Two epochs VLBA Imaging of Sgr A* at 86 GHz

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In collaboration with

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- M.-C. Liang (Caltech/ASIAA)
Sgr A* - as a gravitational source

- dark mass $\sim 3 \times 10^6 \, M_{\odot}$ within a radius of 15 mas = 120 AU = 2000 $R_{\odot}$
  (motions of *s like S0-2)
- $M_{SgrA^*} > 4 \times 10^5 \, M_{\odot}$
  (motions of Sgr A* itself)
Sgr A* - as a radiative source

- X-ray flaring of 200 – 900 sec rise/fall timescales
  \[ \Rightarrow 7 - 30 \, R_{\text{sch}} \text{ or } 0.05 - 0.2 \, \text{mas} \]
  (Chandra and XMM-Newton)

- IR flares of 30 – 40 min
  \[ \Rightarrow 5 \, \text{AU (80} \, R_{\text{sch}}) \text{ or } 0.6 \, \text{mas} \]
  (VLT and Keck)

- Correlated radio/X-ray variation (Zhao et al 04’)
  \[ \Rightarrow r_{\text{Radio}} > r_{\text{X-ray}} = 7 \, R_{\text{sch}} \text{ or } 0.05 \, \text{mas} \text{ At 30} \]
Interstellar scattering effect dominates the cm-VLBI images of SgrA* by $\lambda^2$—law, with an *apparent* E-W elongated shape.

- need for the mm-VLBI
Mm-VLBI Observations of Sgr A*

- The mm-VLBI plagued by 2 facts
  - southerly Dec of SgrA* (~ - 30°)
  - northern lat. for most mm-VLBI antennas
Uptime plot of VLBA Observations of Sgr A*
(u,v) coverage of VLBA
Observations of Sgr A*
Mm-VLBI Observations of Sgr A*

- The mm-VLBI plagued by 2 facts
  - southerly Dec of SgrA* (~ - 30°)
  - northern lat. for most mm-VLBI antennas

- lack of spatial resolution in N-S ( = minor axis)
- severe atmospheric effects on data calibration
  (large and variable opacity, short and variable $T_{coh}$)

- compromised sensitivity at mm-band
  (high $T_{sys}$: >100 K at zenith; low antenna efficiency: < 45%)
How to improve

- During the observations
  - dynamic scheduling -> best weather condition
  - compact SiO masers for amp cal and pointing

- During the data analysis
  - closure amplitudes to constrain the model-fitting
1st epoch 3mm VLBA Observation

- Nov 3, 2002 (dynamic since Feb 2001)
- 512 Mbps (highest recording rate)
- Frequent pointing check (every 15 min)
- Very good detections among 5 antennas (FD/KP/LA/OV/PT), plus some to NL
- First 3mm VLBI image of SgrA*
1st epoch 3mm VLBA Observation

- Very good detections among 5 antennas (FD/KP/LA/OV/PT), plus some to NL
1st epoch 3mm Observation

- First 3mm VLBI image of SgrA*

- Unresolved (no extended structure) → single component
- Zero closure phases
- ~ E-W elongated emission → consistent with $\lambda \geq 7$mm data
Model-fitting using the closure amplitude constraints

- $\chi^2$ – minimization algorithm

$$\chi^2 = \sum_t \sum_{ij} w_{ij} \left| A_{ij}^{\text{obs}}(t) - G_i(t) G_j(t) A_{ij}^{\text{mod}}(t) \right|^2$$

Here, the visibility amplitude $A_{ij}$ is used, "good observable" - the closure amplitude is conserved by assuming an antenna-dependent gain $G_i$ only.

This is equivalent to the use of closure quantities!

\[ C_{ijkl} = \frac{A_{ij} A_{kl}}{A_{ik} A_{jl}} \]
**Bias Correction**

The measured visibility amplitude \(<Z>\) has a **positive bias** with respect to the true amplitude \(A\)

\[
< Z > \approx A \left( 1 + \frac{\sigma^2}{2A^2} \right) \quad \text{(strong signal : } A \gg \sigma \text{)}
\]

\[
< Z > \approx \sigma \sqrt{\frac{\pi}{2}} \left( 1 + \frac{A^2}{4\sigma^2} \right) \quad \text{(weak signal : } A \ll \sigma \text{)}
\]

Here, \(\sigma\) is the rms deviation of a single component of the complex noise vector. This is **big at low SNR \(\lesssim 3\)**, but can be corrected (see Thompson, Moran, & Swenson 1986).

However, it is difficult to estimate the unbiased \(C_{ijkl}\) and thus to treat its formal error properly if we fit the closure amplitude directly (see Trotter, Moran, & Rodriguez 1998).
Model-fitting procedure

- \( \chi^2 \) – minimization algorithm

- Bias correction to the measured visibility amplitude \( A_{ij}(t) \)

- Determination of the antenna-based gain \( G_i \) from the observed visibility amplitude \( \tilde{A} \) and the given model \( \tilde{A} \) at each time \( t \)

- Comparison of \( \chi^2 \) for different model \( \tilde{A} \) to get the best fit model

- Error estimate from the \( \chi^2 \) distribution

  \[ 1 \sigma (68.3\% \text{ confidence}): \chi^2(\text{min}) \rightarrow \chi^2(\text{min}) + \chi^2(\text{min}) / N_{\text{dof}} \]
Application to DA193

- DA193 (z=2.365)

GPS source

VLBI calibrator

At 30
Application to DA193

DA193: VLBI calibrator


\[
\text{DR} = 115,000:1
\]

fit with a single Gaussian

\[
0.904 \times 0.514 \, \text{mas} \at 109.5^\circ
\]
Application to DA193

- DA193: EVN+Sh+Ur+Hart (Nov 7, 1997)

  - Standard VLBI self-calibration imaging and model-fitting
    - 0.82 x 0.64 mas @ 111°

  - Our procedure
    - 0.82 x 0.48 mas @ 108°

At 30
1st epoch 3mm Observation

- major axis: 0.21 (+0.02 / -0.01) mas
1st epoch 3mm Observation

- Minor axis: 0.13 (+0.05 / -0.13) mas and PA: 79° (+12° / -33°)

Surface plot of Chi^2 as a function of both minor axis and PA (major axis = 0.21 mas).

Contour plot showing the Confidence intervals of 68.3% and 90.0%.
1st epoch 3mm Observation

- Model fitting:
  - Single elliptical Gaussian
    - major axis: 0.21 (+0.02 / -0.01) mas
    - minor axis: 0.13 (+0.05 / -0.13) mas
    - position angle: 79° (+12° / -33°)
  - Best Circular Gaussian
    - FWHM: 0.20-0.21 mas

At 30
2nd epoch 3mm VLBA Observation

- Observations on Sept 28, 2003
  - 512 Mbps; pointing check every 15 min
  - gust @OV, tape (recording, playback)@KP, PT

Image (preliminary)
2nd epoch 3mm Observation

- Model fitting:
  - Single elliptical Gaussian
    - major axis: 0.21 (+0.01 / -0.01) mas
    - minor axis: 0.00 - 0.13 mas
    - position angle: 87° (+12° / -9°)
  - Best Circular Gaussian
    - FWHM: 0.20 mas
**Apparent** SgrA* structure at 3mm: elongated roughly along E-W with a major axis size of 0.21 mas

<table>
<thead>
<tr>
<th>Date</th>
<th>Observable Parameters</th>
<th>Circular Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 Apr, CMVA (Doeleman et al 2001)</td>
<td>0.34(+/-0.14), 0.17(+/-0.02), 22(+/-20)</td>
<td>0.18(+/-0.02)</td>
</tr>
<tr>
<td>2002 Nov, VLBA</td>
<td>0.21(+0.02/-0.01), 0.13(+0.05/-0.13), 79(+13/-33)</td>
<td>0.20 - 0.21</td>
</tr>
<tr>
<td>2003 Sept, VLBA</td>
<td>0.21(+0.01/-0.01), 0.00-0.13, 87(+12/-9)</td>
<td>0.20</td>
</tr>
</tbody>
</table>
**Discussion**

- **Intrinsic structure of SgrA* emission**

  The best ever measurement in Nov 2002 shows a $3\sigma$ deviation from the extrapolated scattering angle of $0.175 \pm 0.003$ mas along the major axis. If confirmed, this indicates an intrinsic size of $0.116$ mas, or $\sim 1$ AU at $8$ kpc, or $\sim 17$ Rsch ($3 \times 10^6 M_{\odot}$).

  Intrinsic Tb $\sim 1.5 \times 10^{10}$ K (non-thermal origin)
### Discussion – 7mm data

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Ctr Freq(+BW) GHz (+ MHz)</th>
<th>S (Jy)</th>
<th>Major axis (mas)</th>
<th>Minor axis (mas)</th>
<th>P.A (degree)</th>
<th>Reduced chi^2</th>
<th>SC-HN</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994.32</td>
<td>43.151 (64)</td>
<td>1.4</td>
<td>0.72 +/- 0.01</td>
<td>0.39 +/- 0.07</td>
<td>78 +/- 2</td>
<td>1.11</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>1994.75</td>
<td>43.151 (64)</td>
<td>1.3</td>
<td>0.72 +/- 0.01</td>
<td>0.42 +/- 0.03</td>
<td>79 +/- 1</td>
<td>1.17</td>
<td>yes</td>
<td>Bower &amp; Backer 1998</td>
</tr>
<tr>
<td>1997.12</td>
<td>43.213 (32)</td>
<td>1.0</td>
<td>0.71 +/- 0.01</td>
<td>0.42 +/- 0.05</td>
<td>74 +/- 2</td>
<td>2.89</td>
<td>no</td>
<td>Lo et al 1998; dual pol</td>
</tr>
<tr>
<td>1999.31</td>
<td>43.135 (32)</td>
<td>1.0</td>
<td>0.69 +/- 0.01</td>
<td>0.33 +/- 0.04</td>
<td>83 +/- 1</td>
<td>0.97</td>
<td>yes</td>
<td>1.26 x 0.44 @ 7°</td>
</tr>
<tr>
<td>1999.39</td>
<td>43.135 (32)</td>
<td>1.5</td>
<td>0.71 +/- 0.01</td>
<td>0.44 +/- 0.02</td>
<td>79 +/- 1</td>
<td>1.59</td>
<td>yes</td>
<td>1.35 x 0.48 @ 11°</td>
</tr>
<tr>
<td>1999.41</td>
<td>43.135 (32)</td>
<td>1.5</td>
<td>0.75 +/- 0.01</td>
<td>0.49 +/- 0.05</td>
<td>70 +/- 3</td>
<td>0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001.58</td>
<td>39.135 (32)</td>
<td>1.6</td>
<td>0.86 +/- 0.01</td>
<td>0.54 +/- 0.03</td>
<td>78 +/- 1</td>
<td>1.54</td>
<td>39 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45.135 (32)</td>
<td>1.5</td>
<td>0.66 +/- 0.01</td>
<td>0.42 +/- 0.04</td>
<td>75 +/- 3</td>
<td>1.31</td>
<td>45 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.8-43.1 (32)</td>
<td>0.9</td>
<td>0.74 +/- 0.01</td>
<td>0.47 +/- 0.14</td>
<td>77 +/- 6</td>
<td>3.41</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

Average over 7 epochs: major 0.72 +/- 0.02 mas
minor 0.42 +/- 0.04 mas
P.A. 77 +/- 3 deg

At 30
Discussion – 7mm data

P.A.

Major axis

Minor axis

At 30
Discussion – past SgrA* size measurements

Table 1. Summary of published Sgr A* size measurements

<table>
<thead>
<tr>
<th>Epoch (yrs)</th>
<th>SEDIV (Jy)</th>
<th>$\theta_{\text{major}}$ (mas)</th>
<th>$\theta_{\text{minor}}$ (mas)</th>
<th>Axial Ratio</th>
<th>P.A.</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda = 35.6$ mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1971.10</td>
<td>0.73±0.10</td>
<td>18.0±1.53</td>
<td>9.88±1.68</td>
<td>0.55±0.14</td>
<td>78±6</td>
<td>Lo et al. (1998)</td>
</tr>
<tr>
<td>1991.90</td>
<td>17.5±0.5</td>
<td>8.5±1.0</td>
<td>0.49±0.06</td>
<td>87±5</td>
<td>Lo et al. (1993)</td>
<td></td>
</tr>
<tr>
<td>1983.36</td>
<td>16.1±0.3</td>
<td>16.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td>Marcaide et al. (1992)</td>
</tr>
<tr>
<td>1983.35</td>
<td>15.5±0.1</td>
<td>0.55±0.25</td>
<td>98±15</td>
<td></td>
<td></td>
<td>Lo et al. (1985)</td>
</tr>
<tr>
<td>1982.30</td>
<td>17.4±0.5</td>
<td>0.53±0.10</td>
<td>82±6</td>
<td></td>
<td></td>
<td>Jauncey et al. (1989)</td>
</tr>
<tr>
<td>1978.07</td>
<td>0.7</td>
<td>18±2</td>
<td>18</td>
<td>1.0</td>
<td></td>
<td>Lo et al. (1981)</td>
</tr>
<tr>
<td>1976.18</td>
<td>0.9±0.06</td>
<td>14±2</td>
<td>14</td>
<td>1.0</td>
<td></td>
<td>Lo et al. (1977)</td>
</tr>
<tr>
<td>1975.38</td>
<td>0.6±0.1</td>
<td>10±2</td>
<td>10</td>
<td>1.0</td>
<td></td>
<td>Lo et al. (1975)</td>
</tr>
<tr>
<td>1974.50</td>
<td>17.0</td>
<td>17.0</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda = 13.5$ mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997.10</td>
<td>0.74±0.04</td>
<td>2.70±0.15</td>
<td>1.50±0.59</td>
<td>0.56±0.25</td>
<td>81±11</td>
<td>Lo et al. (1998)</td>
</tr>
<tr>
<td>1992.85</td>
<td>1.05±0.10</td>
<td>2.67±0.15</td>
<td>1.63±0.41</td>
<td>0.61±0.12</td>
<td>79±10</td>
<td>Marcaide et al. (1999)</td>
</tr>
<tr>
<td>1991.49</td>
<td>0.98±0.05</td>
<td>2.6±0.2</td>
<td>1.3</td>
<td>0.5</td>
<td>87</td>
<td>Lo et al. (1993)</td>
</tr>
<tr>
<td>1991.47</td>
<td>1.07±0.15</td>
<td>2.60±0.20</td>
<td>1.30±0.88</td>
<td>0.5±0.3</td>
<td>80±15</td>
<td>Alberdi et al. (1993)</td>
</tr>
<tr>
<td>1985.11</td>
<td>1.2±0.4</td>
<td>1.8±0.09</td>
<td>1.8</td>
<td>1.0</td>
<td></td>
<td>Marcaide et al. (1992)</td>
</tr>
<tr>
<td>1983.47</td>
<td>0.98±0.03</td>
<td>2.2±0.2</td>
<td>1.21±0.21</td>
<td>0.53±0.5</td>
<td>87±30</td>
<td>Lo et al. (1985)</td>
</tr>
<tr>
<td>$\lambda = 6.9$ mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997.10</td>
<td>1.03±0.01</td>
<td>0.70±0.01</td>
<td>0.58±0.07</td>
<td>0.83±0.11</td>
<td>87±8</td>
<td>Lo et al. (1998)</td>
</tr>
<tr>
<td>1994.75</td>
<td>1.28±0.10</td>
<td>0.76±0.04</td>
<td>0.55±0.11</td>
<td>0.7±0.10</td>
<td>77±7</td>
<td>Bower &amp; Backer (1998)</td>
</tr>
<tr>
<td>1992.62</td>
<td>2.10±0.10</td>
<td>0.74±0.03</td>
<td>0.46±0.20</td>
<td>0.54±0.29</td>
<td>90±10</td>
<td>Backer et al. (1993)</td>
</tr>
<tr>
<td>1992.40</td>
<td>1.42±0.10</td>
<td>0.75±0.08</td>
<td>0.75</td>
<td>1.0</td>
<td></td>
<td>Krichbaum et al. (1993)</td>
</tr>
<tr>
<td>$\lambda = 3.5$ mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999.27</td>
<td>1.4</td>
<td>0.34±0.14</td>
<td>0.17±0.02</td>
<td>0.50±0.26</td>
<td>22±20</td>
<td>Doelman et al. (2001)</td>
</tr>
<tr>
<td>1995.18</td>
<td>1.4</td>
<td>0.18±0.02</td>
<td>0.18</td>
<td>1.0</td>
<td></td>
<td>Doelman et al. (2001)</td>
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<tr>
<td>1994.25</td>
<td>1.80±0.30</td>
<td>0.19±0.03</td>
<td>0.19</td>
<td>1.0</td>
<td></td>
<td>Krichbaum et al. (1998)</td>
</tr>
<tr>
<td>1993.27</td>
<td>1.25±0.35</td>
<td>0.22±0.10</td>
<td>0.22</td>
<td>1.0</td>
<td></td>
<td>Krichbaum et al. (1999)</td>
</tr>
</tbody>
</table>
**Discussion – reanalysis of the archived VLBI data**

<table>
<thead>
<tr>
<th>$\lambda$ (cm)</th>
<th>major (mas)</th>
<th>minor (mas)</th>
<th>p.a. (deg)</th>
<th>Resolution (mas x mas @ deg)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.03</td>
<td>43.0 +2.5/-1.0</td>
<td></td>
<td></td>
<td>21 x 12 @ 4</td>
<td>Only 1 epoch data!</td>
</tr>
<tr>
<td>3.56</td>
<td>17.5 +0.5/-1.0</td>
<td>8.50 +/- 1.0</td>
<td>87 +/- 3</td>
<td>12.5 x 6.5 @ 5</td>
<td></td>
</tr>
<tr>
<td>1.96</td>
<td>5.33 +/- 0.07</td>
<td>2.70 +/- 0.30/-0.44</td>
<td>83 +/- 3</td>
<td>9.5 x 3.9 @ 26</td>
<td>1 epoch only!</td>
</tr>
<tr>
<td>1.35</td>
<td>2.53 +/- 0.06/-0.05</td>
<td>1.45 +/- 0.23/-0.38</td>
<td>83 +/- 4/-5</td>
<td>6.4 x 2.3 @ 24</td>
<td></td>
</tr>
<tr>
<td>0.69</td>
<td>0.72 +/- 0.02</td>
<td>0.42 +/- 0.04</td>
<td>77 +/- 3</td>
<td>1.6 x 0.5 @ 10</td>
<td>Errors from the scatter of 7 epochs data</td>
</tr>
<tr>
<td>0.35</td>
<td>0.21 +/- 0.02/-0.01</td>
<td></td>
<td>79 +12/-33</td>
<td>1.1 x 0.3 @ 9</td>
<td>Minor axis poor</td>
</tr>
</tbody>
</table>
Scattering law revisited

Major axis: \((1.39 \pm 0.02) \lambda^2\)

Minor axis: \((0.70 \pm 0.06) \lambda^2\)

Fit to all: \((0.76 \pm 0.05) \lambda^2\)
Summary

- First 3mm VLBA image of Sgr A* shows an E-W elongated structure, consistent with the morphology observed at other longer $\lambda$.

- A $3\sigma$ deviation from the extrapolated scattering angle of 0.175 mas at 3mm (from the current $1.43\ \lambda^2$) may suggest an intrinsic size of 1 AU along E-W at 3mm.

- Investigation of the archived multi-wavelength data suggests a slightly smaller scattering effect of $1.39\ \lambda^2$.

- The current scattering law needs to be re-examined with more measurements at both short (mm) and long (cm) wavelengths.