Understanding the Event-Horizon to AU scale radio emission from the Galactic Center with ultra-high-resolution VLBI
- An observer’s view

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With the helps from:
R.-S. Lu (MPIfR), M. Inoue (ASIAA), G.-Y. Zhao (KASI),
H. Falcke (Radboud Univ. & ASTRON), L. Huang & J. Li (ShAO)
Introduction to SgrA*’s size measurements
  - Discovery/Scattering/Elongation/Intrinsic size

Variability of SgrA*
  - Intensity/Structure(?)

EHT observations of SgrA*

Summary
Fact Sheet: Sgr A*

- the best and closest massive black hole candidate

(1 mas = 8AU at D=8 kpc; \( R_{sc} = \frac{2GM_{\odot}}{c^2} = 0.08 \) AU = 10 \( \mu \)as)

- Extremely compact radio source discovered in 1974 (Balick & Brown 1974)
- Extremely low luminosity (\( L \sim 10^{36} \) ergs s\(^{-1}\)\( \sim 100 \) \( L_{\odot} \sim 10^{-9}L_{\text{Edd}} \))

- Stellar orbital measurements: \( M_* \sim 4 \times 10^6 \) \( M_{\odot} \) within 45 AU of Sgr A* (Schödel et al. 2002; Ghez et al. 2005)
- Radio proper motion of Sgr A* itself: \( M_{\text{SgrA}^*} > 4 \times 10^5 \) \( M_{\odot} \) (Reid & Brunthaler 2004)
Discovery paper in 1974

- 3 baselines between 3x26-m of GBI and the 14-m at 35 km
  - **angular resolution**: 0.7 & 0.3 arcsec at 11 & 3.7 cm
  - observed (apparent) source size: ≤0.1 arcsec
  - total flux density: 0.6 Jy@11 cm; 0.8 Jy@3.7cm ; -> non-thermal
Discovery paper

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total flux density: 0.6 Jy@11 cm; 0.8 Jy@3.7 cm

low elevation (<10 deg) data should be ignored!
THE RADIO SOURCE AT THE GALACTIC NUCLEUS

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(Received 1976 May 25)

SUMMARY

Observations of the small diameter radio source in the galactic centre have been made at 0.408, 0.96 and 1.66 GHz. These measurements show a low-frequency cut-off in the spectrum which is considered to be due to free-free absorption in the Sgr A West H II region. The nuclear source has a diameter of 1.5 arc sec at 1 GHz. The observed change of diameter with wavelength indicates that the observed diameters are a result of interstellar scattering. No significant intensity variation has been detected over a period of several years. On the basis of available data the nuclear source is considered to be located at the

First suggestion for lambda^2 scattering

- 3 baselines of early MERLIN
  - MkIA-MkIII: 23.70 km @ 1.66 GHz (18 cm) -> 2.5 arc
  - MkII-MkIII: 23.80 km @ 0.96 GHz (31 cm) -> 4.3 arc
  - MkIA-Defford: 127 km @ 0.408 GHz (74 cm) -> 10 arc

- Circular Gaussian diameter: 1.5 ± 0.3 @ 31 cm; 0.5 ± 0.1 @ 18 cm
- Flux density: 0.56 ± 0.06 Jy@18 cm; 0.26 ± 0.03 Jy@31 cm
On the size of the galactic centre compact radio source: diameter <20 AU

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The existence of a compact nonthermal radio source at the galactic centre was first suggested by Lynden-Bell and Rees as the possible signature of a black hole. Such a source was detected unambiguously by Balick and Brown. Very long baseline interferometry (VLBI) observations of the structure of this source, hereafter referred to as Sgr A*, have been made for several years. In all previous experiments, the visibility amplitudes, measured over a restricted (U, V) range, could be fitted only to the simplest model of brightness distribution, that is, to a circular gaussian. We have re-observed Sgr A* at 3.6 cm and 1.35 cm with many baselines, using the more sensitive receivers and VLBI recording terminals now available. These observations set an upper limit of 20 AU (3 x 10^14 cm) to the diameter of Sgr A* and reveal for the first time an elongated structure at 3.6 cm, with the position angle of the long axis almost parallel to the rotation axis of the Galaxy. Sgr A* is unique in our Galaxy, but resembles most closely the compact radio sources at the centre of external galaxies. Observations of the central 4 arc s (0.2 pc) at radio and other wavelengths are best explained by a single massive collapsed object at the galactic centre.

- Elongated structure revealed at 3.6 cm
  - 3/6 RT @ 3.6 cm; 4 RT @ 1.35 cm
    - 3.6cm: 15.5±0.1 mas along p.a.=98±15 deg with an axial ratio=0.55±0.25
    - 1.35cm: 2.1 ±0.3 mas (circular) or 2.2±0.2 mas, 87±30 deg, 0.55±0.5
    - power-law dependence of the size (E-W) on wavelength: 2.0 ±0.1
  - Necessity for a VLBI map!
VLBI observations of Sgr A*

- Interstellar scattering effect dominates the cm-VLBI images of Sgr A* by $\lambda^2$ with an apparent elongated shape in E-W.

\[ \Theta_{\text{obs}}^2 = \Theta_{\text{scat}}^2 + \Theta_{\text{int}}^2 = (A\lambda^2)^2 + \Theta_{\text{int}}^2 \]

wavelengths: 6.0, 3.6, 2.0, 1.35 and 0.7 cm

(Lo et al. 1998)
Mm-VLBI observations of Sgr A*

- Most VLBA data of SgrA* are taken at low elevations (10-20 deg) where atmospheric effects are substantial
  - large absorption due to spectral line transitions of water vapor and oxygen at mm
  - poor spatial resolution in N-S (happen to be along the minor axis)
  - short and variable coherence time

- limited sensitivity of RT (high Tsys and low efficiency)
  ⇒ large uncertainty in the amplitude self-cal

To improve, we need to use the closure amplitude!
STRUCTURE OF SAGITTARIUS A* AT 86 GHz USING VLBI CLOSURE QUANTITIES

S. S. Doeleman,1 Z.-Q. Shen,2,3 A. E. E. Rogers,1 G. C. Bower,4 M. C. H. Wright,5 J. H. Zhao,6 D. C. Backer,5 J. W. Crowley,1 R. W. Freund,7 P. T. P. Ho,6 K. Y. Lo,3 and D. P. Woody8

Received 2000 September 21; accepted 2001 January 24

ABSTRACT

At radio wavelengths, images of the compact radio source Sagittarius A* (Sgr A*) in the Galactic center are scatter broadened with a $\lambda^2$ dependence due to an intervening ionized medium. We present VLBI observations of Sgr A* at 86 GHz using a six station array, including the VLBA antennas at Pie Town, Fort Davis, and Los Alamos, the 12 m antenna at Kitt Peak, and the millimeter arrays at Hat Creek and Owens Valley. To avoid systematic errors due to imperfect antenna calibration, the data were modeled using interferometric closure information. The data are best modeled by a circular Gaussian brightness distribution of FWHM 0.18 ± 0.02 mas. The data are also shown to be consistent with an elliptical model corresponding to the scattering of a point source. The source structure in the north-south direction, which is less well determined than in the east-west direction because of the limited north-south $u$-$v$ coverage of the array, is constrained to be less than 0.27 mas by these measurements. These results are consistent with extrapolations of intrinsic structure estimates obtained with VLBI at a 7 mm wavelength, assuming the intrinsic size of Sgr A* has a greater dependence than $\lambda^{0.9}$ with wavelength.

- 3mm CMVA observations
  - six of the CMVA in April 1999
    - best-fit circular: 0.18±0.02 mas
    - the measured closure phases consistent with zero
  - The importance of the closure amplitude (!)
Detection of the Intrinsic Size of Sagittarius A* Through Closure Amplitude Imaging

Geoffrey C. Bower,¹* Heino Falcke,²,³,⁴ Robeson M. Herrnstein,⁵ Jun-Hui Zhao,⁶ W. M. Goss,⁷ Donald C. Backer¹

We have detected the intrinsic size of Sagittarius A*, the Galactic center radio source associated with a supermassive black hole, showing that the short-wavelength radio emission arises from very near the event horizon of the black hole. Radio observations with the Very Long Baseline Array show that the source has a size of 24 ± 2 Schwarzschild radii at 7-millimeter wavelength. In one of eight 7-millimeter epochs, we also detected an increase in the intrinsic size of 60⁺²⁵⁻₁₀%. These observations place a lower limit to the mass density of Sagittarius A* of 1.4 × 10⁴ solar masses per cubic astronomical unit.

- Intrinsic size detected at 7mm!
- More accurate measurements (using the closure amplitude analysis)
  - Major axis (E-W): 1.41 lambda^2
  - Intrinsic size: 0."70 @ 1.35cm; 0."24 @ 0.69 cm
  - the intrinsic size as a function of wavelength
A size of \( \sim 1 \text{ AU} \) for the radio source Sgr A\(^*\) at the centre of the Milky Way

Zhi-Qiang Shen\(^1\), K. Y. Lo\(^2\), M.-C. Liang\(^3\), Paul T. P. Ho\(^4,5\) & J.-H. Z. Zhang\(^6\)

Although it is widely accepted that the centres of active galaxies and massive black holes at their centres\(^7\) are dominated by supermassive black holes, the existence of Sagittarius A\(^*\) (Sgr A\(^*\))\(^8\), a compact radio source at the centre of our Galaxy, is the best candidate for the existence of a supermassive black hole because it is the closest. Previous very-long-baseline interferometry observations (at 7 mm wavelength) reported a size of \( \sim 2 \text{ AU} \) for Sgr A\(^*\) is \( \sim 2 \) astronomical units (AU) in size\(^9\), but this is still larger than the ‘shadow’ (a remarkably dim inner region encircled by a bright ring) that should arise from general relativistic effects of the event horizon of the black hole. Moreover, the measured size is wavelength dependent\(^10\). Here we report a radio image of Sgr A\(^*\) at a wavelength of 3.5 mm, demonstrating that its size is \( \sim 1 \text{ AU} \). When combined with the lower limit on its mass\(^11\), the lower limit on the upper mass limit is \( 5 \times 10^5 \text{ M}_{\odot} \)\(^12\) (where \( M \) is the solar mass).

### Intrinsic size of 1 AU at 3mm!

- **Dynamic observations in November 2002 with the VLBA**
  - closure amplitude constraint
  - refine 2-D scattering law: \((1.39 \pm 0.02) \lambda^2 \) (E-W);
    \((0.69 \pm 0.06) \lambda^2 \) (N-S)
  - Size of 0.126 and 0.268 mas (or, 1 and 2 AU) at 3 and 7 mm, respectively

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1. 2010
2. Vol 438 3 November 2005/doi:10.1038
3. "A size of \( \sim 1 \text{ AU} \) for the radio source Sgr A\(^*\) at the centre of the Milky Way" by Zhi-Qiang Shen, K. Y. Lo, M.-C. Liang, Paul T. P. Ho, & J.-H. Z. Zhang
4. Nature
5. November 2005

dark mass concentration of $\sim 4.0 \times 10^6 \, M_\odot$ within 90 AU

stellar motion (Schödel et al. 2002; Ghez et al. 2005)

Sgr A* mass $> 0.4 \times 10^6 \, M_\odot$ within 1 AU!

proper motion of Sgr A* (Reid & Brunthaler 2004)

3mm VLBA (Shen et al. 2005)
SgrA*: the best SMBH

The best ever 3mm measurement in Nov 2002 shows a $4\sigma$ deviation from the extrapolated scattering angle along the major axis, indicating an intrinsic size of

$$0.126 \text{ mas},$$

or, $\sim1$ AU @ 8 kpc,

or, $\sim12$ $R_{sc}$ ($4 \times 10^6$ $M_{\odot}$).

Mass density $> 8.0 \times 10^{21} M_{\odot} \text{pc}^{-3}$

($10^{12}$ times higher than any others)
\( \Theta_{\text{int}} \propto \lambda^{1.09(+0.34/-0.32)} \)

- Emission is stratified
- Shadow diameter: \(~5R_{\text{sc}}\)

Shen et al. 2005

Event horizon

Shadow size
Intrinsic size of Sgr A*

The higher the radio frequency – the closer to the black hole. At 230 GHz the emission comes from the event horizon scale.

Falcke & Markoff, Class. & Quant. Gravity (2013)
shadow of Sgr A*

- The diameter of the shadow is about \( \sim 5 \, R_{sc} \) for any BH.

- This corresponds to an angular size of about 50 \( \mu \text{as} \) for 4 million solar masses SMBH Sgr A*. (\( R_{sc} = 0.08 \, \text{AU} = 10 \, \mu \text{as} \))

- At 1 mm, we will clearly see the intrinsic source structure!
  1. The extrapolated intrinsic size is \( \sim 3.5 \, R_{sc} \), or, \( \sim 35 \, \mu \text{as} \).
  2. The scattering size (decreasing as \( \lambda^2 \)) is \( \leq 14 \, \mu \text{as} \).

\[ \Rightarrow \text{SgrA* is the most important target for the sub-mm VLBI experiment to test the GR effect.} \]

SgrA* possibly best (and cheapest) laboratory for strong field GR
Radio astronomers have produced almost all the good, quantitative affirmations of weak field relativity. Why stop now?
Roger Blandford @ SgrA* at 30 in 2004
Simulation of VLBI observations

1. What kind of emission model is appropriate?

2. How does the light bend due to GR effect?

3. What is the scattering effect?

4. At what band can VLBI observations see the shadow?
the RIAF Model with the Size Measurements
(Yuan, Shen & Huang 2006)

- Calculating the intrinsic intensity profile from RIAF: not Gaussian distribution
  - Assumptions: Schwarzschild BH; face-on RIAF

- Ray-tracing calculation + the relativistic effects (gravitational redshift; light bending; Doppler boosting)
  again not Gaussian

- Simulate the observed (apparent) size by taking into account the scattering broadening and compare it with observations
Intrinsic intensity

Scattered

Gaussian fit


Detailed structures near the black hole survive the ISM smoothing at 1.3 mm or shorter. It would be a good test of the presence of black hole.
Simulated image of Sgr A*
(Huang, Cai, Shen, & Yuan, 2007)

North
East
Observer

RIAF model (Yuan et al. 2003)

1.3 mm (ray-tracing) 1.3 mm (scattered) 3.5 mm (ray-tracing) 3.5 mm (scattered)
RIAF: a large inclination angle (i > 60 deg, edge-on case)
Jet+nozzle: a large viewing angle (i >50 deg) (also i>75 deg by Markoff, Bower & Falcke 2007)
Sgr A* as a radiative source

- **Sgr A***: temporally variable source over all the EM bands
  - **Radio**: known to be variable (Brown & Lo 1982), tends to increase its variability towards shorter wavelengths (Herrnstein et al. 2004)
  - **Mm/Sub-mm**: more variable (Wright & Backer 1993; Tsuboi et al. 1999; Zhao et al. 2003; ……)
  - **IR**: shows both long-term (days to weeks) and short-term (~1 hr) variability (Genzel et al. 2003; Ghez et al. 2004; Eckart et al. ……)
  - **X-ray**: violent variation with short duration (hours) (Baganoff et al. 2001; Porquet et al. 2004)
**IDV (Intraday Variability): detection**

- **IDV (Intraday Variability):**
  - NMA@2- & 3-mm (Miyazaki et al. 2004)
  - OVRO@3-mm (Mauerhan et al. 2005)
  - SMA @1-mm (Marrone et al. 2006) ...

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**2000 March 7 at 140 GHz**

flux increased by 30% from 3.5 to 4.7 Jy in 30 minutes
twofold timescale \( \Rightarrow \sim 1.5 \) hrs
(Miyazaki et al. 2004)
IDVs of Sgr A*:  
- Timescale of a few hours, physical scale of ~10AU (150Rsc)  
- Much smaller fractional variation than X-ray/NIR flares

short observing window (~4-6hr/day) for the northern hemisphere telescopes, resulting in incomplete light curves

Nobeyama Millimeter Array (NMA: 6x10m)
Observations: ATCA

- **Australia Telescope Compact Array (ATCA)**
  - 5x22m telescopes
  - ~9 hr per day at elevations >40 deg for Sgr A*
  - Available at 3mm since 2005 October
2 IDV events

- **2006 August 12**: 33% fractional variation in ~2.5 hr
- **2006 August 13**: 2 peaks separated by ~4 hr, and maximum variation of 22% within ~2 hr
Expanding plasmon model
(van der Laan 1966, Yusef-Zadeh et al. 2006, 2007)

- Flare at a given frequency is produced through the adiabatic expansion of an initially optically thick blob
- The initial rise due to the increase of blob’s surface area

particle energy spectral index = 2.2; quiescent flux density = 1.4 Jy

2006 August 12
Expanding velocity: 0.004c
Blob’s radius: 1.8 Rsc
Ne: 1.4x10^6 /cm^3
B: 29 Gauss
T1/2: 5.6 hr

2006 August 13
Expanding velocity: 0.007c, 0.005c, 0.003c
Blob’s radius: 1.9 Rsc
Ne: 1.9x10^6, 5.8x10^6, 2.6x10^6 /cm^3
B: 23, 19, 21 Gauss
T1/2: 3.1, 3.9, 5.3 hr

B=29 Gauss, synchrotron cooling time of ~8hr!
Expanding plasmon model
(van der Laan 1966, Yusef-Zadeh et al. 2006, 2007)

- Flare at a given frequency is produced through the adiabatic expansion of an initially optically thick blob
- The initial rise is related to the increase of blob’s surface
- Taking into account the synchrotron cooling

Particle energy spectral index = 2.2; quiescent flux density = 1.4 Jy

<table>
<thead>
<tr>
<th>Date</th>
<th>( R_0 (\text{r}_p) )</th>
<th>v ( \left( 10^{-3}c \right) )</th>
<th>( N_0 ) ( \left( \text{cm}^{-3} \right) )</th>
<th>( B_0 ) ( \left( \text{Gauss} \right) )</th>
<th>( S_p ) ( \left( \text{mJy} \right) )</th>
<th>( \chi^2 )</th>
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<tbody>
<tr>
<td>2006 Aug 12</td>
<td>2.37(^{+0.3}_{-0.1})</td>
<td>6.0(\pm)0.8</td>
<td>( 8^{+12}_{-7} \times 10^4 )</td>
<td>( 10^{13} )</td>
<td>0.26</td>
<td>1.35</td>
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<tr>
<td></td>
<td>2.9(^{+0.5}_{-0.7})</td>
<td>3.2(\pm)1.2</td>
<td>( 1^{+4}_{-2.8} \times 10^7 )</td>
<td>( 14^{+16}_{-10} )</td>
<td>0.59</td>
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<td>2006 Aug 13</td>
<td>4.2(^{+1.0}_{-0.9})</td>
<td>6.6(\pm)0.2</td>
<td>( 1^{+9.9}_{-2.2} \times 10^6 )</td>
<td>2(^{+23}_{-21} )</td>
<td>0.67</td>
<td>2.69</td>
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<td>2.2(\pm)0.1</td>
<td>5.4(\pm)0.8</td>
<td>( 8^{+2}_{-1} \times 10^7 )</td>
<td>( 9^{+1}_{-2} )</td>
<td>0.66</td>
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<td>1.9(\pm)0.7</td>
<td>5.2(\pm)2.5</td>
<td>( 9^{+2}_{-0} \times 10^7 )</td>
<td>( 9^{+2}_{-2} )</td>
<td>0.48</td>
<td></td>
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Orbiting hot spot model


- The hot spot is an over-density of non-thermal electrons at a certain point of the orbit
- (quasi) periodic variation (e.g. NIR 17 min)
- Rise/decay due to the Doppler shift and beaming of its orbital motion

<table>
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<th>Date</th>
<th>$R (r_g)$</th>
<th>$\omega (\omega_K)$</th>
<th>$N_e (\text{cm}^{-3})$</th>
<th>$B$ (Gauss)</th>
<th>$D (r_g)$</th>
<th>$\chi^2_\nu$</th>
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<tr>
<td>2006 Aug 12</td>
<td>$4.0^{+3.5}_{-1.0}$</td>
<td>$0.35^{+0.15}_{-0.20}$</td>
<td>$5 \times 10^7$</td>
<td>$1^{+7}$</td>
<td>15</td>
<td>3.50</td>
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<tr>
<td>2006 Aug 13</td>
<td>$3.5^{+3.0}_{-0.6}$</td>
<td>$0.6^{+0.05}_{-0.45}$</td>
<td>$2 \times 10^7$</td>
<td>$4^{+5}$</td>
<td>15</td>
<td>12.17</td>
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</tbody>
</table>

Sub-Keplerian!
VLBI structural variability

- Larger (than usual) deviations
- 3 sigma along the minor axis
- Intrinsic sizes derived
  - $0.334 \pm 0.042$ mas (EW)
  - $0.359 \pm 0.095$ mas (NS)
- Intrinsically symmetric
- First detection of intrinsic size along minor axis of 2.87 AU
- Increased (cf. $0.268 \pm 0.025$ mas) by $\sim 30$

@ 7mm on 31 May 1999
possible geometry of the outburst

Assuming Gaussian distribution:
FWHM of flare: $1R_{Sch} - 5R_{sch}$
Fractional amplitude: 30%-50%

active region
accretion flow
7mm radio emission

-- 40 $R_{Sch}$
26.8$R_{Sch}$
Other reported variation of the intrinsic size

- At 7mm in July 2001, a 60% increase in the source intrinsic size from 0.24 to 0.38 mas without a flux density change (Bower et al. 2004)

- At 3.5 mm, Krichbaum et al. (2006) reported large apparent diameter (circular) at two epochs:
  
  Apr 1997: 0.28 ± 0.08 mas (w/o flux change)
  Oct 2005: 0.27 ± 0.05 mas (with flux increase)

  compared to the best-fit circular diameter of 0.18 ± 0.02 mas
A firm detection at 1.3mm!

- 230 GHz VLBI Observations in April 2007 with three antennas
  - Detected on two baselines (SMT-JCMT, SMT-CARMA)
  - Not detected on the baseline JCMT-CARMA
  - Size of 37(+16/-10) micro arcsec at 1.3 mm.
- SgrA* arises in a region offset from the SMBH, compact portion of AD/jet?
Horizon-scale structure in Sgr A*

About 4 Schwarzschild radii across

1.3 mm emission offset from the BH

\[ \rho = 10^{23} M_\odot pc^{-3} \]

(Doeleman et al. 2008, Nature)
Current development: The Event Horizon Telescope

- Mauna Kea, Hawaii:
  - SMA (~8 x 6-m, single polarization)
  - JCMT (15-m, single polarization)

- Mount Graham, Arizona:
  - SMT (10-m, dual polarization)

- Inyo Mountains, California:
  - CARMA (5 x 10-m + 3 x 6-m, dual polarization; 10-m, dual polarization, reference)

- Sierra Negra, Mexico: LMT (50-m)

- Atacama desert, Chile, APEX, (12-m)
- Atacama desert, ALMA, (85-m)

- Pico Veleta (Sierra Nevada, Spain, 30-m)
- Plateau de Bure (France, 37-m)

- South Pole Telescope (10-m)
- Greenland Telescope (12-m)

new test observations at 0.8mm!

The EHT as viewed from Sgr A*
EHT: Adding baselines

- CARMA
- SMT
- GLT
- LMT
- ALMA
- SPT
- PdBI
- PV
- Hawaii
SgrA* flares on $R_{\text{sch}}$ scales

(Fish et al, 2011, ApJL)
Observation/data summary

- 2007: SMT + 1 CARMA + JCMT
  (Sgr A*: Doeleman et al. 2008, Nature)
- 2009: SMT + 2 CARMA + JCMT
- 2010: SMT + phased/ref SMA (+ ASTE)
  test observations for phased-array processor
- 2011: SMT + phased/ref CARMA + phased/ref Hawaii (+APEX +IRAM 30 m)
- 2012: SMT + phased/ref CARMA + phased SMA +JCMT
  dual pol at 3 sites (M87: Akiyama et al. close to submission)
- 2013: SMT + phased/ref CARMA + phased SMA +JCMT + APEX + PdBI +PV
  dual pol at 3 US sites+ PV (data reduction underway)
  New fringes to LMT(@3mm with VLBA, 2013/2014)
KaVA 43 GHz monthly monitoring of Sgr A*

- KaVA: KVN (3x21m) and VERA (4x20m)
- 7 stations, baseline lengths: 300-2300 km
- Monitoring started in early 2013
  (KaVA AGN KSP since September 2014)

Configuration

UV Coverage for Sgr A*

KaVA

inner part of VLBA
SgrA*: the closest SMBH candidate with the largest angular size of its event horizon (1 mas = 8 AU at D=8 kpc; $R_{sc} = 2GM_{\bullet}/c^2 = 0.08$ AU = 10 μas)

The (sub)mm-VLBI array (EHT) is growing fast (new detections, 16GBPS, 345 GHz)

New observations point towards “complex” and extremely compact structures in Sgr A*

Future EHT imaging of Sgr A* is a key to questions
- SMBH nature (shadow)
- Spin (break in the wavelength-dependent intrinsic size)
- Geometry of the accretion flow or jet
The quest for high resolution VLBI

typical resolution
(ground-based):

\[ \frac{\lambda}{D} \text{ (cm)} \sim 0.5 \text{ mas} \]

for a given frequency (e.g., maser sources),
resolution can be improved only by increasing D (space VLBI)

Both are challenging, but feasible

future: space (sub)mm-VLBI
The Chinese Space VLBI Array

A Science-Driven Mission

(unanswered question; broader impact; unique to space VLBI)

To be Supported by Advanced and Mature Technologies

Circa 2020
Main Scientific Objectives:

- High-resolution imaging of emission structure surrounding super-massive black hole (SMBH) to study
  - SMBH Shadow (e.g. M87)
- Disk structure & dynamics, SMBH mass (water mega-masers)
- Astrophysical Jet in Active Galactic Nuclei (AGN)

Specifications:

- Two 10-m (in diameter) space antennas
- Three frequency bands (8, 22 & 43 GHz)
- Dual polarization (LCP/RCP)
- Date rate (1.2 Gbps, or 2.4 Gbps)
- Angular resolution: 20 micro-arc-second
- Optimized orbits for a better (u,v) coverage
  - Apogee: 60,000 km
  - Perigee: 1,200 km
  - Inclination: 28.5 deg
- Life time: 3 year
Sciences vs. Payloads

1. Black Hole Imaging (M87)
2. Disk Structure and dynamics, mass of SMBH
3. Jets in AGNs (formation, acceleration & collimation; B-field; gamma-ray)

1. Space Antenna
   - Q-Band 40–46 GHz
   - K-Band 20–24 GHz
   - X-Band 6–9 GHz

3. On-board H-maser

2. Receiving system

4. Data Trans

3. Time & Frequency

5. Laser reflector

Ground VLBI Sta

SLR

Correlator output

Up-link
Supermassive Black Hole (SMBH) - M87

The longest baseline (>60,000 km) between the proposed Chinese Space VLBI satellites and collaborating ground stations will provide a high angular resolution of ~20 micro as (at 43 GHz) and sufficient sensitivity to support:

- Mapping of the emission structures surrounding SMBHs (mainly M87)
- Direct detection and imaging of the shadow (dark region) of M87
  - Distance 14.7 Mpc
  - Central SMBH with ~3.2 x 10^9 M☉
  - Apparent shadow size ~26 μas
The Best Two Potential Candidates

× Sgr A* (angular size $\theta_g \sim 6.5 \, \mu\text{as}$)

This candidate is ruled out due to its high scattering noisy background in the galaxy.

✓ M87 (angular size $\theta_g \sim 4 \, \mu\text{as}$)

This is probably the best SMBH candidate for space VLBI imaging and analysis with a reasonably large angular size and relatively clean environ.
Supermassive Black Hole (SMBH) - M87

Image of M87 obtained with the ground VLBI array (VLBA)

Image of M87 obtained with a VSOP-ground configuration (~ 490 μas res.) in comparison with the 20 μas res. of the proposed Chinese Space VLBI satellite-ground configuration
Shanghai 65m Radio Telescope

- 65-m in diameter, fully steerable radio telescope
- Active surface system installed (3rd in the world)
- Covering 1 - 50 GHz with 8 bands
  - L (1.6GHz), S/X (2.3/8.4GHz), C (5GHz), Ku (15GHz), K (22GHz), X/Ka (9/30GHz), Q (43GHz)
- Sensitivity & frequency coverages enable a wide-range of science
- State-of-the-art detector suite for spectroscopy, pulsar observations, continuum, VLBI
Project Timeline

• 2008: funded; contract to CETC54 for the antenna construction
• 2009: complete design (international review panel); start manufacturing; foundation laying ceremony on December 29
• 2010-11: site construction started on March 19, 2010; foundation completed; antenna construction (wheel-on-track, BUS, alidade, panels, …); active surface system (contract, design, fabrication, installation of actuators)
• 2012-13: L, S/X and C band Rxs in place; first light on October 26, 2012 & inauguration 2 days later; start commissioning; got named TianMa on December 2, 2013; participation in the Chinese Lunar Mission (ChangE); DIBAS installed & tested
• 2014-15: on-site system testing; science observation at L/S/C/X; active surface tested; Ku, X/Ka, K and Q band commissioning; project accomplished!
First light on October 26, 2012
Testing observations
Open Use of the TianMa Telescope

- As a VLBI station, join world-wide networks:
  - EVN, IVS, VLBA, EA-VLBI, CVN

- As a single dish, open to the world
  - 1st "Call for proposal" for pulsar observation made on Sept. 15, 2014
    - 22 proposals received,
    - PIs from 7 institutes, co-Is from 12 (domestic) + 3 (oversea)
  - 2nd "Call for proposal" for spectroscopic observation made on Dec. 29, 2014
    - 16 proposals received,
    - PIs from 5 institutes, co-Is from 8 (domestic) + 2 (oversea)
  - Goal is to operate TM with an open access driven by scientific merit!
Thanks!