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R. Lico

C. Casadio

J. L. Gomez

M. Giroletti

M. Orienti

See next page for additional authors

Authors

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Very Long Baseline Polarimetric monitoring at 15 GHz of the TeV blazar Markarian 421

R. Lico[1,2,a], C. Casadio[3], J.L. Gómez[3], M. Giroletti[1], M. Orienti[1,2], G. Giovannini[1,2], M.G. Blasi[1,2], W. Cotton[4], P. G. Edwards[5], L. Fuhrmann[6], S. Jorstad[9,10], M. Kino[11], Y.Y. Kovalev[7,6], T.P. Krichbaum[6], A. Marscher[9], D. Paneque[12], M.A. Perez-Torres[3], G. Piner[13], and K.V. Sokolovsky[7,8]

[1] *INAF Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy*
[2] *Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, 40127 Bologna, Italy*
[3] *Instituto de Astrofísica de Andalucia, IAA-CSIC, Apdo. 3004, 18080 Granada, Spain*
[4] *National Radio Astronomy Observatory, Charlottesville, 520 Edgemont Road, VA 22903-2475, USA*
[5] *CSIRO Australia Telescope National Facility, Locked Bag 194, Narrabri NSW 2390, Australia*
[6] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*
[7] *Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia*
[8] *Sternberg Astronomical Inst. , Moscow State University, Universitetskij prosp. 13, 119992 Moscow, Russia*
[9] *Institute for Astrophysical Research, Boston University, 725 Commonwealth Av. Boston, MA 02215, USA*
[10] *Astronomical Inst. , St. Petersburg State University, Universitetskij Pr.28, 198504 St. Petersburg, Russia*
[11] *ISAS/JAXA, 3-1-1 Yoshinodai, 229-8510 Sagamihara, Japan*
[12] *Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany*
[13] *Dep. of Physics and Astronomy, Whittier College,13406 E. Philadelphia Street,Whittier,CA 90608, USA*

Abstract. Thanks to high resolution radio observations it is possible to obtain a direct imaging of the innermost regions of Active Galactic Nuclei; in particular, it is possible to investigate about the jet's morphology and any proper motions, and the time evolution of physical parameters, such as flux densities and spectral index. Furthermore, with the study of the polarization properties, it is possible to obtain important information about the magnetic field structure and the emission mechanisms. In this work we present recent results about the nearby (z=0.031) TeV blazar Mrk 421. We analyzed data obtained with the Very Long Baseline Array (VLBA), both in total and polarized intensity, at twelve epochs (one observation per month from January to December 2011) at 15, 24 and 43 GHz, in the context of a broadband campaign from the radio to gamma-ray. We investigate the inner jet structure on parsec scale through the study of model-fit components for each epoch. At these frequencies the source shows a compact (about 0.13 mas, or 0.08 pc) and bright component, with a one sided jet detected out to about 10 mas. All model-fit components in the jet appear to be almost stationary during our observation period, and the spectral index is fairly flat in the core region and steepens along the jet's length. In particular, we present a preliminary study of the polarization properties for the 15 GHz dataset: we found a degree of polarization of $\sim$ 1% for the core region and for the C3 component, at near 1 mas from the core, we found a value of near 14%.

1 Introduction

Mrk 421 (R.A.=11^h 04^m 27.313943^s, Dec.=+38° 12′ 31.79906″, J2000) is one of the best blazars useful to probe and to investigate the physics of the innermost regions of relativistic jets, mainly because of its proximity (z=0.03). For this, Mrk 421 has been intensively studied throughout the entire electromagnetic spectrum, since its detection as a very high energies gamma rays (TeV) emitters in 1992 [17].

In general, the spectral energy distribution (SED) of blazars is dominated by the emission of the jet, and it consists of two separate components: a low frequency hump, due to synchrotron emission by relativistic electrons within the jet, and a high energy hump, most likely due to inverse Compton (IC) scattering of low energy photons by the same electrons. In the case of Mrk 421 the synchrotron hump peaks at soft X rays, and for this it is classified as a high-frequency peaked BL Lac object [1].

Being the emission of these peculiar objects dominated by non-thermal radiation from relativistic electrons within the jet interacting with the magnetic field, with the study of its polarization properties we can provide important information on the magnetic field structure and the emission mechanisms. Furthermore, thanks to the multi-wavelength observations, we can try to investigate on the precise location where the radiation is produced.

Here we present Very Long Baseline Array (VLBA) observations taken during 2011 at 15, 24 and 43 GHz. At

[a] e-mail: rocco.lico@studio.unibo.it

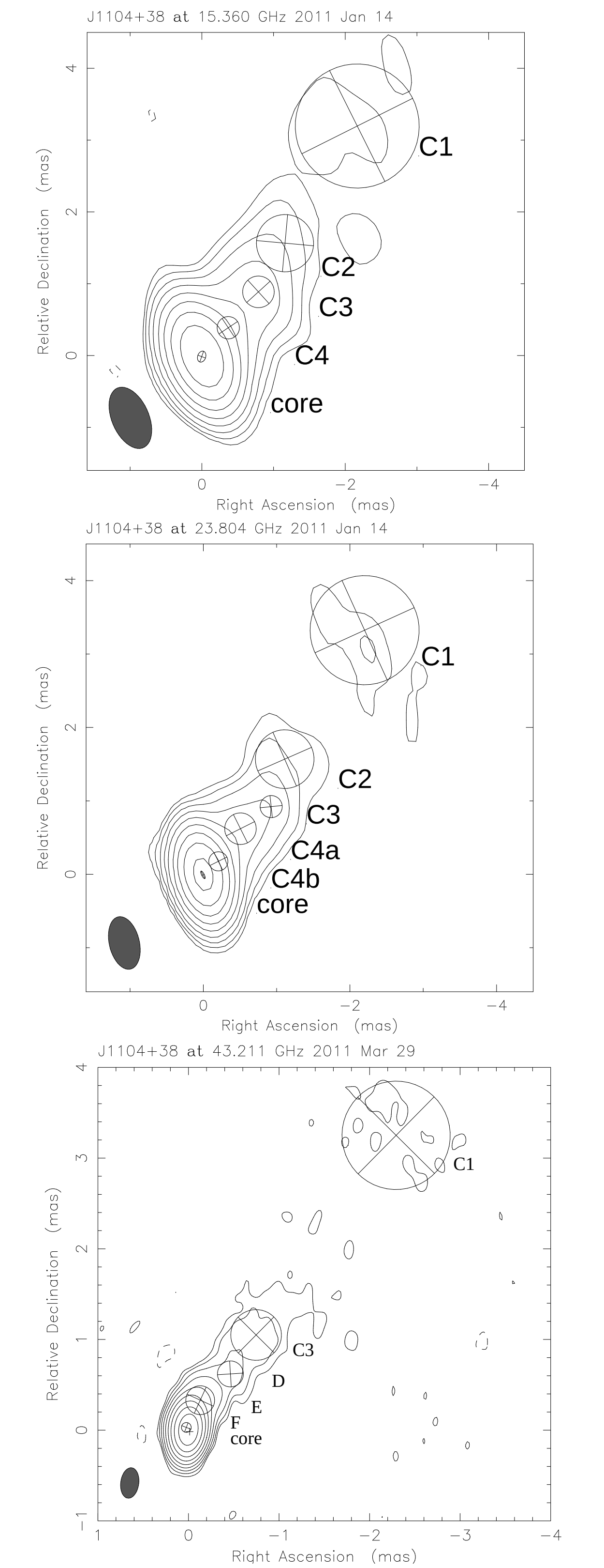

Figure 1. Images of Mrk 421 with model-fit components for the first epoch at 15 GHz (top panel), 24 GHz (central panel) and for the third epoch at 43 GHz (bottom panel). Levels are drawn at $(-1, 1, 2, 4...)\times$ the lowest contour (that is at 1.0 mJy/beam for 15 and 24 GHz images and 0.65 mJy/beam for 43 GHz image) in steps of 2. The restoring beam, shown in the bottom left corner, has a value of 0.92 mas × 0.54 mas, 0.58 mas × 0.35 mas and 0.42 mas × 0.27 mas, respectively for 15, 24 and 43 GHz.

these frequencies, the source shows a well defined one-sided jet structure aligned at a small angle with respect to the line of sight [7]. This dataset belongs to a multi-frequency campaign, carried out during 2011, which involves observations also in the sub-mm (SMA), optical/IR (GASP), UV/X-ray (Swift, RXTE, MAXI), and γ rays (Fermi-LAT, MAGIC, VERITAS).

In two previous works we presented the complete analysis of observations in total intensity for 15 and 24 GHz data [11] and for 43 GHz data [2]; we constrained with great accuracy some physical parameters as the Doppler factor (in the radio emission region we found $\delta_r \sim 3$, while in the high-energy emission region we found $\delta_{\mathrm{h.e.}} \sim 14$), the viewing angle ($2^\circ < \theta < 5^\circ$), apparent speeds and the brightness temperature ($T_{\mathrm{B,var}} \sim 2.1 \times 10^{10}$ K).

In this work we present the preliminary analysis of the observations in polarized intensity at 15 GHz, confirming and determining with great accuracy some physical parameters (e.g. the degree of polarization and the absolute orientation of the electric vector position angles (EVPAs)) and obtaining some useful information on the magnetic field morphology.

To determine the absolute orientation of EVPAs we use the method developed by Leppanen et al. in 1995 [10], based on the instrumental polarization parameters (the so called D-terms), that provide an independent way to calibrate the absolute right-left (R-L) circular polarization phase offset with respect the usual method that consists in the comparison of VLBA and Jansky Very Large Array (VLA) polarimetry. As in previous works (e.g. [8]) we confirm the validity and the great accuracy of this method.

2 Observations

This dataset for Mrk 421 was produced with VLBA, with one observation per month during the entire 2011, at three frequencies: 15, 24 and 43 GHz. Observations were carried out both in total and polarized intensity (in right and left circular polarization). All technical details about the observations can be found in [11] (for 15 GHz and 24 GHz data) and in [2] (for 43 GHz data). For the calibration process we used AIPS [9] while the cleaned and final images were produced with DIFMAP [18] and IDL.

2.1 Methods for the polarization analysis

The D-terms parameters were determined with the task LPCAL in AIPS. To determine all the polarization parameters (e.g. EVPAs orientation and polarization percentage) and the relative EVPAs rotations by comparing the antenna tables, we used IDL routines developed by J.L. Gómez. We also observed the source J1310+3220 used as calibrator for the polarization percentage and for the determination of the absolute EVPAs orientation.

To obtain the absolute orientation for the EVPAs (third column in table 1) we used the D-terms method, that consists in the comparison of the D-terms for each antenna in consecutive epochs, obtaining the relative rotation (fourth column in table 1) both in right (R) and Left (L) circular polarization.

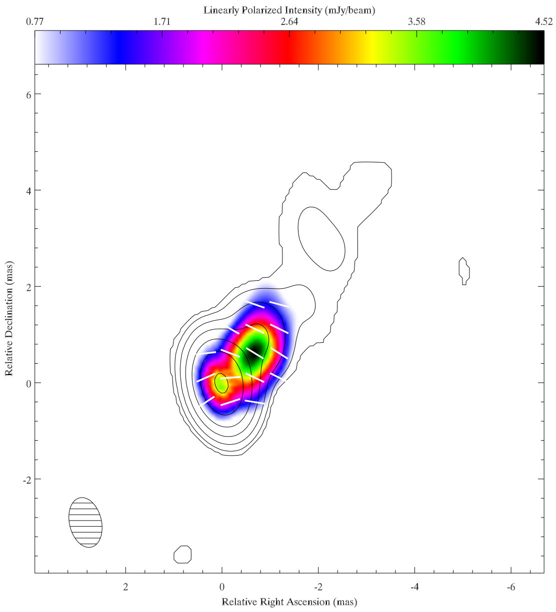

Figure 2. Polarization image at 15 GHz for the first observing epoch. White sticks represent the absolute orientation of the EVPAs and the contours show the total intensity. The peak in the linear polarized intensity is at 4.52 mJy/beam and the noise is the 17% of the polarization peak. The beam size is 1.04 mas × 0.66 mas.

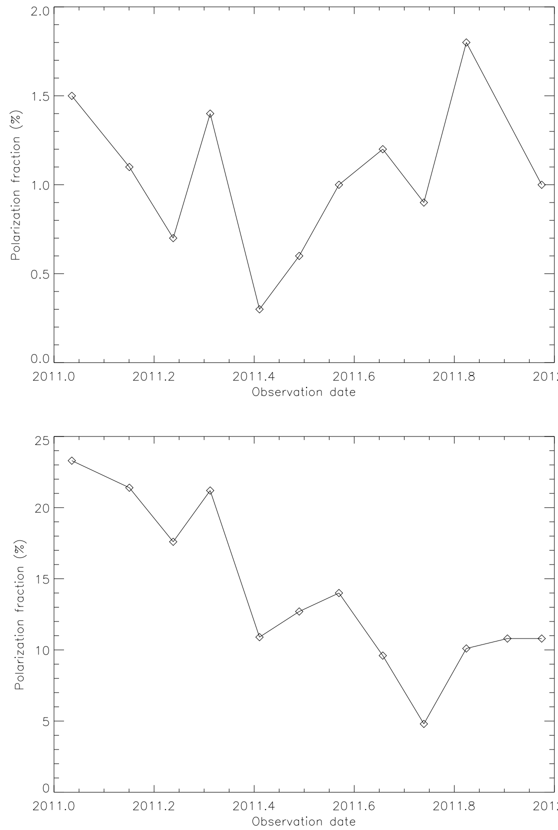

Figure 3. Evolution of the degree of polarization with time, at 15 GHz, for the core region (upper panel) and for the C3 model-fit component at ∼ 1 mas from the core (lower panel).

After the determination of the relative rotations, it is enough to set the absolute EVPA calibration just for one epoch, by the comparison with a VLA observation (values in boldface in the third column in table 1); then we obtain the absolute rotation for all the EVPAs by applying the relative rotations obtained by the D-terms. In practice, after having fixed a value in the third column by the comparison with VLA, then any other value is obtained by summing the previous value in the same column, and the relative rotation for the same epoch in the fourth column. At 15 GHz we have three VLA measurements taken during 2011 (*http : //www.aoc.nrao.edu/ ∼ smyers/evlapolcal/polcal_master.html*), so it has been possible to make two cross checks. We found an agreement, between the two methods, within 5 deg.

3 Results and discussion

3.1 Images

In Fig. 1 we show three images of Mrk 421 at 15, 24 and 43 GHz respectively. We can clearly identify a well-defined and collimated one-sided jet structure, emerging from a compact nuclear region (this is the typical structure of a BL Lac object [5]), that extends for about 4.5 mas (2.67 pc)[1], showing a position angle (PA) of about −35° (measured from North through East). This morphology also agrees with the results of other studies of similar angular resolution (e.g. [13]).

[1] 1 mas corresponds to 0.59 pc.

In Fig. 1 we also show the components of the model-fit performed in DIFMAP; they are numbered in ascending order from the outermost to the innermost one. Because of the higher resolution achieved with the increase of the frequency, at 43 GHz we have a larger number of components with respect to the 15 and 24 GHz data. For all details about the complete model-fit analysis on this dataset see [11] and [2].

In Fig. 2 we show the polarization map for the first observing epoch at 15 GHz, produced with DIFMAP and IDL. White sticks represent the absolute orientation of the EVPAs and the contours show the total intensity. The peak in the linear polarized intensity is at 4.52 mJy/beam, and it is not coincident with the total intensity peak, but it lies in the jet. In the image the noise is at the 17% of the polarization peak.

3.2 Polarization properties at 15 GHz

With the total intensity analysis we found that all the model-fit components appear to be essentially stationary, only in some cases they show subluminal motion. This finding strengthens early results on this topic (e.g.[6, 15, 16]), which are quite surprising for a TeV blazar. For the discussion on this topic see [11] [2].

Here we make use of the same model-fit components to study the evolution of some important polarization pa-

Table 1. In the following table there are the final EVPAs rotations (third column). Numbers in boldface refer to the comparison with VLA values. In the fourth column there are the relative rotations obtained by comparing antenna tables for consecutive epochs.

Epoch year/month/day	MJD	Final Δ (deg)	ΔD-Terms (deg)	Reference antenna
2011/01/14	55575	-21.7		PT
2011/02/25	55617	-21.7	0	PT
2011/03/29	55649	**-21.7**	0	PT
2011/04/25	55675	-21.7	0	PT
2011/05/31	55712	-21.7	0	PT
2011/06/29	55741	**22.2**	45	OV
2011/07/28	55770	22.2	0	OV
2011/08/29	55802	85.2	63	KP
2011/09/28	55832	157.2	72	PT
2011/10/29	55863	157.2	0	PT
2011/11/28	55893	**25.5**	45	OV
2011/12/23	55918	70.5	-45	PT

rameters. We just present a partial analysis for the core and for the C3 component. In these observations, components outer than C3 are too faint to be detected in polarized emission. For the core region we found a mean degree of polarization of ∼ 1% (see upper panel in Fig. 3), while for the C3 model-fit component, located at near 1 mas from the core, we found a mean degree of polarization of ∼ 14% (see lower panel in Fig. 3). This increase in the degree of polarization outward the jet seems to be a common feature in blazars [12]. The trend that we found for Mrk 421 in this work is in good agreement with previous studies (e.g. [14]).

We also show the final EVPAs plot for the core region and for the C3 component in Fig. 4. For the core region, during one year period (2011), we found that the EVPAs varies between two main states: orthogonal and parallel orientation with respect the jet axis. These are known to be the two common polarization states for the core region for this peculiar source [3]. This result is in agreement with other works (e.g. [14, 16]). An interpretation of these EVPAs changes could be that they are associated to some activity which involves the propagation of a shock, but no new components and no significant motion were detected in total intensity images. In a forthcoming paper we will present the complete analysis of the whole dataset, giving additional details and a more accurate interpretation of this behavior.

For the C3 component, located at about 1 mas from the core region, we found that EVPAs are orthogonal to the jet for the entire observation period. This implies a magnetic field parallel to the jet direction. Piner et al. in 2010 [16] found similar results for a component located at near the same distance from the core. No corrections for Faraday rotation are applied in this preliminary analysis.

3.3 Conclusions

In this work we presented a partial polarization analysis of a multi-frequency (15, 24 and 43 GHz) dataset obtained

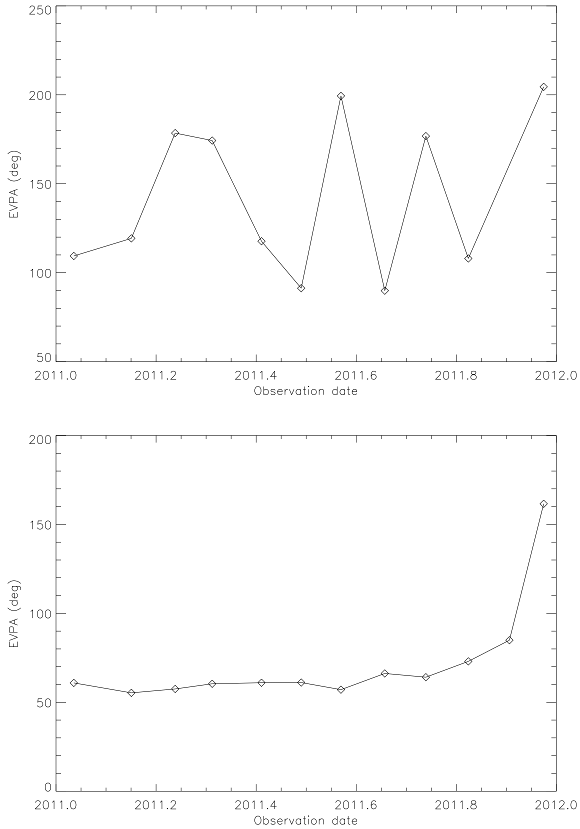

Figure 4. Evolution of the EVPAs orientation with time, at 15 GHz, for the core region (upper panel) and for the C3 model-fit component at ∼ 1 mas from the core (lower panel).

with VLBA throughout the entire 2011. In two previous works ([11] and [2]) we presented the complete total intensity analysis, in which we investigated the inner jet structure on parsec scales through the study of model-fit components for each epoch. We found that all these Gaussian components in the jet appear to be almost stationary during the entire observation period, and we estimate a different jet velocity for the radio and the high-energy emission regions, such that the respective Doppler factors are $\delta_r \sim 3$ and $\delta_{h.e.} \sim 14$.

Here we presented a preliminary polarization analysis for the 15 GHz dataset. For the core region we found a degree of fractional polarization of ∼ 1% while for the C3 model-fit component, located at about 1 mas from the core, we found value of ∼ 14%.

Furthermore, for the core region we found swinging EVPAs between two main states (orthogonal or parallel to the jet), while for the C3 component EVPAs are almost perpendicular to the jet axis for the entire observation period. Both these results, fractional polarization values and EVPAs orientation, are in good agreement with previous works [14, 16]. The complete study of polarization for the whole multi-frequency dataset, with all details about the d-terms method, will be presented in a forthcoming paper.

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