibration. At the VLA angular resolution Mrk 501 was strong and unresolved therefore it was used to calibrate the data and to phase the array.

On 14 Oct 2005 we observed Mrk 501 with the Global mm-VLBI Array (GMVA). The standard frequency was 86.198 GHz, with a bandwidth of 128 MHz divided in eight 16 MHz IFs. The participating telescopes were Effelsberg, Pico Veleta, the Plateau de Bure interferometer, Onsala, Metsähovi, and 8 VLBA stations (i.e. all except Saint Croix and Hancock). The European telescopes observed for $\sim$ 9 hours and the American ones joined in for the last $\sim$ 6 hours (Mauna Kea only for the last $\sim$ 4 hours). This experiment tested the sensitivity limits of the array, since on the basis of the observed centimeter wavelength flux density and spectral index (Giroletti et al. 2004a), Mrk 501 was expected to be only a few hundreds of milliJanskys at this frequency. The calibrator 3C345 was well detected on all baselines, except those to Metsähovi and North Liberty. From the fringe fitting of 3C345 we determined rates and single-band delays, and applied them to the whole data set. We obtained an image of 3C345 and found it to be in agreement with published images of comparable or slightly lower resolution (Lobanov et al. 2000; Lister & Homan 2005).

At this stage, it was then possible to fringe fit Mrk 501 itself, averaging over the 8 IFs. A solution interval as long as the scan, and a SNR cutoff of 3.0 was used.

3. Arcsecond scale

Mrk 501 was observed with the VLA by Koolgaard et al. (1992) and by Cassaro et al. (1999). In these images the source is core dominated, but a two sided extended structure is also visible, which has been identified as the symmetric extended emission characteristic of a radio galaxy. The source structure is in agreement with an orientation near to the line of sight as expected from a BL Lac source. The symmetric emission implies that at this distance from the core no relativistic jet remains.

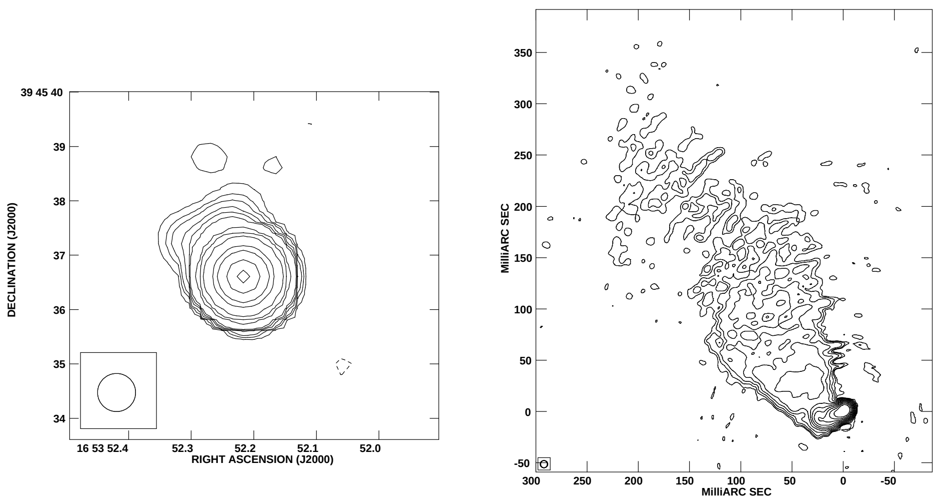

Figure 1. left: VLA image of Mrk 501. Contours are -1, 1 2 3 5 7 10 30 50 100 300 500 1000 1500 mJy/b; right: HSA image of Mrk 501. Contours are -1 1 1.4 2 2.8 4 5.6 ... × 0.25 mJy/b

In Fig. 1 left, we show the image obtained with the VLA during the HSA observations. The phased array image is dynamical range limited (∼ 10000:1), and it shows a one sided emission with a short jet like structure at the same PA as the extended symmetric structure. From this one sided emission we can derive constraints on the jet velocity (βc) and orientation (θ) with respect to the line of sight. At 2" we have $\beta\cos\theta > 0.36$ and at 1" $\beta\cos\theta > 0.63$. This result implies that at 0.67 kpc (projected) from the core the jet is still at least mildly relativistic ($\beta > 0.63$).

4. Sub-arcsecond scale

Thanks to the good sensitivity and uv-coverage of the HSA data, we can obtain images of the one-sided jet up to 300 mas from the core at a resolution of 9 × 5 mas (Fig. 1 right). Near the core the jet is bright and compact and after the well known change in its projected PA, it shows a large opening angle (∼

40°) and a diffuse emission which becomes limb-brightened in lower resolution images in agreement with previous results (Giroletti et al. 2004a).

From the jet brightness assuming intrinsic symmetry we derive that at 100 mas from the core $\beta\cos\theta > 0.61$ and that at 50 mas from the core $\beta\cos\theta > 0.77$

5. Milliarcsecond scale

New HSA observations confirm the structure near the core discussed in Giroletti et al. (2004a). The jet in the inner 25 mas is limb-brightned and oriented in PA 110°. With respect to previous results the low noise allows stronger constraints such that at 10 mas from the core we derive β $\cos\theta > 0.92$.

6. Sub-milliarcsecond scale

The 86 GHz VLBI image is shown in Fig. 2 left. The HPBW is 0.21×0.09 mas in PA -3° corresponding to a linear HPBW size of 014×0.06 pc at the distance of Mrk 501; the image peak flux is 208.2 mJy/b. The image shows a bright source at the core position with a short one-sided emission in PA 160°. At about 1 mas there is a faint radio knot extended in the E-W direction. Comparing this image with the 22 VLBA GHz image published in Giroletti et al. (2004a) we can identify this knot as the C4 region. The brightness decrease from the "core" region is very abrupt. No bright jet is visible despite of the high Doppler factor expected in a relativistic jet oriented at a small angle with respect to the line of sight.

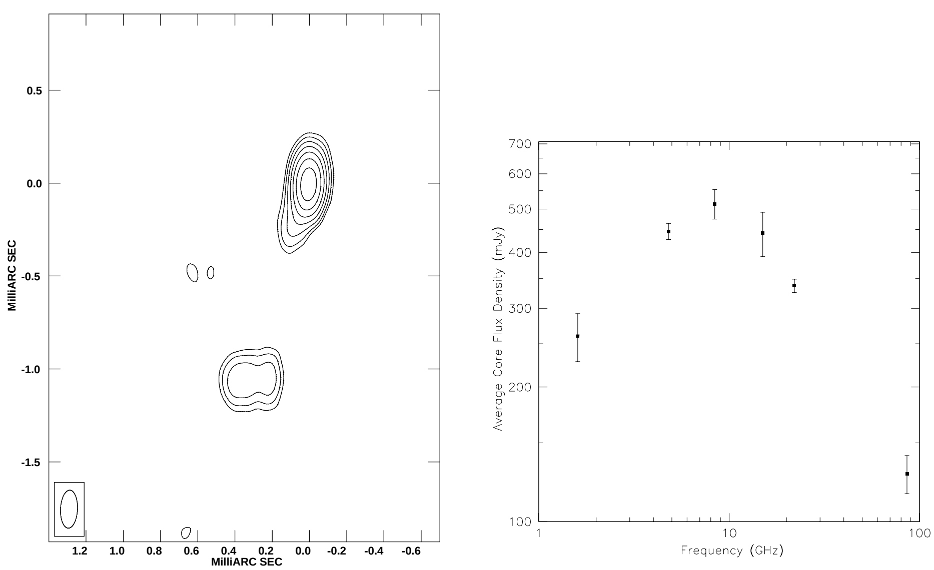

Figure 2. left: GMVA image of Mrk 501. Contours are: -1 1 2 4 8 16 32 64 $\times$ 2 mJy/b (3 σ level); right: Radio spectrum of the nuclear source of Mrk 501.

7. Discussion

- We estimated the core radio spectral index using the best available measures (Giroletti et al. 2004a). The radio spectrum is shown in Fig. 2 right (note that the different measurements were obtained at different epochs, however no strong radio variability has been found for Mrk 501). It is self-absorbed at about 8 GHz, suggesting that observations at higher resolution should resolve the nuclear source present in the 86 GHz image. The estimated magnetic field from the self-absorbed spectrum is in the range 0.01 - 0.03 G.

- A comparison of the 86 GHz image and the 22 GHz VLBA image (Giroletti et al. 2004a) confirms the changes in the projected jet PA: it is $\sim 160^\circ$ in the inner 1 mas, $\sim 90^\circ$ from 2 to 10 mas, 110° from 10 to 30 mas where the jet bends to $\sim 30^\circ$ afterwhich the jet PA is constant up to the kpc scale.

- The Gamma-ray emission detected from Mrk 501 requires a inner high velocity jet ($\Gamma \sim 15$) and a small angle with respect to the line of sight ($\theta \sim 4\,^\circ$) (Giroletti et al. 2004a). Moreover Ghisellini et al. (2005) discuss how a velocity structure in the jet could produce Gamma-ray emission.

  The absence of a bright jet in the sub-mas image at 86 GHz and the limb-brightened structure of the radio jet can be explained assuming a fast inner spine and a slower shear layer, with the inner spine at a larger angle with respect to the line-of-sight (10 - 15 degree). This results in a higher Doppler factor for the slow shear layer compared to the fast spine. The reason for the change in the jet PA with respect to the line-of-sight as well as of the projected jet direction, is unknown.

- The jet velocity decrease is slow: from HSA data we estimate that at 1 arcsecond (projected) from the core the velocity is still $\beta > 0.6$. This result is in agreement with the constant jet opening angle ($\sim 40^\circ$) in the region after the last major change in the jet PA up to ~ 150 mas from the core. Such an observed opening angle implies in a freely expanding jet a Lorentz factor of ~ 5. At 5 arcsecond from the core the jet is no longer relativistic.

- The observational data (in particular the high jet velocity in the inner region and the slow velocity decrease) are in agreement with the adiabatic model discussed in Baum et al. (1997) and in Giroletti et al. (2004a), with a magnetic field mostly perpendicular to the jet direction. A parallel magnetic field predicts a large velocity decrease in the region imaged using HSA data, in contrast with the observed results (a counter-jet should be visible well above our detection limit). Constraints from HSA and VLA data suggest a jet orientation of $\sim 15^\circ - 20^\circ$.

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