1.3 and 3 mm wavelength VLBI: probing the Event-Horizon to AU structure of Sgr A* 

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Sgr A*: black hole candidate

$M \approx 4 \times 10^6 \, M_\odot$ (Ghez et al. 2003)

$d \approx 8 \, \text{kpc}$ (Reid et al. 2009)
• Which **emission mechanism** operates in Sgr A*?
  
  – processes in the **accretion flow** itself?
  – **jet/outflow** originating in the accretion disk?

• Which are the evidences in favor of jets/accretion flow?
Radio properties of Sgr A*

- Linear polarization: ~10% in the sub-mm
- Variability: on time scales of days
- High brightness temperature
- Spectrum:

  Typical spectrum seen in some nearby low-luminosity galaxies

- Synchrotron emission from the jet
- Emission from the accretion flow
- Melia & Falcke 2001
Very Long Baseline Interferometry

Ultra-high angular resolution

$$\theta \sim \frac{\lambda}{B}$$

M87 jet:
VLBA, 43 GHz
Interstellar scattering

Observer

~133 pc (Lazio & Cordes 1998)
5.8±0.3 kpc (Bower et al 2014)

Galactic Center
Angular broadening of Sgr A* observed size $\propto \lambda^2$

$1.31 \text{ mas cm}^{-2} \times 0.64 \text{ mas cm}^{-2}$; P.A. $\sim 80^\circ$ (Bower et al 2006)

\[
\theta_{\text{int}} = \sqrt{\theta_{\text{meas}}^2 - \theta_{\text{scat}}^2}
\]
Determination of the intrinsic size

- Affected by poor north-south resolution of the VLBA

THE INTRINSIC TWO-DIMENSIONAL SIZE OF SAGITTARIUS A*

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ABSTRACT

We report the detection of the two-dimensional structure of the radio source associated with the Galactic Center black hole, Sagittarius A*, obtained from Very Long Baseline Array observations at a wavelength of 7 mm. The intrinsic source is modeled as an elliptical Gaussian with major-axis size $35.4 \times 12.6 \, R_S$ in position angle $95^\circ$ east of north. This morphology can be interpreted in the context of both jet and accretion disk models for the radio emission. There is supporting evidence in large angular-scale multi-wavelength observations for both source models for a preferred axis near $95^\circ$. We also place a maximum peak-to-peak change of 15% in the intrinsic major-axis size over five different epochs. Three observations were triggered by detection of near infrared (NIR) flares and one was simultaneous with a large X-ray flare detected by NuSTAR. The absence of simultaneous and quasi-simultaneous flares indicates that not all high energy events produce variability at radio wavelengths. This supports the conclusion that NIR and X-ray flares are primarily due to electron excitation and not to an enhanced accretion rate onto the black hole.

- Intrinsic size is likely not circular
3 mm VLBI

- The **Large Millimeter Telescope** (LMT)
  - High sensitivity antenna
  - Active surface for optimal operation at millimeter wavelengths

Altitude: 4,600 m
3 mm VLBA+LMT observations

- **LMT**
  - Superb geographical location relative to VLBI stations
  - Three observing seasons successfully completed
  - Robust operation as a VLBI station

![VLBI backend](image)
1.3 mm VLBI with the LMT

The Event Horizon Telescope

black hole shadow

Doeleman et al

Broderick et al 2011
Measuring the size of Sgr A* 

3 mm: variable antenna gain and variable atmospheric opacity 
Miscalibrated data affect reconstructed images
Measuring the size of Sgr A*

Closure quantities: independent of all station-dependent errors

\[ \phi_{123} = \phi_{12} + \phi_{23} + \phi_{31} \]

\[ C_{1234} = \frac{A_{12}A_{34}}{A_{13}A_{24}} \]

closure phase

closure amplitude
Intrinsic size

major = (144.8±7.0) \( \mu \)as

minor = (125.7±5.8) \( \mu \)as

Axial ratio

1.15±0.08
Frequency-dependent intrinsic size

\[ \beta = 1.34 \pm 0.01 \]

\[ \beta = 1.0 \pm 0.1 \]
Implications for jet models

• Intrinsic structure of Sgr A* at 3 mm is symmetric.
  – Rule-out jet models that predict an elongated morphology (axial ratio 4:1)

• Models should reproduce:
  – Frequency-dependent intrinsic size
  – Frequency-dependent anisotropy

![Graph showing relative positions and 1.6 AU scale]
Closure phases

V. Fish slide, EHT 2014
Closure phases

closure phases from 2015 LMT+VLBA observations are close to zero

EHT, 1.3 mm
California-Hawaii-Arizona triangle: nonzero median closure phase weighted mean: 6.5 ± 0.7 deg

Fish et al in prep
The addition of the GBT

- Measurement of small closure phases at 3 mm
- Study structural variability in Sgr A*
The addition of the GBT

VLBA+LTM+GBT baseline tracks

Scattering is invertible
Mitigation of scattering

1.3 mm EHT simulated image
Convolved with scattering kernel
uncorrected
corrected

Fish et al 2014
Image reconstruction of Sgr A*

3 mm VLBA+LMT data

Andrew Chael et al
Summary

• The addition of the LMT to the VLBI network has allowed precise measurement of the intrinsic size of Sgr A* at $\lambda=3$ mm.

• The intrinsic structure of Sgr A* at $\lambda=3$ mm is symmetric, with important implications in the context of jet models.

• LMT participated in the EHT run at 1.3 mm.

• The addition of the GBT will expand the capability to study structure variability, and to reconstruct images of the source.