Study of the TeV blazar Mrk 501 with mm-VLBI

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• Radio core astrometry of Mrk 501 with 43-GHz VLBI
• EHT+ALMA 2018 observations toward Mrk 501 at 230 GHz
RADIO CORE ASTROMETRY
The locations of blazar radio cores at mm-wavelengths have not been studied with enough positional accuracy.

Blazar radio cores may wander if they are located far from the BH.
Purpose

• Probe the precise location of radio cores in blazars
• Investigate the stability of it’s location
VLBI astrometry

Position accuracy of the target

\[ \sim \frac{c^0}{D} \sec Z \tan Z \sec Z \tan Z \]

\(\delta \tau_0\): atmospheric zenith delay, \(D\): baseline, \(Z\): zenith angle, \(\Delta Z\): separation

e.g.: VERA

\(D=2300 \text{ km}, \delta \tau_0=2 \text{ cm}, \Delta Z=2^\circ \) \(Z=50^\circ\)

\(\rightarrow \delta \theta \sim 0.12 \text{ mas} \) \((\theta \sim 0.6 \text{ mas @ 43 GHz})\)

e.g.: VLBA

\(D=8600 \text{ km}, \delta \tau_0=2 \text{ cm}, \Delta Z=2^\circ \) \(Z=50^\circ\)

\(\rightarrow \delta \theta \sim 0.04 \text{ mas} \) \((\theta \sim 0.2 \text{ mas @ 43 GHz})\)

\(\rightarrow\) Achieve a positional accuracy several times higher than the resolution
Target: TeV γ-ray blazar Mrk 501

① One of the closest blazars
   \( z=0.034, \ 1 \text{ mas}=0.66 \text{ pc} \)

② Multiple close calibrators

③ Radio core spectrum

→ The best source for radio core astrometry

Giroletti+04

VLBA 15 GHz

Giroletti+08

> 8 GHz optically thin
Radio core astrometry with VLBI 43 GHz

- **VERA**:
  - 4 stations
  - Obs. time: 8 hrs/1d
  - Obs. date:
    - 2011.Feb.15,16,17,18
  - Obs. mode
    - 2beam mode (VERA 7)
      - Abeam(1IF=16Mhz):3C 345
      - Bbeam(15IF=240Mhz): NRAO 512 & Mrk 501
  - \(D_{\text{max}} = 2300 \text{ km}\)

- **VLBA**:
  - 10 stations
  - Obs. time: 4 hrs/1d
  - Obs. date:
    - 2012. 2/12, 3/16, 5/6, 6/11, 2013. 1/18, 2/15
  - Obs. mode
    - Fast switching below 30sec
    - BW= 128MHz
  - \(D_{\text{max}} = 8600 \text{ km}\)
Configuration of sources around Mrk 501

- VLBA max. baseline ~ 4 X VERA max. baseline
  ➔ position accuracy will be improved ~4-5 times
- Closer calibrator 1659+399 is also available for check source
Results of VERA 43GHz astrometry

Koyama+2015

- Position accuracy $\sim 200$ uas/day
- No positional change of the radio core within 200 $\mu$as during it’s quiescent state
Results of VLBA 43GHz astrometry

Koyama+in prep.
Results of VLBA 43GHz astrometry
Jet position angles with VLBA 43 GHz

Extract the radio core positions orthogonal to the jet direction of calibrators, then project it to the jet directions of Mrk 501.
Results of VLBA 43GHz astrometry

Mrk 501 (-3C345)

- Position accuracy \( \sim 50 \mu\text{as}/\text{day} \)
- No positional change of the radio core within 42 \( \mu\text{as} \) (1\( \sigma \)) along its SE jet (78%)
Results of VLBA 43GHz astrometry

Mrk 501 (-NRAO512)

- Position accuracy ~ 70 μas/day
- No positional change of the radio core within 56 μas (1σ) along it’s SE jet (97%)
Summary and discussions

- The radio core of Mrk 501 doesn’t wander significantly even with VLBA, begin stable enough along its NE and SE jets during it’s quiescent state. This suggests that the radio core could be located close to the BH.
- On the other hand, we found a significantly wandering radio core in Mrk 421 soon after it’s historical X-ray flare. It could be related to the source activity.
VLBA multi-frequency astrometry of Mrk 501 in 2016 PI: M. Giroletti (Fermi-GI project)

KVN multi-frequency observations (PI: Zhao) were also performed during 2015-2016.

8 epochs in 2016
EHT+ALMA 230 GHZ OBSERVATIONS TOWARD MRK501 IN 2018
1. Probing the size comparable to γ-ray emitting region
2. Discrimination of the jet foot point of a blazar

**Approved by EHT and ALMA for 2018 April observations!!**

(flux>0.5 Jy at 230 GHz with ACA is required)
EHT+ALMA 230 GHz in 2018

Spatial resolution will reach up to ~30 μas
1. Probing the size comparable to γ-ray emitting region in Mrk 501

• One of the closest blazars
  – 1 mas = 0.66 pc
  – 30 μas = 2-3 × 10^{16} cm
    = 60 Rs (M_{BH}=3.4 \times 10^9 M_{\text{sun}}, \text{Barth+02})
    \rightarrow\text{comparable to the size of γ-ray emission region with its prediction (variability, SED modeling)}
  – First direct information to compare the possible observed size of γ-ray emission region in a blazar
2. Discrimination of jet foot point in a blazar: accretion disk or black hole?

Assuming jet viewing angle ~4°
2. Discrimination of jet foot point in a blazar: accretion disk or black hole?

new data obtained in 2017/3 with global VLBI at 43 GHz → (KVN+EVN+VLBA)
THANK YOU FOR LISTENING.
APPENDIX
Global VLBI observations at 43 GHz

- Date: 2017 March 10
- 17 stations: KVN-Yonsei, KVN-Ulsan, KVN-Tamna, VLBA10 (BR, FD, HN, KP, LA, MK, NL, OV, PT, SC), Metsaehovi, Effelsberg, Onsala60m, Yebes
- Note: Noto Q-band receiver was failed, Effelsberg LCP was failed
- Mode: Dual-polarization, 16 MHz x 8 IFs = 128 MHz
Results of VLBA 43GHz astrometry

Mrk 501 (-1659+399)

- Position accuracy $\sim 40 \, \mu \text{as/day}$
- No positional change of the radio core within 33 $\mu$as (1$\sigma$) along its SE jet (50%)
① Close case

- $R_{\text{core}} \sim 0.01$ pc
- Radio galaxy: M87, NGC4261 (e.g., Hada+2011, Haga+2015)
- Multi-freq. core shift + astrometry
② Distant case

- $R_{\text{core}} > 1$-$10 \text{ pc}$
- Several blazars
  - the BL Lac, OJ 287, 3C 454.3, PKS 1510-089, etc.
    (eg. Marscher+08, Agudo+12)
- Using time difference of light-curve between radio and $\gamma$-rays
- Assuming radio core is stationary

Where is the location of blazar’s radio core?
Results of VLBA 43 GHz astrometry

Mrk 501 (-1659+399)

Preliminarily Stationary within <0.2 mas

1: 2012/02/12
2: 2012/03/16
3: 2012/05/06
4: 2012/06/11
5: 2013/01/18
6: 2013/02/15
Jet position angles with VLBA 43 GHz

- Jet position angles were averaged over 6 epochs.
  - 1659+399, NRAO 512, 3C345, NE : average of the PA of the innermost jet component
    - 1659+399, NRAO512 : only one jet component
    - 3C 345, NE : non-ballistic (straight) jet
  - SE jet: average of the PA of a few components in south-east direction because of its straightness