J. Astrophys. Astr. (2014) **35,** 209–213 © Indian Academy of Sciences

Multi-Frequency VLBA Studies of the Parsec-Scale Jets in 3C 66A and 3C 66B

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Abstract. We report multi-frequency VLBA phase-referencing observation results of 3C 66A and 3C 66B, including high resolution maps and relative position measurements. The resulting images show similar morphology with that presented in previous works. We find core shift variations in both sources, indicating some physical condition changes in the jets.

Key words. Radio continuum: galaxies—galaxies: active—galaxy: individual (3C 66A, 3C 66B)—galaxies: jet.

1. Introduction

The radio source, 3C 66 was found to actually consist of two unrelated sources separated by only 6 arcminutes (Mackay 1971). The west source, 3C 66A ($z = 0.444$), is now a well-known blazar and has been further classified as an intermediate synchrotron peaked BL Lac object (IBL) (Abdo *et al*. 2010). The east source, 3C 66B, is a nearby radio galaxy ($z = 0.0213$). Both sources show peculiar properties, so they have been targets of many observations in the past few decades (e.g. Fraix-Burnet 1997; Sudou *et al*. 2003; Böttcher *et al*. 2005; Cai *et al*. 2007; Abdo *et al*. 2010). At radio wavelengths, previous Very Long Baseline Interferometry (VLBI) images revealed a typical core-jet structure on parsec scales for 3C 66A (e.g. Cai *et al*. 2007) and also detections of superluminal motions have been frequently reported in this source (e.g. Jorstad *et al*. 2001). 3C 66B also shows a core-jet structure at mas resolutions (e.g. Zhao *et al*. 2011) while its VLA maps reveal a bent, twin-jet structure. Quasi-periodic flux variations was detected at 3 mm band (Iguchi *et al*. 2010). The small separation between the two sources makes them an ideal pair for phase-referencing observations (e.g. Sudou *et al*. 2003). In this paper, we present our multi-frequency VLBA phase-referencing observation toward 3C 66A&B at epoch 2005.05. The observation and data reduction are described in section 2 and the results and discussion are presented in section 3.

2. Observation and data reduction

The observation towards 3C 66A&B were carried out at 2.3, 8.4 and 22 GHz with the VLBA on January 20th, 2005. The total on-source time is about 30 min at 2.3 and 8.4 GHz and 40 min at 22 GHz. The data were recorded with 2 Intermediate Frequency (IF) bands at 2.3 and 8.4 GHz and with 4 at 22 GHz. Each IF has a bandwidth of 8 MHz. The total bit rate is 128 Mbps using a 2-bit sampling mode.

Data reduction mainly follows the standard VLBA phase referencing reduction process with the NRAO AIPS and Caltech DIFMAP packages. First, amplitude calibration was done using the measured system temperature and antenna gain curves. Then ionospheric correction was done using JPL TEC maps. The residual phase delays and delay rates were calibrated using global fringe-fitting. Bandpass calibration was performed using $0133 + 476$ and $0218 + 357$. Then the 3C 66A data were split and loaded into DIFMAP for hybrid mapping and model fitting. Then self-calibration solutions were applied to 3C 66B to get the phase-referenced images and relative position measurements.

3. Results and discussion

In Fig. 1, we show the self-calibrated images of 3C 66A with circular Gaussian models at all observing frequencies. The mapping parameters, including the beam size, peak flux and the contours are shown at the bottom of each panel. On parsec scales, 3C 66A is characterized by a one-side jet toward the south with two bending structures. The northernmost component is identified as the core due to its brightness, compactness and flatter spectrum. This morphology is consistent with previous works (e.g. Cai *et al*. 2007). By combining the model fitting results with Cai *et al*. (2007), we were able to study the proper motion of the jet components. Our results show that the kinematics of 3C 66A jet is very complicated. Superluminal motions as well as apparent inward motions have been detected for some components. A detailed study focusing on the morphology, spectra and proper motion of 3C 66A will appear elsewhere soon (Zhao *et al*. in preparation).

Figure 2 shows the phase-referenced images of 3C 66B at 2.3, 8.4 and 22 GHz. It shows a compact core and a straight smooth one-sided jet at all observing frequencies. The jet gets weaker and smoother at higher frequencies. A detailed discussion on the jet structure and the proper motion of the jet components in 3C 66B is available in Sudou & Iguchi (2011).

The position measurements of the core in 3C 66B at 2.3, 8.4 and 22 GHz with reference to that in 3C 66A are shown in Fig. 3 (filled icons). We found a large positional difference at each frequency when compared to previous measurements.

The core is believed to be located in the region of the jet where the optical depth is $\tau = 1$. So the core position should be frequency-dependent. This is the so-called 'core shift' effect. The measured relative positions between 3C 66A and 3C 66B are

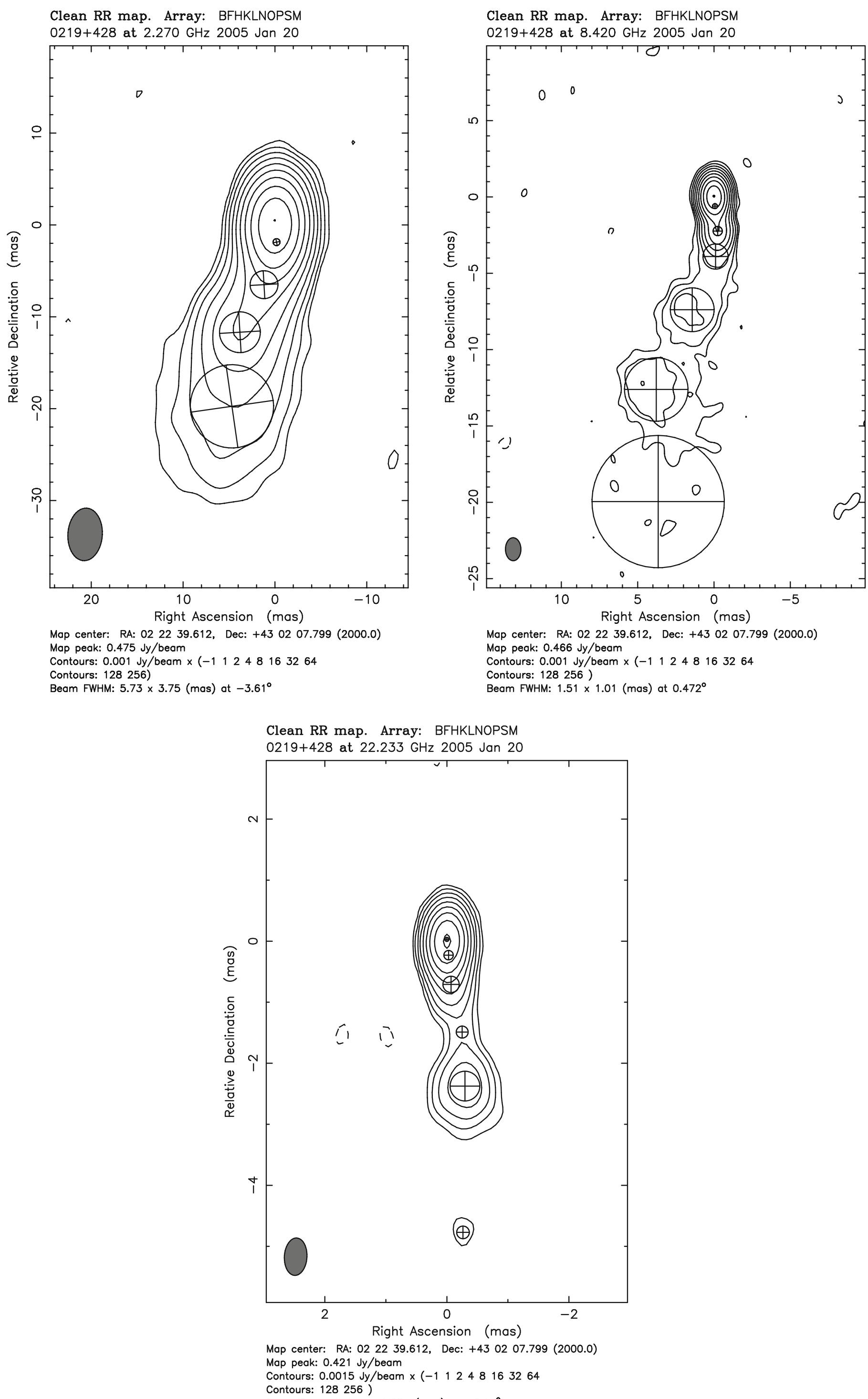

Figure 1. Maps of 3C66A at 2.3, 8.4 and 22 GHz.

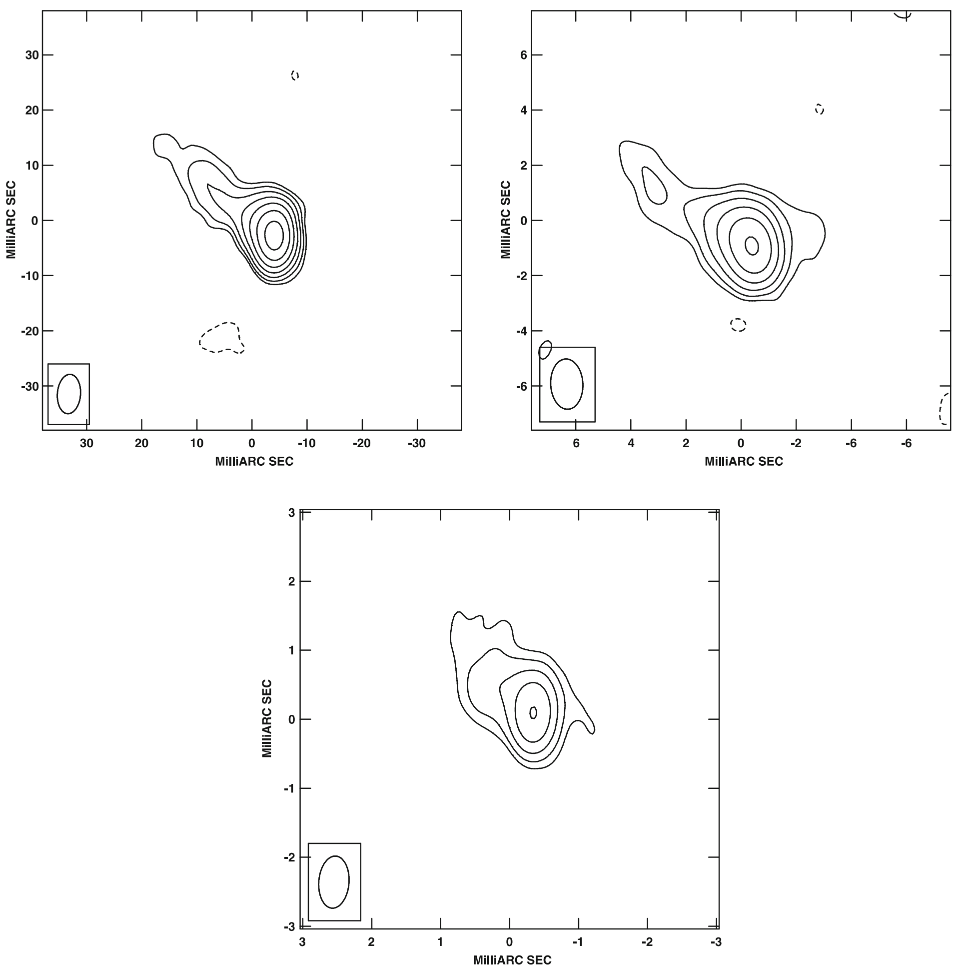

Figure 2. Maps of 3C66B at 2.3, 8.4 and 22 GHz. Contours start at 3σ and increase by factors of 2. The restoring beams are shown in the bottom left of each image.

different at different frequencies, which is consistent with the core position dependence. By assuming that the core-shift effect only occur along the jet axis, the core shift for each source can be calculated. For 3C 66A, P.A. $\approx 180°$ and for 3C 66B, P.A. $\approx 55°$, we have $r^{\mathrm{3C66A}}_{2.3-8.4} = 0.44 \pm 0.09$ mas, $r^{\mathrm{3C66A}}_{8.4-22} = 0.08 \pm 0.05$ mas and $r^{\mathrm{3C66B}}_{2.3-8.4} = 0.74 \pm 0.09$ mas, $r^{\mathrm{3C66B}}_{8.4-22} = 0.20 \pm 0.05$ mas. The uncertainties are calculated using the method presented in Hada *et al.* (2011). Compared to the core shifts calculated from the previous position measurements (open icons in Fig. 3), the core shifts in both sources changed, i.e., smaller in 3C 66A and larger in 3C 66B. That means, the core in the 3C 66A jet shifted towards the central black hole while the core in the 3C 66B shifted downstream along the jet, according to the relation between absolute core position and the observing frequency, $r_{\mathrm{core}} \propto (\nu_{\mathrm{obs}})^{-1/k_{\mathrm{r}}}$ (Königl 1981). Such position changes indicate that the physical parameters such as

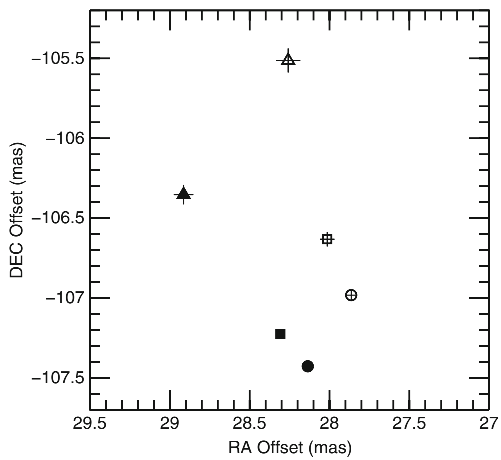

Figure 3. The positions of the jet cores in 3C 66B with respect to that of 3C 66A (filled icons). The triangles, squares and circles are results at 2.3, 8.4 and 22 GHz, respectively. The open icons are previous measurements taken from Shang (2005).

density and pressure gradients in both jets may have changed. A detailed multi-epoch study of the core-shift variations in these two sources is ongoing.

Acknowledgements

This work is partly supported by China Ministry of Science and Technology under State Key Development Program for Basic Research (2012CB821800), the Natural Science Foundation of China (grants 10625314, 11121062, 11173046, 11273042, 12ZR1436100 and U1231106) and the CAS/SAFEA International Partnership Program for Creative Research Teams.

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