Probing the Precise Location of the Radio Core in Mrk 501 with VLBA Astrometry

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We report astrometric results on the stability of the core in the nearby TeV blazar Mrk 501 based on 6-epoch monitoring with the VLBA at 43 GHz. Our results suggest a stable position of the core within $98 \pm 73\,\mu$as, refining our earlier findings by VERA in 2011, which pinpointed the position within 200 μas. We constrain bulk Lorentz factors of the jet based on the results of core position measurements. We will further discuss a possible relation between the source activity and the distributed scale of the radio core position.

Keywords: VLBI, Astrometry, Blazars.

1 Introduction

Mrk 501 is the closest and brightest TeV blazar ($z = 0.034$), and therefore one of the best sources to study the so-called "blazar-zone" with VLBI. We have investigated the position of the radio core of blazars Mrk 501 and Mrk 421 by multi-epoch astrometric observations at 43 GHz and 22 GHz, respectively, with the VLBI Exploration of Radio Astrometry (VERA) [1, 2]. In the case of Mrk 501, there was no positional change of the radio core peak of Mrk 501 relative to the distant quasar NRAO 512 within $\sim 200\,\mu$as or de-projected ∼2.0 pc in 2011 during its quiescent state [1]. On the other hand, the radio core of Mrk 421 changed its location toward 0.5 mas downstream soon after its large X-ray flare [2]. This time we attempt to put further constraint on the stability of the radio core of Mrk 501 and study whether there is a relation between the source activity and the distributed scale of the radio core position.

2 Observations and Data Reduction

The astrometric observations with the VLBA have more advantages compared to our previous ones with VERA [1]. VLBA astrometric observations have longer baselines than VERA in a factor of 3 (up to 8600 km), and the baseline sensitivity is improved by the larger collecting surface and higher antenna efficiency of the dishes. The smaller beam size will reduce the main positional error due to troposphere, and the higher baseline sensitivity enables us to use fainter and closer calibrators. More antennas also enable us to get a much enhanced uv-coverage and better data constrains due to the larger number of closures in phase and amplitude.

Our six-epoch observations were performed between February 2012 and February 2013 with the VLBA at 43 GHz in astrometric mode. The observations include rapid switching within 30 seconds between Mrk 501 and three nearby radio sources: 3C 345 ($z = 0.593$), NRAO 512 ($z = 1.66$), and 1659+399 ($z = 0.507$). The alignment of the sources in the sky plane is shown in Fig. 1, together with contour plots of the parsec-scale images.

The initial data calibration was performed using AIPS. We performed a fringe-fitting on all the four sources and removed residual delays, rates and phases assuming a point source model. We further corrected the source structure phases due to the deviation of the point source model by iterative clean–self-calibration procedures, then obtained the clean models for them. By performing a fringe-fitting again by including the clean models for each sources, we obtained the gain time variability to be assigned to atmosphere or instrumental effects.

Since Mrk 501 is enough bright to perform fringe-fitting and self-calibration, we chose Mrk 501 as a phase calibrator and transferred the derived fringe solutions including its clean models to all the other sources. In the standard phase-referencing data reduction, after the calibrator phases and the target gain time variability are applied to each target, its phase-referenced images were created, and the peak position of phase-referenced images were measured by fitting a single Gaussian to the peak component using the AIPS task JMFIT. In the case of the VLBA 43 GHz observations, this peak position measurement would include non-negligible component identification errors, because the target sources also have extended source structure. This time we perform the new data reduction procedure to remove the phase effect of target source structure. We will explain this procedure in a forthcoming paper by using observation equations, which are consisted of various phase terms. We measured the peak position of phase-referenced target source by minimizing its structure effect.

3 Results

The phase-referencing between Mrk 501 and the closest, compact target 1659+399 yields following results: the measured core positions of Mrk 501 along its jet axis relative to the peak position of 1659+399 for all the observations lie within a small region, shown in Fig. 2. This figure is produced by inverting the measured position of phase-referenced image of 1659+399 referencing to Mrk 501. The core

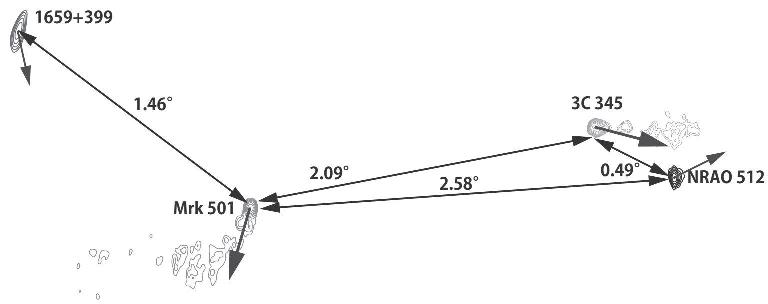

Fig. 1. Source configuration and self-calibrated images of our VLBA astrometric observations at 43 GHz. Thanks to the higher sensitivity, we added the fainter and closer point-like calibrator 1659+399 to the calibrators 3C 345 and NRAO 512, which we used for the VERA astrometric observations. The arrows indicate the direction of the jet flow next to the radio core

position error is estimated as the root-sum-square of each error [1, 4]. Typically, the core position error of 1659+399 relative to Mrk 501 is estimated to be $\sim 39\,\mu$as in right ascension and $\sim 41\,\mu$as in declination, which is around one-tenth of the major axis of the synthesized beam size. The major error contribution comes from the tropospheric zenith delay errors, which are typically $\sim 3\,$cm for the VLBA [5], corresponding to the position error of $\sim 37\,\mu$as for the separation of 1.46° between Mrk 501 and 1659+399. Thanks to its proximity and the high angular resolution, the position errors due to the tropospheric errors were reduced to around one-fourth of those between Mrk 501 and NRAO 512 with VERA [1]. The signal-to-noise ratio of the phase-referenced images are ranging from 13 to 17, corresponding to a random error of around 5–10$\,\mu$as. By taking into account all the error contributions, the resulting position error for single epoch was reduced to around one-fifth of that with VERA.

We performed a chi-squared test of the phase-referenced core positions over the six epochs for the evaluation of its stability. The core positions of Mrk 501 relative to 1659+399 coincide along the jet position angle ($\sim 156^\circ$ in [3]) with the significance probability of 38%. This probability is much lower than that of the VERA ($> 98\%$ in [1]), such that it could be a small variability of the radio core peak positions along jet position angle, however, motion of the core peak position is not significant. The maximum difference of the core peak positions along the jet axis is $98 \pm 73\,\mu$as between the first and the last epochs. Therefore, we can conclude that the phase-referenced core peak positions of Mrk 501 relative to 1659+399 lie within $171\,\mu$as (1σ) along its jet direction. Similar amount of the maximum difference were obtained for the phase-reference pair of Mrk 501 and NRAO 512.

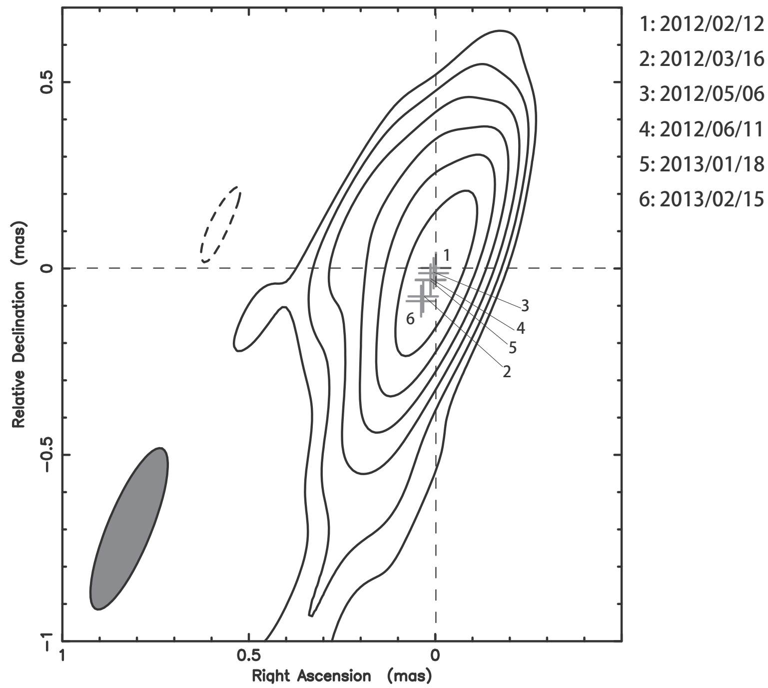

Fig. 2. Astrometric results on the absolute location of the core of Mrk 501 relative to 1659+399, plotted over a self-calibrated image of Mrk 501 for the first epoch. The phase-referenced core positions are projected along the averaged position angle of Mrk 501 jet ($\sim 156^\circ$ for the components C1, C2, and C3 derived in [3]). The phase-referenced core positions are shifted as epoch 1 corresponding to $(0, 0)$

4 Discussion

The de-projected distributed scale of the phase-referenced core position of Mrk 501 is approximately $\leq 1.9 \times 10^4\, R_\mathrm{s}$ or ≤ 1.6 pc for a jet viewing angle of $\theta_\mathrm{j} \geq 4^\circ$ [5], where 1 mas corresponds to 7.7×10^3 Schwarzschild radii (R_s), or $1\, R_\mathrm{s} = 8.6 \times 10^{-5}$ pc. Here we set the lower limit of the central black hole mass of Mrk 501 as $M_\mathrm{BH} = 0.9 \times 10^9\, M_\odot$ in the case of the single black hole [7].

Based on the standard internal shock model of blazars [e. g., 8], we attempt to constrain bulk Lorentz factors of the jet based on the results of core position measurements. When the source is in its quiescent state, we can assume that the Lorentz factor ratio between the faster and the slower colliding ejecta is close to unity ($\Gamma_\mathrm{f}/\Gamma_\mathrm{s} \leq 1.01$) [1]. By applying the same assumptions in [1], the maximum value of Γ_s ($\Gamma_\mathrm{s,max}$) and minimum value of Γ_s ($\Gamma_\mathrm{s,min}$) only depends on the de-projected distributed scale of the core positions ΔD_IS as follows:

$$\frac{\Gamma_\mathrm{s,max}}{\Gamma_\mathrm{s,min}} \leq 2.0 \times \left[\frac{1}{2}\left(\frac{\Delta D_\mathrm{IS}}{1.9 \times 10^4\ R_\mathrm{s}}\right)\left(\frac{A}{51}\right)^{-1}\left(\frac{I_\mathrm{IS}}{1\ R_\mathrm{s}}\right)^{-1}\left(\frac{\Gamma_\mathrm{s,min}}{8}\right)^{-2}+1\right]^{1/2}, \qquad (1)$$

where $A \equiv (\Gamma_f/\Gamma_s)^2/[(\Gamma_f/\Gamma_s)^2 - 1]$ and $A \geq 51$. I_{IS} is the separation length of the colliding ejecta. Thus, we find that the maximum-to-minimum ratio of Γ_s during our six-epoch observations are less than 2.0, i. e., $8 \leq \Gamma_s \leq 16$, which is slightly tighter than or comparable to our previous constraint [1]. When the source is in its active state, we can assume that $\Gamma_f \gg \Gamma_s$ and $\Gamma_{s,max} \gg \Gamma_{s,min}$ [2]. In this case, we can assume that the distance of the internal-shocks (or the radio core) from the black hole is $D_{IS} \sim \Delta D_{IS}$, and it is proportional to the product of the square of Γ_f and I_{IS}. By assuming the same value for I_{IS} as in [2], a Lorentz factor of very fast ejecta is estimated to be

$$\Gamma_f \leq 18 \left(\frac{D_{IS}}{1.9 \times 10^4 \, R_s} \right)^{1/2} \left(\frac{I_{IS}}{30 \, R_s} \right)^{-1/2}. \quad (2)$$

This value is less than one-third of that for Mrk 421 soon after the large X-ray flare ($\Gamma_f \sim 60$). Therefore, by following the discussions in both [1] and [2], our results on the phase-referenced core positions of Mrk 501 do not require a high Lorentz factor as is required in the case of Mrk 421. This could be related to lack of significant high-energy flares in Mrk 501 during or close in time with our observations. We will further study whether there is a relation between the stationarity of the radio core and the source activity with longer monitoring.

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References

1. *Koyama S., Kino M., Doi A., et al.* Probing the precise location of the radio core in the TeV blazar Mrk 501 with VERA at 43 GHz // Publ. Astron. Soc. Japan. — 2015. — Vol. 67. — P. 67–77.
2. *Niinuma K., Kino M., Doi A., et al.* Discovery of a Wandering Radio Jet Base after a Large X-Ray Flare in the Blazar Markarian 421 // The Astrophysical Journal Letters. — 2015. — Vol. 807. — P. 14–18.

3. *Koyama S., Kino M., Giroletti M., et al.* Discovery of off-axis jet structure of TeV blazar Mrk 501 with mm-VLBI // Astron. & Astrophys. — 2016. — Vol. 586. — P. 113–122.
4. *Hada K., Doi A., Kino M., et al.* An origin of the radio jet in M87 at the location of the central black hole // Nature. — 2011. — Vol. 477. — P. 185–187.
5. *Reid M. J., Readhead A. C. S., Vermeulen R. C., et al.* The Proper Motion of Sagittarius A*. I. First VLBA Results // The Astrophysical Journal. — 1999. — Vol. 524. — P. 816–823.
6. *Giroletti M., Giovannini G., Feretti L., et al.* Parsec-Scale Properties of Markarian 501 // The Astrophysical Journal. — 2004. — Vol. 600. — P. 127–140.
7. *Barth A. J., Ho L. C., Sargent W. L. W., et al.* Stellar Velocity Dispersion and Black Hole Mass in the Blazar Markarian 501 // The Astrophysical Journal Letters. — 2002. — Vol. 566. — P. 13–16.
8. *Spada M., Ghisellini G., Lazzati D., et al.* Internal shocks in the jets of radio-loud quasars // Mon. Not. R. Astron. Soc. — 2001. — Vol. 325. — P. 1559–1570.