High-resolution polarimetric study of Sgr A* with the GMVA

Michael Janssen
Radboud University Nijmegen

in collaboration with:


and

I. van Bemmel, M. Kettenis, D. Small
Outline

- Recent results of 3mm VLBI studies of Sgr A*:  
  → Closure amplitude – source shape  
  → Closure phase – source asymmetry

- Polarization properties of Sgr A* & upper limit for LP at 3mm on VLBI scales

- CASA as a VLBI data calibration tool:  
  Recent developments & a future pipeline
Sgr A* at mm wavelengths

Falcke & Markoff 2000: jet model

Narayan & Mahadevan 1995: disk model
Sgr A* at mm wavelengths

Falcke & Markoff 2000: jet model
Narayan & Mahadevan 1995: disk model
Mościbrodzka et al. 2014
Sgr A* at mm wavelengths

Mościbrodzka et al. 2014

Doeleman et al. 2008
VLBI observations of Sgr A* at 3mm

- Ortiz-León et al. 2016: VLBA+LMT from April 2015, single pol
- Brinkerink et al. 2016 and Müller et al. 2017 (in prep.): VLBA+GBT+LMT from May 2015, single pol
- Janssen et al. 2017 (in prep.): GMVA (this talk: only VLBA+GBT) from May 2016, dual pol and full-Stokes correlation

The Global Millimeter VLBI Array (GMVA)

Imaging with $\sim$45 $\mu$as resolution at 86 GHz

Baseline Sensitivities

in Europe:
30 – 250 mJy

in US with GBT:
50 – 250 mJy

best transatlantic:
30 – 100 mJy

Array:
0.5 – 1 mJy / hr

(assume 7$\sigma$, 100 sec, 2 Gbps)

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsahovi (14m), Yebees (40m), KVN (3 x 21m), planned: SRT, NOEMA, ...
- America: 8 x VLBA (25m), GBT (100m), planned: LMT, ALMA, ...

Proposal deadlines: February 1st, August 1st

Taken from Thomas Krichbaum
VLBI observations of Sgr A* at 3mm Imaging & closure amplitudes

<table>
<thead>
<tr>
<th></th>
<th>BD183C</th>
<th>BD183D</th>
<th>Doeleman+(01)</th>
<th>Shen+(05)</th>
<th>Lu+(11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closure Amp.</td>
<td>214.9 ± 4.0 μas</td>
<td>217.7 ± 5.0 μas</td>
<td>217 ± 3.6 μas</td>
<td>180 ± 20 μas</td>
<td>210 ± 10 μas</td>
</tr>
<tr>
<td>Self-Calib.</td>
<td>212.7 ± 2.3 μas</td>
<td>217.7 ± 5.6 μas</td>
<td>217 ± 3.6 μas</td>
<td>...</td>
<td>130 ± 10 μas</td>
</tr>
<tr>
<td>Minor axis</td>
<td>139.0 ± 8.1 μas</td>
<td>147.3 ± 8.0 μas</td>
<td>145.6 ± 4.0 μas</td>
<td>...</td>
<td>83 ± 1.5 μas</td>
</tr>
<tr>
<td>Major axis</td>
<td>214.9 ± 4.0 μas</td>
<td>217.7 ± 5.0 μas</td>
<td>217 ± 3.6 μas</td>
<td>180 ± 20 μas</td>
<td>210 ± 10 μas</td>
</tr>
<tr>
<td>P.A.</td>
<td>80°8 ± 3°2</td>
<td>80°7 ± 4°8</td>
<td>75°2 ± 2°5</td>
<td>79° ± 12°</td>
<td>83° ± 1°5</td>
</tr>
<tr>
<td>Axial ratio</td>
<td>1.55 ± 0.08</td>
<td>1.54 ± 0.04</td>
<td>1.48 ± 0.07</td>
<td>1.52 ± 0.05</td>
<td>1.62 ± 0.11</td>
</tr>
</tbody>
</table>

- Müller et al. 2017 (in prep.): 217x165 μas at 77°
- Janssen et al. 2017 (in prep.): 229 x 159 μas at 79°

Modeling Sgr A* with a Gaussian
VLBI observations of Sgr A* at 3mm
Asymmetry & closure phases

Brinkerink et al. 2016: 2. component towards south-east

Based on data from Ortiz-León et al. 2016: 2. component towards north-west

Janssen et al. 2017 (in prep.): 2. component towards north-west
Polarization properties of Sgr A*

- Highly variable (e.g., Yusef-Zadeh et al. 2007)

- Bower et al. 1999: Observations in 1998 with BIMA array (as resolution) → LP < 1% at 3mm

- Macquart et al. 2006: 2004 with BIMA → LP ~ 2% at 3mm (unrepeated)

- Marrone et al. 2006: 
  \[
  RM = -6 \times 10^5 \text{ rad/m}^2
  \]
  → \( 2 \times 10^{-9} \text{ M}_{\odot}/\text{yr} < \frac{dM}{dt} < 2 \times 10^{-7} \text{ M}_{\odot}/\text{yr} \)
Polarization properties of Sgr A*

- Highly variable (e.g., Yusef-Zadeh et al. 2007)

- Bower et al. 1999: Observations in 1998 with BIMA array (as resolution) \( \rightarrow \) LP < 1% at 3mm

- Macquart et al. 2006: 2004 with BIMA \( \rightarrow \) LP \( \sim \) 2% at 3mm (unrepeated)

- Janssen et al. 2017 (in prep.): LP < 1% at 3mm at 0.2mas resolution

- Marrone et al. 2006: RM = \( - \) 6\( \times 10^5 \) rad/m\(^2\)  
\( \rightarrow 2 \times 10^{-9} \) M\(_{\odot}\)/yr < dM/dt < \( 2 \times 10^{-7} \) M\(_{\odot}\)/yr
CASA as VLBI calibration tool

Advantages of CASA:
- Easily scriptable → pipeline
- Supports MPI parallelization
- Widely used and secure future

Recent developments:
- JIVE developers: Ilse van Bemmel, Mark Kettenis and Des Small
- At Radboud: Code testing and verification with EHT, GMVA and VLBA data
- mm VLBI expertise: MPIfR and Radboud
- CfA and Haystack involvement soon
CASA as VLBI calibration tool

Advantages of CASA:
- Easily scriptable → pipeline
- Supports MPI parallelization
- Widely used and secure future

Recent developments:
- JIVE developers: Ilse van Bemmel, Mark Kettenis and Des Small
- At Radboud: Code testing and verification with EHT, GMVA and VLBA data
- mm VLBI expertise: MPIfR and Radboud
- CfA and Haystack involvement soon

Status:
- Python version of Cotton-Schwab fringe-fitter is working (sbd&mbd) → being ported to CASA c++ code
- Amplitude calibration based on telescope metadata (ANTAB) works
- Bandpass calibration works
- Polarization calibration works (delay+phase)
- DiFX fits-idi format supported
- Will go into CASA 5.1 release
- For now: Binary tarball with dynamically linked libraries is working under Linux
- Cross-comparison of results is ongoing
Summary & Outlook

- CASA is now VLBI ready
- Work towards a fully automated pipeline
- 2.10 – 6.10 CASA VLBI workshop @JIVE: contact Ilse van Bemmel
  
  [Link to JIVE CASA VLBI 2017 webpage]

- LP < 1% at 3mm on sub-mas scales in Sgr A*
- Clear asymmetry at 3mm in Sgr A* detected – unclear if intrinsic or due to scattering
- Next steps: Analyze data from European stations & check consistency with self-calibration