Perseus in Sicily: From Black Hole to Cluster Outskirts
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Observations of nearby relativistic jets with EAVN and EATING VLBI

Kazuhiro Hada[1,2] and EAVN/EATING VLBI Collaboration

[1]Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
email: kazuhiro.hada@nao.ac.jp

[2]Department of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

Abstract. The international collaboration of VLBI in East Asia (EA) is rapidly growing. Besides the recent successful operation of the KVN and VERA Array (KaVA), the effort of joint VLBI operation in EA is being expanded into China. This forms the East Asian VLBI Network (EAVN), which offers detailed imaging and monitoring of the innermost regions of relativistic jets at cm wavelengths and thus complementary to the Event Horizon Telescope operated at mm wavelengths. In this contribution we present some of the ongoing KaVA/EAVN studies for the inner jets of the two important nearby radio galaxies 3C84 and M87. The observations have revealed detailed kinematics for the parsec-to-subparsec-scale structures of these jets. Future regular observations with the East-Asia-To-Italy-Nearly-Global (EATING) VLBI, a joint effort between EAVN and the Italian VLBI Network, will enable us to resolve and regularly monitor the innermost regions of nearby AGN jets at tens of micro-arcsecond scales.

Keywords. instrumentation: high angular resolution, galaxies: active, galaxies: jets, radio continuum: galaxies

1. Introduction

It is now widely believed that relativistic jets in active galactic nuclei (AGN) are powered by the accretion onto the central supermassive black holes (SMBH). The AGN jets carry a significant fraction of the accretion energy into the interstellar or/and intergalactic space, playing a key role in AGN feedback. However, detailed processes of jet propagation from the central engine to the large scales are still not well understood. The inner jet regions at parsec to subparsec scales are particularly important since a number of key physical processes are expected to take place, such as the flow acceleration, collimation, interaction with circumnuclear medium, and production of high-energy γ-ray emission. VLBI at cm-wavelengths is particularly suited to probe these scales.

The KVN and VERA Array (KaVA) has recently emerged as the first regularly operated international VLBI network in East Asia, consisting of 7 stations available at 22 and 43 GHz. Since KaVA operates for a quasi-full year and has angular resolution down to $\sim$0.5 mas, the array is suitable for monitoring the detailed structural evolution of nearby AGN jets at parsec to sub-parsec scales (Niinuma *et al.* (2014); Oh *et al.* (2015); An *et al.* (2016); Zhang *et al.* (2017)). Moreover, KVN has a unique capability of quasi-simultaneous multi-frequency full-polarimetric receiving system at 22/43/86/129 GHz, which allows us to study high-frequency properties of relativistic jets (e.g., Lee *et al.* (2014)).

Here we introduce some of recent and ongoing studies on the radio galaxies 3C84 and M87 with the VLBI facilities in East Asia. Since these two sources are nearby and the

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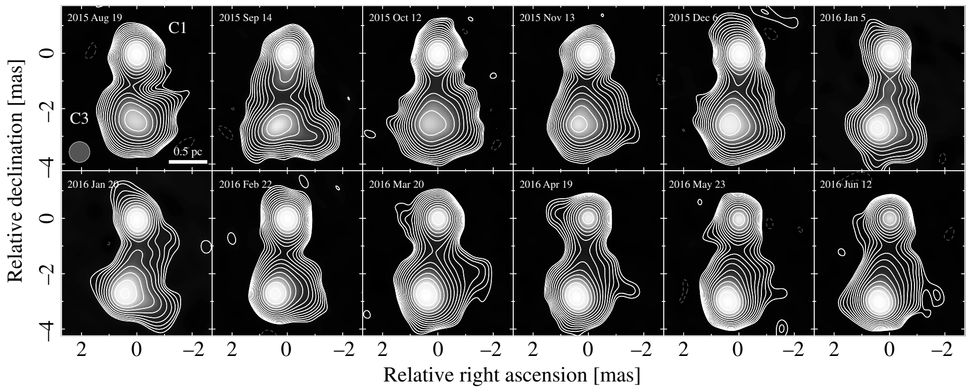

Figure 1. Multi-epoch KaVA 43 GHz images of 3C84 between August 2015 and January 2016 (Kino *et al.* submitted). The bright core is C1 while the moving feature in the southern part of the jet is C3.

jets are quite active over a wide range of energy spectra from radio to γ-ray, we can study in detail the innermost active jet scales near the black boles with high-resolution radio observations (e.g., Giovannini *et al.* (2018)).

2. 3C84

3C84 is a rare object that enables us to study the evolution of the active parsec-scale jet and its interaction with the external medium because of the dense gas-rich nuclear environment. Over the past years the source has intensively been monitored by VERA and KVN (Nagai *et al.* (2010); Suzuki *et al.* (2012); Kim *et al.* (2015); Hodgson *et al.* (2018)). From 2015, we started monthly 43 GHz observations of this source with KaVA (Fig.1). The aim of this program is to monitor the parsec-scale jet evolution including the C3 component, which was ejected from the core after the 2005 outburst (Nagai *et al.* (2010)). Until early 2015, C3 was straightly moving toward the south. However, during mid 2015, we found a sudden change of the C3 position toward the east by 0.4 mas (0.14 parsec in linear scale). After the flip, C3 wobbled there for a few months and then restarted to move to the south. C3 showed a monotonic increase in flux density during this period. This kind of behaviour is hard to be explained solely by the intrinsic motion of the jet, but is in good agreement with the interaction between jet and clumpy ambient that is often seen in some numerical simulations (e.g., Wagner & Bicknell (2011)).

As a complementary program, we are also monitoring the source with KVN at 43 and 86 GHz, where the synchrotron emission is less absorbed. Recently Fujita & Nagai (2017) has discovered a new feature N1 located at 0.8 pc north from the core. Since this feature shows an inverted spectrum between 15 and 43 GHz, it is proposed that N1 is associated with a counter-jet that is affected by the free-free absorption by the nuclear accretion disk. Our KaVA and KVN observations consistently detected this feature (Wajima *et al.* in prep). In particular, this is the first detection of N1 up to 86 GHz. Remarkably, N1 shows a highly inverted spectrum even at 86 GHz, suggesting a high electron density of the absorbing medium. While the presence of a 10-parsec-scale plasma torus was already suggested in the past VLBI studies, the KaVA/KVN results newly suggest a much smaller scale ($\sim$1 parsec) absorbing plasma. These programs are still ongoing, and further monitoring of C3 or N1 will allow us to better understand the geometry and spatial extent of the nuclear environment of 3C84.

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3. M87

M87 is a unique jet source that one can directly resolve the jet formation scales within a few tens to hundreds Schwarzschild radii (R_s) by VLBI. Recent high-sensitivity VLBI imaging studies at 86 GHz revealed a limb-brightened, wide-opening-angle jet launching at a scale of 10 R_s (Hada *et al.* (2016); Kim *et al.* (2018)). Moreover, extensive analyses of multi-frequency VLBI images revealed a parabolic collimation over a distance from $z{\sim}100\,R_s$ to $z{\sim}10^5 R_s$ (Asada & Nakamura (2012); Hada *et al.* (2013)), which is consistent with magnetic collimation processes (e.g., Nakamura & Asada (2013)).

Nevertheless, the kinematics or velocity fields of the inner jet of M87 is still controversial. Previous multi-epoch VLBI studies of this jet report a variety of jet speeds such as quasi-stationary, subluminal and superluminal motions (Kovalev *et al.* (2007); Ly *et al.* (2007); Asada *et al.* (2014); Mertens *et al.* (2016); Walker *et al.* (2018)). Since M87 is one of the very few jets for which the acceleration scales of $10^{2-4} R_s$ are directly resolvable, having a regular monitoring program should be of great value for testing the magnetically driven jet paradigm.

In this context, we started a dense monitoring program of M87 with KaVA from 2014. The initial outcome from the pilot study was reported by Hada *et al.* (2017) The densely sampled multi-epoch KaVA images have traced the detailed structural evolution of this jet. We detected superluminal motions at these scales, together with a trend of gradual acceleration. These results are similar to those obtained by another recent M87 monitoring with VLBA at 43 GHz (Mertens *et al.* (2016); Walker *et al.* (2018)). The independent confirmation at different time, at different frequency and with different instruments suggests that the acceleration near the jet base is not episodic but a fundamental property of this jet. Also, the accelerating signature at these scales imply that the jet collimation and acceleration coexist, which is consistent with magnetic processes (e.g., Komissarov *et al.* (2009)).

From 2016 we have upgraded our KaVA monitoring program of M87 by adding 43 GHz. The dual-frequency strategy allows us to investigate the jet velocity fields over a wider range of distances from the black hole. Also, we can derive spectral index maps and their evolution with time, which will provide additional insights into the underlying particle energetics, density, and magnetic fields. The analysis is actively going on and these will update our knowledge of the M87 jet at these scales.

4. EAVN and EATING VLBI

Beyond KaVA, the international VLBI collaboration in East Asia is now rapidly expanding. In particular, efforts have been made to combine KaVA with some more telescopes in China, Korea and Japan. This ultimately forms the East Asian VLBI Network (EAVN; Wajima *et al.* (2016); An *et al.* (2018)). Thanks to the more number of stations and improved uv-coverage, EAVN will allow us to image and monitor the innermost regions of relativistic jets in much more detail.

From late 2018 EAVN is going to start regular operation at 22/43 GHz by adding the two large telescopes to KaVA – Tianma 65m in Shanghai and NRO 45m in Nobeyama. Thanks the large collecting areas of Tianma and NRO, we can greatly improve the overall array sensitivity (compared to KaVA, a factor of 10 improvement in baseline sensitivity, and a factor of 4 in image sensitivity). Concurrently, we are also commissioning EAVN with Urumqi and JVN at 22 GHz. EAVN test observations at 6.7 GHz are also actively ongoing. We plan to start regular operation of these capabilities in 2019.

Beyond EAVN, we are also expanding the array by collaborating with the Italian VLBI Network (IVN). By combing EAVN and IVN, we can obtain 10000 km baselines, which realizes a nearly global VLBI (East-Asia-To-Italy-Nearly-Global VLBI, or

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EATING VLBI). 3C84 and M87 are among the key targets of EATING VLBI. For M87, along with the Event Horizon Telescope (EHT) observations in spring 2017 and 2018, we succeeded in coordinating biweekly EATING observations at 22 GHz. Such a frequent monitoring is generally very difficult to realize with global VLBI. The analysis of these data is still in progress, but our preliminary image resolves the jet base of M87 at scales of $\sim 18\,R_s$, which is quite comparable to the scales of the EHT. This demonstrates that EATING VLBI would be useful as a guide to properly interpret the contemporaneous EHT images. For 3C84, this source is actually a very good target for EATING VLBI because it is a high declination source and there is sufficient common sky between East Asia and Italy. Similarly, other famous high declination sources such as BL Lac, Mrk421, Mrk501, OJ287 and Cygnus A are suitable targets of EATING. Future regular EATING monitoring of these sources at 22/43 GHz will uniquely determine the structural evolution of these jets at scales of $\sim 70\,\mu$as.

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