

KEY SCIENCE OBSERVATIONS OF AGNs WITH THE KaVA ARRAY

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ABSTRACT

KaVA (KVN and VERA Array) is a new combined VLBI array composed of KVN (Korean VLBI Network) and VERA (VLBI Exploration of Radio Astrometry). Here, we report the following two issues. (1) We review the initial results of imaging observations of M87 at 23 GHz following Niinuma et al. (2014). The KaVA images reveal extended outflows including complex substructures such as knots and limb-brightening, in agreement with previous VLBI observations. KaVA achieves a high dynamic range of ~ 1000 , more than three times better than that achieved by VERA alone. (2) Based on subsequent observations and discussions led by the KaVA AGN Sub Working Group, we set monitoring observations of Sgr A* and M87 as our Key Science Project (hereafter KSP) because of the closeness and largeness of their central super-massive black holes. The main science goals of the KSP are (i) testing the magnetically-driven-jet paradigm by mapping velocity fields of the M87 jet, and (ii) obtaining tight constraints on physical properties of the radio emitting region in Sgr A*. Towards KSP, we show the first preliminary images of M87 at 23 GHz and Sgr A* at 43 GHz with the bandwidth of 256 MHz.

Key words: journals: individual: M87, galaxies: active, techniques: interferometric

1. INTRODUCTION

Many active galactic nuclei (AGN) produce powerful and collimated jets of magnetized relativistic particles which can extend beyond galactic scales, and have an impact on galaxy evolution. Although the magnetic acceleration scenario of relativistic jets is widely discussed (e.g., Blandford & Znajek 1977; McKinney 2006; Komisarov et al. 2007), there is no conclusive observational evidence to prove it. In order to explore jet formation processes by a central engine composed of a supermassive black hole and accreting matter falling onto it, Very Long Baseline Interferometry (VLBI) is one of the most powerful tools, as it can probe the innermost regions of jets with high spatial resolution.

Recently, a new VLBI facility consisting of the Korean VLBI network (KVN) and the VLBI Exploration of Radio Astrometry (VERA) has been constructed in the East Asia region. KVN is the first VLBI array dedicated to the mm-wavelength radio observations in East Asia operated by the Korean Astronomy and Space Science Institute (KASI) (Lee et al. 2011; Lee et al. 2014). KVN consists of three 21-m diameter radio telescopes: one in Seoul, one in Ulsan, and one on Jeju Island, Korea. In each, four different frequency band receivers are installed (22, 43, 86, and 129 GHz; Han et al., 2013).

In this proceedings, we present some initial results of KaVA observations of M87 and Sgr A* at 23 GHz and 43 GHz.

2. BASIC SYSTEM OF KaVA

Here, we briefly review the basic system of the KaVA array.

- The KaVA array consists of seven antennas located in VERA-Mizusawa, VERA-Iriki, VERA-Ogasawara, VERA-Ishigakijima, KVN-Yonsei, KVN-Ulsan and KVN-Tamna with 21 baselines. The maximum baseline length is 2270 km between Mizusawa and Ishigakijima, and the minimum baseline length is 305 km between Yonsei and Ulsan. The maximum angular resolution expected from the baseline length is about 1.2 mas for K band and about 0.6 mas for Q band.
- The aperture efficiency of each VERA antenna is about 40% to 50% in both K and Q band (see VERA Status Report¹ and reference therein). The measurements in the status report were based on the observations of Jupiter assuming that the brightness temperature of Jupiter is 160 K in both the K band and the Q band. Due to bad weather

¹<http://veraserver.mtk.nao.ac.jp/restricted/CFP2013/status13.pdf>

conditions in some of the sessions, the measured efficiencies show large scatter. The aperture efficiency of each KVN antenna is about 50% to 60% (see KaVA Status Report² and references therein).

- Receiver specifications can be briefly summarized as follows. For VERA, the low-noise HEMT amplifiers in the K and Q bands are enclosed in the cryogenic dewar, which is cooled down to 20 K, to reduce the thermal noise. For KVN, the 22, 43 and 86 GHz band receivers are cooled HEMT receivers and the 129 GHz band receiver is a SIS mixer receiver. All receivers receive dual-circular-polarization signals.
- The KaVA observations are basically supposed to be recorded with a 1 Gbps data rate. To achieve 1 Gbps recording, VERA and KVN have a DIR-2000 and Mark5B recording system, respectively. DIR-2000 is a high speed magnetic tape recorder, and Mark5B is a hard disk recording system developed at Haystack observatory. Their total bandwidths are 256 MHz because of 2-bit sampling. The recording time per roll of tape is 80 mins in the DIR-2000 system. In the case of the Mark5B system, the recording time depends on data size of disk-pack.

3. EVALUATION OF IMAGING CAPABILITY

Following Niinuma et al. (2014), here we evaluate the imaging capability of KaVA by showing the dynamic ranges and signal-to-noise ratio of radio images obtained by KaVA at 23 GHz. The obtained values are summarized in Table 1. In radio interferometers the detection limit (equivalent to thermal noise level) of images is given by Thompson et al. 2001;

$$\sigma_{\text{th}} = \frac{2k_{\text{B}}T_{\text{sys}}}{A_{\text{eff}}\eta_{\text{q}}\sqrt{N_{\text{ant}}(N_{\text{ant}} - 1)BWt_{\text{int}}}}, \quad (1)$$

where A_{eff} , η_{q} , T_{sys} , N_{ant} , BW , t_{int} , are the effective aperture area of the antennas, the quantization loss factor, the system temperature, the number of antennas, bandwidth, and the total integration time, respectively. When using natural weighting, a typical thermal noise for KaVA observation at 23 GHz is $\sigma_{\text{th}} \approx 0.7 \text{ mJy beam}^{-1}$.

Regarding the dynamic range of images, one may estimate it as follows (Perley 1999):

$$\frac{I_{\text{p}}}{\sigma_{\text{im}}} = \frac{\sqrt{M_{\text{scan}}}\sqrt{N_{\text{ant}}(N_{\text{ant}} - 1)}}{\max[\epsilon, \Delta\phi]} \quad (2)$$

where M_{scan} , ϵ , and $\Delta\phi$ are the number of scans for each observation, and degrees of amplitude and phase errors, respectively. Since all of the ϵ and $\Delta\phi$ for the KaVA observations with $BW = 32 \text{ MHz}$ are tabulated in Niinuma et al. (2014), we do not repeat it here.

² http://kava.kasi.re.kr/status_report/node02.html?mid=020301

Table 1
COMPARISON OF IMAGE DYNAMIC RANGES AND SNR AT
23 GHz

Array, Band Width (BW)	$I_{\text{p}}/\sigma_{\text{im}}$	$I_{\text{p}}/\sigma_{\text{th}}$	ObsID
VERA, BW=32 MHz:	190	505	r13103a
KaVA, BW=32 MHz:	1017	1453	r13104a

The values are adopted from Niinuma et al. (2014).

4. KEY SCIENCE PROJECT

4.1. M87

M87, a nearby giant radio galaxy located at a distance of 16.7 Mpc, hosts one of the most massive super-massive black holes, with a mass of $6 \times 10^9 M_{\text{sun}}$. Thanks to its proximity and the largeness of the black hole, M87 is well known for being the best source for imaging the innermost part of the jet base (e.g., Hada et al. 2011; Doeleman et al. 2012). The formation mechanism of relativistic jets in AGNs is one of the big questions in astrophysics. According to the leading scenario of jet formation models, a jet is thought to be powered by a central engine in a highly magnetized state, and accelerated via conversion of magnetic energy into kinetic. Recent general relativistic magnetohydrodynamic simulations have suggested that jets are gradually accelerated up to a distance of 1000 Schwarzschild radii (Rs) scale from the central black hole (e.g., McKinney, 2006; Komissarov et al., 2007). Hence, it is possible to test such a magnetically-driven jet model by comparing the model-predicted velocity field and an observed one. The aim of this KSP is measuring the actual velocity field in the M87 jet to test the magnetically-driven jet paradigm.

In Figure 1, we compare KaVA and VERA images of M87 at K-band. From this, we can see that the higher dynamic range of KaVA enables us to obtain the extended structure of the M87 jet up to a 10 mas scale. In Figure 2, we present the first preliminary image of M87 at K-band, but with a bandwidth of 256 MHz.

4.2. Sgr A*

The center of Milky Way hosts Sagittarius A*, a super massive black hole with the largest angular size, and therefore one of the best laboratories to explore the vicinity of black holes (e.g., Doeleman et al. 2008; Akiyama et al. 2013).

The origin of radio emission from Sgr A* is still an open issue (i.e., accretion flow or jet). The observational goal of the KaVA Sgr A* monitoring observations is to measure the radio fluxes accurately and to obtain resolved images of the inner most region of Sgr A* before/during/after the G2 encounter (Gillessen et al. 2012).

We have continued the monitoring of Sgr A* at 43 GHz³. Accurate measurements of the size and flux of Sgr A* by KaVA at 43GHz before/during/after the G2 encounter will enable us to give tight constraints on

³ <https://wiki.mpe.mpg.de/gascloud/Proposallist>

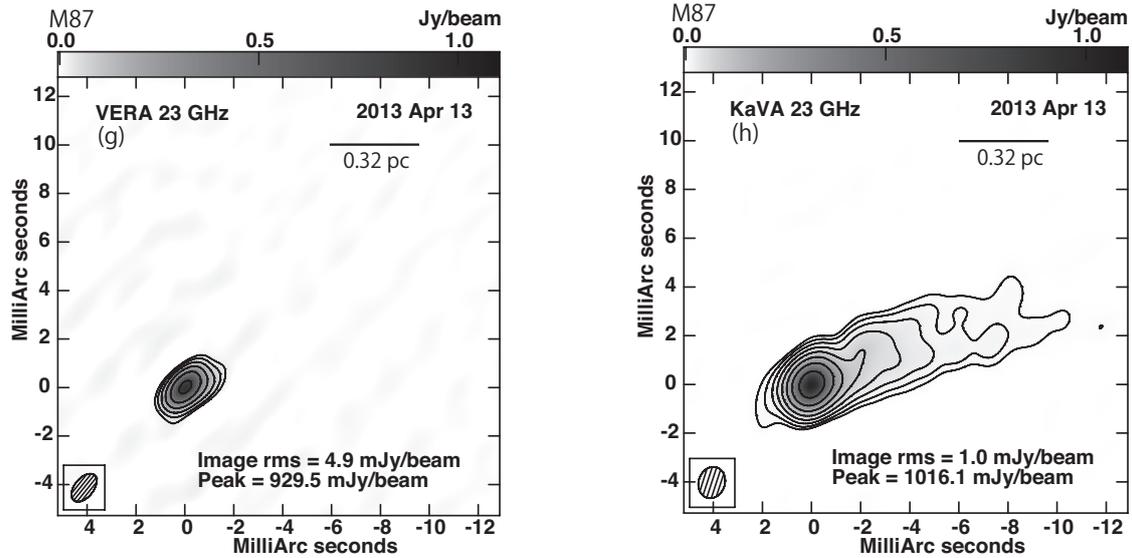


Figure 1. The comparison of VERA and KaVA images of M87 at K-band with the bandwidth 32 MHz.

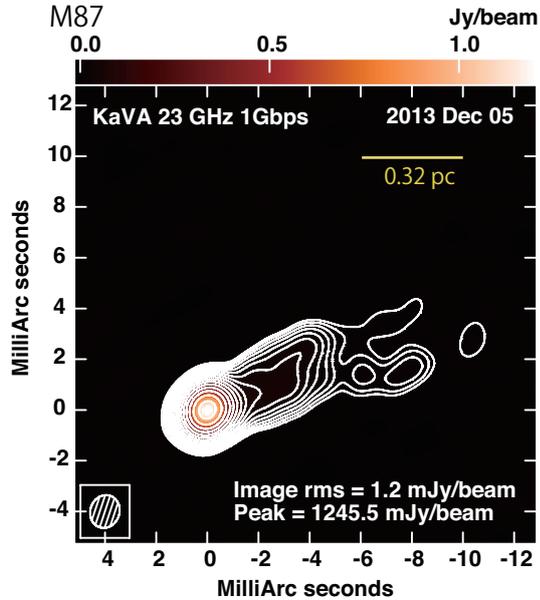


Figure 2. KaVA image of M87 at K-band with the bandwidth of 256 MHz

the origin of radio emission from Sgr A*.

In Figure 3, we present the u, v coverage and the preliminary image of Sgr A* at 43 GHz with a bandwidth of 256 MHz. In Table 2, we summarize the measured total flux, position angle, and major and minor axes of Sgr A*. We emphasize that KaVA can achieve good performance for Sgr A* observations, since it has more short baselines than other VLBI arrays. Short baselines in KaVA provide more effective sampling of the visibilities of Sgr A* than VLBA (Akiyama et al. 2014), and it enables us to get better measurements of the source size.

Table 2
OBTAINED QUANTITIES OF SGR A* (PRELIMINARY)

Array (band)	S (Jy)	Position Angle (degree)	θ_{maj} (mas)	θ_{min} (mas)
KaVA (Q-band)	1.1	70	0.75	0.42

5. SUMMARY

Towards the KSP of AGN with KaVA array, we have continuously performed KaVA observations of M 87 at 23 GHz and Sgr A* at 43 GHz. The main results in early phase observations are as follows:

- To evaluate the imaging capability of KaVA array, we conducted KaVA observations of M87 at 23 GHz (with $BW=32$ MHz). By comparison of KaVA and VERA images for the M87 jet, we found that the image dynamic range is improved by a factor of ~ 3 due to the reduction of residual phase and amplitude errors in the KaVA image (Niinuma et al. 2014).
- Based on discussions among the AGN SWG, we describe our KSP, the monitoring observation of Sgr A* and M87, due to the closeness and largeness of their central super-massive black holes. This aims to (i) test the magnetically-driven-jet paradigm by mapping the velocity field of the M87 jet, and (ii) obtain tight constraints on physical properties of the radio emitting region in Sgr A*. We show the first preliminary images of M87 at 23 GHz and Sgr A* at 43 GHz with a wide bandwidth of 256 MHz.

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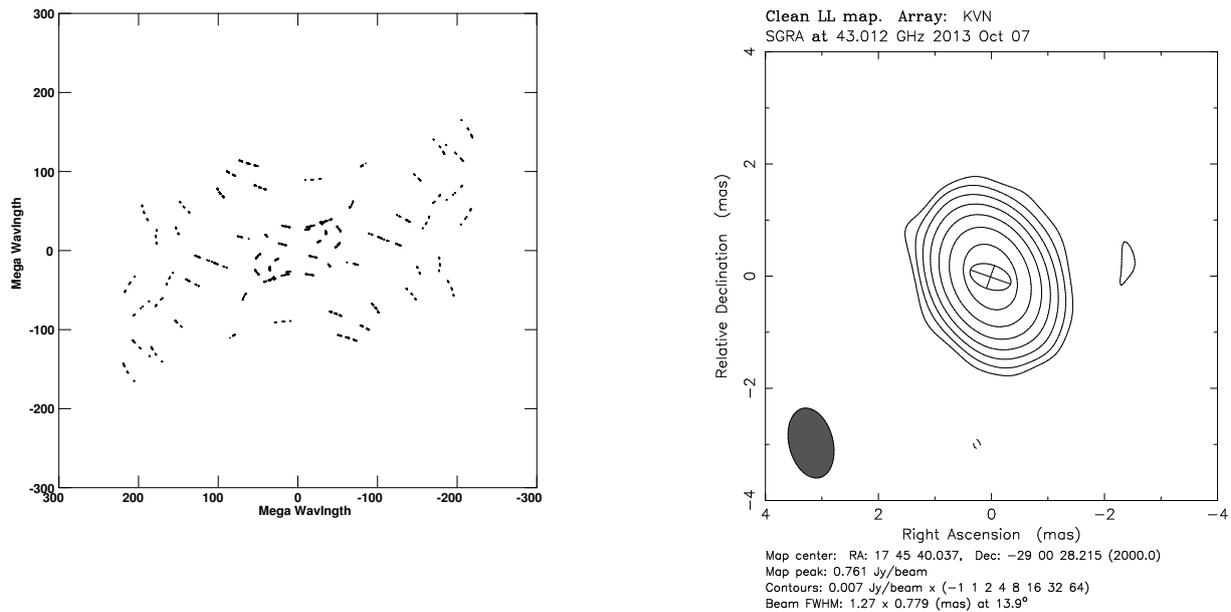


Figure 3. Left: The u, v coverage of KaVA observation of Sgr A* at 7 mm performed on Oct 7th 2013. Right: Corresponding KaVA image of Sgr A* with the best-fit elliptical Gaussian model. The position angle, the sizes of major and minor axes, peak intensity, total flux, are shown in Table 2.

tronomical Observatory of Japan in collaboration with Japanese universities.

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