The Multi-Messenger Astrophysics of the Galactic Centre
Proceedings IAU Symposium No. 322, 2016
R.M. Crocker, S.N. Longmore & G.V. Bicknell, eds.

doi:10.1017/S1743921316012497

Millimeter VLBI observations of Sgr A* with KaVA and KVN

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Abstract. We present recent observation results of Sgr A* at millimeter obtained with VLBI arrays in Korea and Japan.

7 mm monitoring of Sgr A* is part of our AGN large project. The results at 7 epochs during 2013-2014, including high resolution maps, flux density and two-dimensional size measurements are presented. The source shows no significant variation in flux and structure related to the G2 encounter in 2014. According to recent MHD simulations by kawashima *et al.*, flux and magnetic field energy can be expected to increase several years after the encounter; We will keep our monitoring in order to test this prediction.

Astrometric observations of Sgr A* were performed in 2015 at 7 and 3.5 millimeter simultaneously. Source-frequency phase referencing was applied and a combined "core-shift" of Sgr A* and a nearby calibrator was measured. Future observations and analysis are necessary to determine the core-shift in each source.

Keywords. Galaxy: center, Galaxies: nuclei, Individual: Sgr A*, techniques: interferometric, techniques: phase-referencing

1. Introduction

Sgr A*, the compact radio source at the Galactic Center, is by far the best constrained supermassive black hole (SMBH) candidate. It has a mass of around $4 \times 10^6 M_\odot$ and lies at a distance of around 8 kpc (see Boehle *et al.* 2016, for the most recent mass and distance measurements). Sgr A* is the best laboratory to explore the ultimate vicinity of black holes. High resolution observation around Sgr A* will be an incomparable probe for understanding the fundamental nature of black hole inflow/outflow.

Emission from Sgr A* has been detected at radio, infrared, and X-ray wavelengths. There have been a number of theoretical models proposed to explain the low luminosity of Sgr A*: e.g. accretion flow model (RIAF, Yuan *et al.* 2003), jet model (e.g. Falcke & Markoff 2000) and others (e.g. Melia *et al.* 2001).

The apparent size of the Schwarzschild radius of Sgr A* is about 10 μas, so currently only VLBI could resolve the structure in the vicinity of the SMBH. However, previous imaging studies have found that the emission is scattered by interstellar medium in the foreground. The scattered size follows a λ^2 law. Only at a wavelength shorter than 1.3 cm, does the scattering effect become weaker and the intrinsic size would not be negligible (e.g. Bower *et al.* 2004). The intrinsic size also has a frequency dependence, which suggests it is determined by the photosphere of an optically thick plasma (e.g. Falcke *et al.* 2009).

The emission from Sgr A* is also found to be variable. The origin, intrinsic or extrinsic, and the mechanism of the longer time-scale variation at radio band are still under discussion (e.g. see Falcke *et al.* 2009, for a review). Monitoring of the time variation would be very important. In particular, the recent G2 event (Gillessen *et al.* 2012) has triggered the attention of lots of observatories towards the Galactic Center. In this paper, we present our recent observational results at millimeter wavelengths with VLBI facilities located in Korea and Japan.

2. 7 millimeter monitoring of Sgr A* with KaVA

2.1. *Motivation*

In 2012, the object G2 was observed approaching the Galactic Center SMBH with a pericenter distance of $\sim 1500 - 2200 R_{sch}$ (Gillessen *et al.* 2012). An increase of activity of Sgr A* was expected due to the interaction of G2 with the accretion flow. The gas stripped from G2 would accrete on the black hole in a viscous time. The detection of flux increase at radio wavelength would provide direct measurement of the viscous time at the pericenter. Furthermore, an increase in the mass accretion rate could lead to structure changes which would be detectable with VLBI.

The KVN and VERA array, KaVA, started early operation in 2010 and Sgr A* has been a major target of the KaVA AGN observations since then. The baselines of KaVA range from 300 to 2300 km. The array has a good imaging capability (Niinuma *et al.* 2014). One promising advantage of KaVA for Sgr A* observation is the good u,v-coverage (see Figure 1 for an example). KaVA has more baselines at short and intermediate u,v-range ($50 - 300 M\lambda$ at 7 mm). At longer baselines, the source is resolved due to the extended structure as a result of scattering. KaVA has a better sampling and thus can offer more closure quantities (amplitudes and phases) of Sgr A*, which are very important for obtaining high quality maps and size measurements (see Akiyama *et al.* 2014, for a comparison between the u,v coverages of KaVA and VLBA).

2.2. *Observation and data analysis*

The observation of Sgr A* with KaVA started soon after G2 was discovered approaching the Galactic Center SMBH. Several test observations were done in 2013 and regular monthly monitoring was started as part of the KaVA AGN large project in 2014. Currently, this is the only regular long-term VLBI monitoring project of Sgr A*. The observing frequency was selected taking into account the effect of scattering and the performance of the antennas. The data were recorded with 256 MHz bandwidth in left-hand circular polarization (1 Gbps recording rate). The duration of each observation was about 6 hours and total on source time for Sgr A* was around 220 minutes. The bright and compact blazar, NRAO 530 was observed as a fringe finder. The data recorded at each station were correlated with the hardware correlator at KJCC (Lee *et al.* 2015).

We analyzed the data following the standard procedure for VLBI data processing with NRAO AIPS and Caltech DifMAP packages. Figure 2 shows an example of the visibility

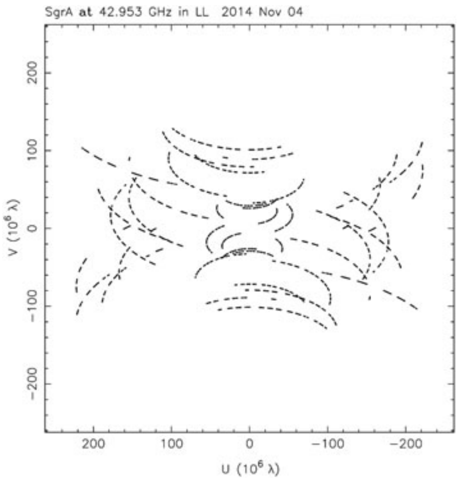

Figure 1. The u,v-coverage of KaVA for Sgr A* at epoch November 4th, 2014. Only the data with fringe detections are plotted.

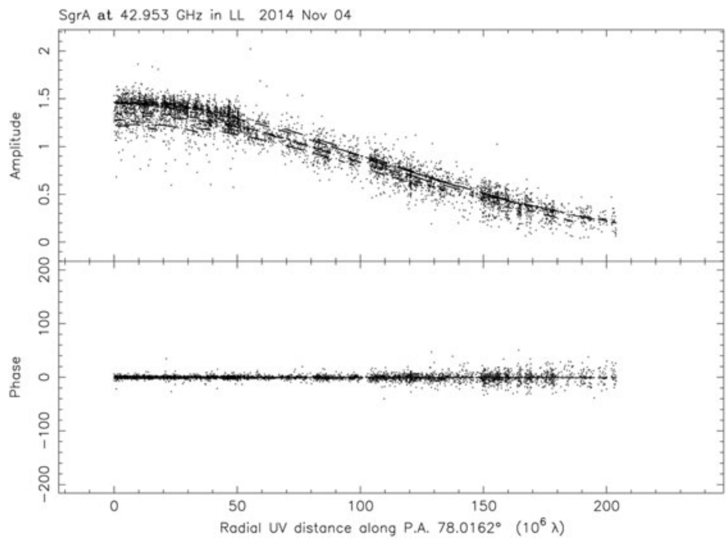

Figure 2. Visibility amplitudes and phases of Sgr A* as functions of the projected u,v-distance at epoch November 4th, 2014 . All visibilities are plotted along P.A. 78.1° East of North, which corresponds to the position angle of the model-fitted major axis. The solid lines represent the model obtained by elliptical Gaussian fitting as also shown in Figure 3.

amplitude and phase versus u,v-distance. The data were averaged over 30 seconds and the whole bandwidth. We have fringe detections up to 200 Mλ, and the minimum detected flux is about 100 mJy. The closure phases of Sgr A* are consistent with 0 at each triangle (Zhao *et al.* in prep), which means the source shows a symmetric structure. We modeled the calibrated data with one elliptical Gaussian component for each epoch based on these characteristics.

2.3. *Results and discussion*

Figure 3 shows an example of the natural weighted clean images. The elliptic superposed on the map indicates the Gaussian model-fitting result. The source shows an elongated structure with major axis along nearly east-west direction and the axis ratio is about 0.5. This morphology is consistent with previous results (e.g. Akiyama *et al.* 2013; Bower *et al.* 2014). The dynamic range on the map is nearly 1000 which is much higher than the previous VERA only results (Akiyama *et al.* 2013). This again confirms the power of the good u,v-coverage.

Figure 4 shows the model-fitted parameters, flux, major and minor axis size, of all the epochs with good weather condition and antenna performance in 2013-2014. Our multi-epoch results show no significant changes in flux density and size of Sgr A* in 2013-2014. This result is consistent with the one epoch GMVA observation in October 2013 (Park *et al.* 2015) and multi-epoch VLA, SMA, and ALMA observation during 2012-2014 (Bower *et al.* 2015).

We combined our results with those in Lu *et al.* (2011) to check the relation between the two dimensional size and the flux density over a wider flux range. The results are plotted in Figure 5. We found that the major axis remains stable as the flux varies, while the minor axis seems to show a more complex behaviour. It appears that the size-flux relation may be divided into two different states, quiescent and flaring, with a break at $\sim$1.7 Jy. The quiescent state shows a more stable minor axis size, with a mean of 0.39 mas and a standard deviation of 0.02 mas while the flaring state, with a similar mean of 0.41 mas shows a larger standard deviation of 0.05 mas and a clear tendency for the minor axis to increase with flux, with a correlation coefficient of $r = 0.7$. The different behavior during flaring event may be explained by change of accretion rate for both jet model (Falcke *et al.* 1993) and accretion disk model (e.g. Mahadevan 1997; Mościbrodzka *et al.* 2012). The expanding plasma model(Yusef-Zadeh *et al.* 2006) could also have a size variation, but this is unlikely the case, as discussed in Akiyama *et al.* (2013), since no additional components are detected. Future observations during flaring events (e.g. related to G2) will provide us additional information which will help to check this possible correlation and put more constrains on the models.

As described above, we found no flaring activity related to the G2 encounter. Recent NIR observations show that G2 may have survived the encounter (Valencia-S. *et al.* 2015). The authors also argue that G2 is not a cloud but a stellar object. On the other hand, recent X-ray observations found a flux increase which maybe related to G2 (Ponti *et al.* 2015). Furthermore, given the large shear, much of the surrounding gas could be dissolved even there is a central star, so the flare could be still upcoming. A recent simulation by Kawashima *et al.* also predicts the magnetic energy enhancement will appear several years after the encounter. In addition, viscous timescale is estimated as a few years with $\alpha \approx 0.1$, well consistent with this prediction. Our monitoring will continue in the next several years in order to detect the possible flares and test the predictions.

3. KVN simultaneous dual-frequency observations of Sgr A* (Cho *et al.* in prep)

One of the puzzling problems of Sgr A* is whether it is launching a jet. There have been successful jet models (e.g. Falcke & Markoff 2000), but no radio jet has been convincingly detected (but see Li *et al.* 2013). One way to test the jet model is to measure the relative position between emissions at two different frequencies. The core position in a one-sided jet will have a frequency dependence due to opacity effect, know as "core-shift" (Lobanov 1998).

With the unique simultaneous multi-frequency receiving system, the Korean VLBI network(KVN) would be the most suitable array to carry out millimeter astrometric observations (Jung *et al.* 2015). The method used by KVN is source-frequency

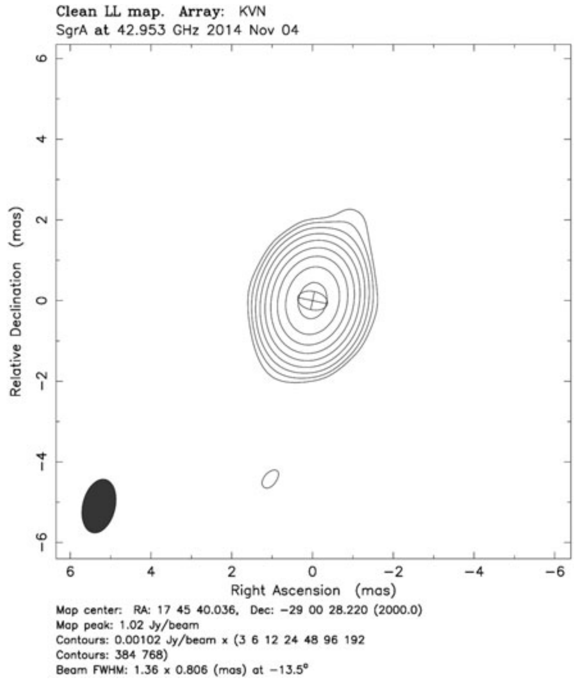

Figure 3. The natural weighted clean map of Sgr A* at epoch November 4th, 2014. The contours start from 3σ level and increase by a factor of 2. The beam is plotted at bottom left corner. The epileptic on the contours represents the Gaussian model-fitting result.

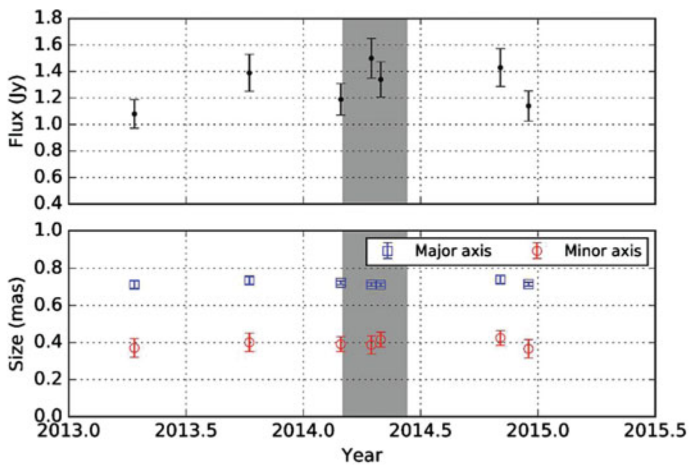

Figure 4. The time variations of the flux (upper) and observed structure (lower) of Sgr A* in 2013-2014. In the lower panel, the squares and circles represent the major and minor axis, respectively. The shaded area represents the time of G2 encounter.

phase-referencing (SFPR), which involves transferring phase calibrations first between frequencies and then among sources. In the same way relative positions between sources are measured by conventional phase-referencing, the combined core-shift of a pair of sources can be measured with SFPR (Rioja & Dodson 2011).

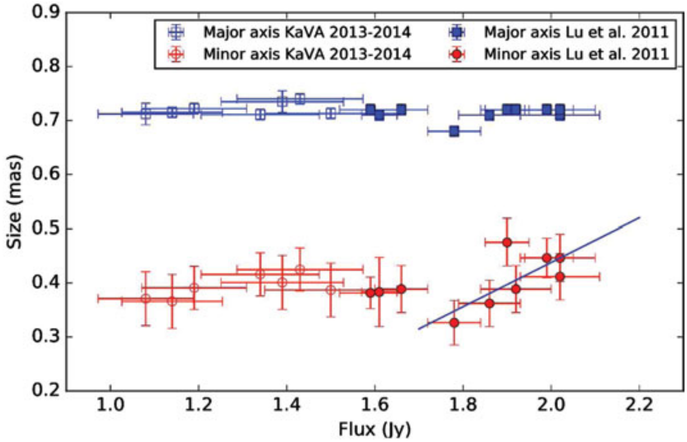

Figure 5. The measured angular sizes as functions of flux density. The squares and circles represent major and minor axis, respectively. The open symbols correspond to the KaVA results while the filled ones are from Lu *et al.* (2011). The solid line indicate the linear fit of the data with flux above 1.7 Jy.

3.1. *Observations and data analysis*

The first KVN astrometric observations of Sgr A* were carried out in early 2015 at 7 and 3.5 mm simultaneously. Two AGNs, J1744-3116 and J1700-2610, were observed as reference sources. The total observing time at each epoch was 6 hours. The data were recorded in dual polarizations with 64 MHz bandwidth at each frequency and correlated with DiFX correlator.

The data analysis was carried out with AIPS. The amplitude calibration was performed with the measured system temperature and gain curves. For phase calibration, global fringe-fitting was first done for each source at the lower frequency using the whole bandwidth, the solutions were then scaled up by the frequency ratio and applied to the higher frequency data obtained simultaneously. This step is known as frequency phase transfer (FPT, see e.g., Rioja & Dodson 2011; Algaba *et al.* 2015). A second fringe-fitting was then performed on the data of the reference source and applied to the target. The target source data were then imaged and the combined core-shift was obtained by measuring the offset from the brightest peak to the center of the map.

3.2. *Preliminary results and discussion*

SFPRed maps of Sgr A* at 3.5 mm were successfully obtained at 4 epochs by referencing to J1744-3116 after FPT from 7 mm. SFPR between Sgr A* and J1700-2610 failed at all epochs because of the large separation and low elevation of the sources. An example of the SFPRed map of Sgr A* is shown in Figure 6 (Left). The astrometric measurements at all 4 epochs are plotted in Figure 6 (Right).

Sgr A* appears to be a point source under the KVN resolution ($\sim$ 1 mas). The astrometric measurements are consistent with each other, which show a $\sim$ 0.3 mas to the south direction. Note this core-shift is larger in angular scale compared with those in other AGN jets when extrapolated to the same frequency (e.g. Sokolovsky *et al.* 2011), and the direction is not consistent with the recent VLBA result (Bower *et al.* 2015). We consider the origin of this measured core-shift as the combined core-shifts of both target and calibrator plus the structure blending effect. The core-shift of the reference source, J1744-3116, would only contribute a small portion to the measurement as estimated based on the statistics of core-shift in other AGNs (e.g. Sokolovsky *et al.* 2011).

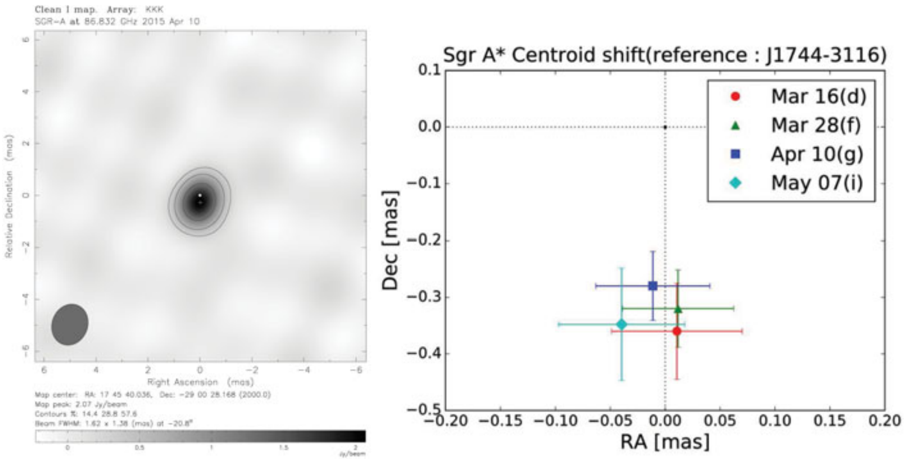

Figure 6. Left:The SFPR-ed image of Sgr A* at 3.5 mm obtained with KVN on April 10, 2015. Contours start 3-sigma and increase by 2. The beam pattern is shown at the left-bottom side of the plot. The cross and dot indicate the position of the peak and center of the map, respectively. Right: Preliminary measurements the centroid shifts at all 4 epochs. The uncertainties are taken as beam/SNR.

The structure blending effect is quite common in KVN measurements due to the large beam size (e.g. Rioja *et al.* 2014). We think the contribution from structure blending of Sgr A* itself is not significant as it shows symmetric structure at 7 mm and the asymmetric structure at 3.5 mm is along the east direction (Brinkerink *et al.* 2016). However, the inner structure of J1744-3116 could contribute partially or even dominate the measurements, although the source appears compact under KVN resolution. Future high resolution maps of this source is needed to subtract this effect. The uncertainties in the measurements are estimated as the beam size divided by the signal-to-noise ratio in the map. The actual uncertainties could be larger by considering also the contributions from all the propagation effects such as ionospheric and instrumental effects (e.g. Rioja & Dodson 2011; Hada *et al.* 2011).

3.3. *Future observations*

Inclusion of more reference sources could reduce the ambiguity in determine the core-shift of each source (Rioja *et al.* 2015). New observations with careful selection of sources and improved scheduling is on-going with the KVN. These will provide more robust measurements of the core-shift in Sgr A*.

4. Summary

We present results of our recent mm VLBI observations of Sgr A* with KaVA and KVN.

• KaVA has a good *u,v*-coverage for Sgr A* observation. High quality images at 7 mm are obtained with KaVA in 2013-2014. Our data at each epoch can be modeled with one elliptical Gaussian component. We found no asymmetric structure at this wavelength.

• By combining our data with previous VLBA results we found the emission of Sgr A* may be divided into two states. In the flaring state, a possible correlation between the variation in the minor axis size and flux density was found while in quiescent state, there are no obvious size changes.

• We found no flux increase related to the G2 encounter. However, our monitoring will continue since the flare may still occur on a viscous timescale.

• We conducted astrometric observations of Sgr A* with the KVN at 7 and 3.5 mm simultaneously. The preliminary results show a ~ 0.3 mas position shift between emissions at the two bands. However, the contributions from the inner structure and core-shift of the reference source to the measurements are unclear. New observations with more reference sources are expected to address this issue in the future.

We are grateful to all staff members and students at KVN and VERA who helped to operate the array and to correlate the data. GYZ and TJ are supported by Korea Research Fellowship Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2015H1D3A1066561).

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