Millimeter-VLBI Observations of Sgr A* with KaVA and EAVN

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On behalf of KaVA/EAVN AGN Science Working-Group & KVN Sgr A* Astrometry project

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Outline

Highlights, updates, challenges, future mitigations

• long-term monitoring at 7 mm with KaVA
  – Asymmetric structure?
  – G2-encounter
  – Sizes and scattering

• KVN Multi-Frequency/Astrometric observations
  – Core-shift in Sgr A*?

• New opportunities with EAVN
  – Fringe detections/GC Magnetar/Scattering
Fact sheet: Sgr A*

Sgr A*: The best laboratory for studying SMBH

- Nearest SMBH: $\sim 4 \times 10^6 M_{\text{sun}}$ BH at 8kpc (Ghez+2005)
- Largest angular size of event horizon: $1 R_s \sim 0.01$ mas (Ghez+2005)
- Extremely low luminosity: $\sim 10^{-9} L_{\text{Edd}}$
- Frequency-dependent sizes: scattered & intrinsic

(Schoedel+2002)  (Falcke & Markoff 2013)
I. LONG TERM MONITORING AT 7 MM WITH KAVA

- Tests in 2013 + Regular monitoring Since 2014
- Aim: Structure, variability, imprints of G2, etc
Sgr A* at 7 mm with KaVA:

- Clean maps with circular beam
On the asymmetric structure

Discovered at other frequencies with closure phases

@1.3 mm (Fish+ 2016)

@3 mm (Brinkerink+ 2016)
On the asymmetric structure

@7 mm, other works
(Rauch+ 2016)

@7 mm KaVA
CP consistent with 0 at all triangle, all time

• No significant asymmetric structure at 7 mm
On G2 encounter

Discovery of close encounter of G2 at ~2000 Rsch (Gillesson+ 2012)
Expected observational effects
- Bow shock
- Multi band flares
- Structural change detectable with VLBI

G2 Survived the close encounter
There’s a stellar core?

This annotated composite image shows the motion of the dusty cloud G2 as it closes in, and then passes, the SMBH at the centre of the Milky Way. These new observations with ESO’s VLT have shown that the cloud appears to have survived its close encounter with the BH and remains a compact object that is not significantly extended. The blobs have been colourised to show the motion of the cloud, red indicated that the object is receding and blue approaching. The cross marks the position of the SMBH.

Credit: ESO/A. Eckart
On G2 encounter

- KaVA results at 7mm from 2013 to early 2015

KaVA map of Sgr A*

Uncertainties
Flux: 10%
Major axis: 2~3%
Minor axis: 5~10%
On G2 encounter

Consistent with other monitoring/observations

- γ-ray with MAGIC (Ahnen+2017)
- X-ray with XMM-Newton and Chandra (Ponti+2015)
  - 15 years of observation
  - A increase of flare luminosity between 2013 & 2014 (sampling)
- Infrared with VLT, Keck etc
  No detection of drag force or hydrodynamic interaction (e.g. plewa+2017)
- Radio, mm
  JVN@22 GHz (Tsboi+2015)
  VLA + SMA + ALMA (Bower+ 2015)
  GMVA@86 GHz (Park+2015, 1epoch)

SMA&ALMA light curve (Bower+2015)
The nature of G2

Stellar object?

Dust-enshrouded young star in accretion phase (zajacek+2015)

Related with G1?

Precursor G1: another object passed peri-center >1 decade ago
Trajectory of G2 and previous position of G1 (plewa+2017)

- Flaring event maybe still upcoming?
- Kawashima prediction valid for G1?
  - A flare event in 2007 (Lu+2011, Akiyama+2013), related?
## Sizes and scattering

<table>
<thead>
<tr>
<th>Bower et al. (2014)</th>
<th>Zhao+ KaVA SWG in prep</th>
<th>Zhao+ KaVA SWG in prep</th>
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<tbody>
<tr>
<td><strong>Closure-Amp</strong></td>
<td><strong>Closure-Amp</strong></td>
<td><strong>Self-Cal</strong></td>
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<tr>
<td><strong>Major axis (μas)</strong></td>
<td>722 +/- 3</td>
<td>734.2 +/- 2.7</td>
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<tr>
<td><strong>Minor axis (μas)</strong></td>
<td>345 +/- ~30</td>
<td>427.0 +/- 21.8</td>
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<tr>
<td><strong>Pos. angle (degrees)</strong></td>
<td>82.4 +/- ~1.0</td>
<td>81.79 +/- 2.74</td>
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</table>

**Diagram:**
- Left: Maps at 1.6 mJy/beam showing resolution and noise levels.
- Right: Plot of normalized visibility versus baseline length.
Sizes and scattering

Effect of Sgr A* imaging (c) Honma-san

1. Initial model mock-image @230GHz
2. Blurred by new scatter law w/ KaVA’s minor axis
3. Reconstruction with old law:
   Fourier Transform of image 2 scattering corrected with Bower’s scattering law, and inverse FTed
   (full UV sampling, no noise)
4. Image difference between 3 and 1

The difference of the minor axis causes image error at 20% level of peak intensity! i.e., KaVA data is crucial for proper reconstruction of EHT image!
Deburring the diffractive scattering

Visibility amplitudes

Log Closure amplitudes

Plots made by Sparselab
Variations introduce by refractive effects

- Demonstrations of refractive effects

(Script by M. Johnson)
Variations introduce by refractive effects

- On major axis ($\alpha = 5/3$, $r_{in} = 10^5$ km, $\text{int\_size}=270 \mu$as)

(MJD: 51544)

(Script by M. Johnson)
Variations introduce by refractive effects

- On major axis ($\alpha = 1.2$, $r_{\text{in}} = 10^5$ km, int_size=$270\mu$as)
II. KVN SIMULTANEOUS DUAL-FREQUENCY OBSERVATIONS OF SGR A*

Cho, Sohn, Jung (KASI/UST), Kino, Zhao (KASI), Agudo (CSIC), Rioja, Dodson (ICRAR)
Core-shift in Sgr A*?

- Does Sgr A* have a jet?
- Does it have core-shift as other AGN jets?

Core-shift in AGN jets

Image credit: T. Jung
The Korean VLBI Network (KVN)

- 3 stations in South Korea
- 21m diameter
- 300-500 km baselines
- 22, 43, 86, 129 GHz
- Simultaneous 4-frequency receiving
- operating from 2011

Han+ 2008
KVN observations of Sgr A*
Method: Source-Frequency Phase-referencing (SFPR)

self-calibration
Position information is lost

With phase-referencing
Relative position can be measured
But at mm, PR is difficult
KVN observations of Sgr A*
Method: Source-Frequency Phase-referencing (SFPR)

SFPR step 1, frequency phase transfer, FPT
- Much longer coherence time
- Core-shift

SFPR step 2, phase-referencing between sources
- Calibrated remaining effects
- Combined core-shift

Image credit: M. Rioja
KVN observations of Sgr A*

- 2015 March~May, 4 epochs
- 7mm / 3.5mm, simultaneous
- 64MHz, Dual polarization
KVN observations of Sgr A*: Phases

- Raw phase
- After FPT
- SFPR
KVN observations of Sgr A*:
Preliminary result

SFPRed Maps

Combined core-shift measurements

Sgr A* Centroid shift (reference: J1744-3116)

- Mar 16 (d)
- Mar 28 (f)
- Apr 10 (g)
- May 07 (i)

2015 March 28

1 mas
Resolving the Calibrator's Structure

Expected Structure blended shift in KVN beam

J1744-3116, Convolved with KVN 43 GHz beam

J1744-3116, Convolved with KVN 86 GHz beam

169 uas
10.7 uas
53 uas
4.7 uas
SFPRRed Phase

phase at 86 GHz

after SFPR

Sgr A* as reference

large residual in J1700-2610
To be solved: SFPR phase vs. secZ difference

SFPR phase vs. time

However, what's this trend?! J1700-2610 : Sgr A*

Elevation difference vs. time

Similar trend!

Without any correction
This will give very small core-shift!
KVN observations of Sgr A*: Summary of Challenges and possible mitigations

• Inner structure of the reference source
  – High resolution imaging with KaVA
  – More source pairs

• Residual delta_SecZ dependent phase
  – fitting for the dependence
  – MCMC fitting

• Future observations
  – VLBA observation in 2018A
  – KVN observations with more calibrators and wider BW
III. EAVN OBSERVATIONS IN 2017 SPRING
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Better detection with NOB on long baselines

Fringe-detection with KaVA only
KUS as reference station

Fringe-detection with EAVN
NOB as reference station

For MIZ and OGA, many failed solutions at the beginning due to the extended structure

The failed solutions are recovered
Higher sensitivity with Tianma

EAVN a17094a
KaVA + Tianma; Q-band

Resolution: 0.90*0.45 mas
KaVA; rms: 2.0 mJy/b

Resolution: 0.91*0.35 mas
KaVA + T6; rms: 1.1 mJy/b
New opportunities with EAVN: Magnetar

Ideal source for exploring scattering and Astrometry
New opportunities with EAVN: Scattering

Quasi-simultaneous 22/43 GHz observation in April 2017
Modeling with MCMC: intrinsic size at each Freq + Scattering kernel

Preliminary results

Model-fitted parameters for Gaussian Kernel (Akiyama+ in prep)
Summary

• 7mm monitoring of Sgr A* with KaVA
  – Regular long-term monitoring with good uv-coverage
  – No obvious asymmetric structure at 7 mm
  – 2013-2015: No significant variations related with G2
  – Constrains on the scattering parameters

• KVN astrometric observations
  – Combined core-shift along N-S direction
  – SecZ dependent SFPR residual phases

• EAVN observations in Spring 2017
  – Higher sensitivity & better detection rate
  – Possible new opportunities: Magnetar & Scattering law