Extragalactic Masers with ALMA and mmVLBI

Liz Humphreys

European ALMA Regional Centre (ESO)
### Mm VLBI Network

- 3mm to 0.85mm (100 to 345 GHz)
- 11 μas at 345 GHz (Krichbaum 2008)

#### Table 1: Properties of Radio Telescopes suitable for VLBI at $v = 230$ GHz and above

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Country</th>
<th>Altitude [m]</th>
<th>D [m]</th>
<th>Surface [μm]</th>
<th>Eff.</th>
<th>SEFD [Jy]</th>
<th>H-maser</th>
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<tr>
<td>PdB-1</td>
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<td>ALMA</td>
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<td>Chile</td>
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<td>50x12</td>
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Extragalactic Maser (cm) Environments

- **Active Galactic Nuclei**
  - disk and/or jet origin
  - AGN physics, galaxy evolution
  - Maser cosmology, independent $H_0$

- **Starbursts**

- **Galactic Analog Star-forming Regions**
  - Water masers in e.g. Antennae (Brogan et al. 2010)
  - Submm hydrogen maser (? M82; Seaquist et al. 1996)
  - Methanol – variation in fundamental constants

- **AGB Stars & Red Supergiants**
  - SiO, $\text{H}_2\text{O}$ OH masers in the LMC (van Loon et al.)
  - 2 O-rich AGB-stars associated with dwarf-galaxy tidal tails (Deguchi et al. 2007)
  - Effect of metallicity on stellar evolution
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  – Effect of metallicity on stellar evolution
22 GHz water masers in AGN central engines
- Nuclear disks ($r<1$ pc)
- Jet/ISM interactions ($r<10$ pc)

>100 water maser galaxies now detected via the Water Maser Cosmology Project
- Hubble Flow, $D=50 - 200$ Mpc
- Gravitationally-lensed maser from MG J0414+0534 $z=2.64$ (Impellizzeri et al. 2009)

Only current way to map the structure of AGN nuclear disks
- distances, warping, AGN unified model, dynamical masses, spiral structure
Inclination & warp (flattening of high velocity rotation curve): 8° across reds. At 7.4 mas, edge-on.
Position angle warp (declinations): 9° across reds
Disk obscures central region – no need for torus? - and black hole mass 38 million $M_\odot$
Systemic masers originate from bowl in front side of side, depth 0.04 pc (also Herrnstein et al.)
Warp parameters suggest origin from Bardeen-Petterson effect (Caproni et al. 2007)
Characterization of AGN accretion disks & supermassive black hole systems

NGC 4258: warped, thin (H/R ~ 0.0015), evidence of spiral structure
Black hole mass: 38 million $M_\odot$
Geometric Distance: < 3 % (Humphreys et al., in prep)

High-Accuracy Black Hole Masses

Geometric Distances of a Number of Sources $\rightarrow$
High-Accuracy Hubble constant

Water Maser Cosmology Project
Braatz, Impellizzeri, Reid, Lo, Henkel, et al.
Outstanding Issues at 22 GHz

- M – σ diagram poorly sampled by masers
  - Need larger range of mass
- AGN disks poorly sampled by masers
  - Never detect emission from back of disks
- Determination of $H_0$ relies on imaging
  - Need stronger masers to probe further out

[Graph showing relationship between $\log (M/M_\odot)$ and $\log (\sigma_*/\text{km s}^{-1})$]
Why the Search for Mm/Submm Masers?

- Probe same regions of AGN as 22 GHz masers:
  - constrain radiative transfer models
  - Map out density and T in AGN central engines
- Probe different regions:
  - trace out conditions and dynamics of uncharted portions of AGN (closer to black hole?)
  - Improve geometric models
  - test AGN unified model
- Search for “supermasers”:
  - probe more distance sources
- Search for masers from “back” of disks:
  - improve geometric disk models
- Better angular resolution
  - Higher accuracy $H_0$
- Probe different SMBH mass range?
  - Constrain the $M - \sigma$ diagram

Humphreys et al. (2001)
Many masers observed towards the same objects

$\text{H}_2\text{O} : \text{W49N}$

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Flux Density (Jy)</th>
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<tr>
<td>22</td>
<td>15000</td>
</tr>
<tr>
<td>325</td>
<td>2000</td>
</tr>
<tr>
<td>321</td>
<td>300</td>
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<td>658</td>
<td>3000</td>
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<td>437</td>
<td>6000</td>
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<td>471</td>
<td>1200</td>
</tr>
<tr>
<td>439</td>
<td>900</td>
</tr>
<tr>
<td>22</td>
<td>1200</td>
</tr>
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</table>

Menten, Melnick & Phillips (1990)

VY CMa
(Menten et al. 1996; 2006)
Mm/Submm Super Masers?

Plasma in the jet core/ionised layer above disk, optically thick at 22 GHz due to free-free opacity, obscures back of the disk. This is optically thin at mm/submm-λ, so supermasers can form.

**b) Potential sites of 183 GHz emission**

- Redshifted masers extend further than at 22 GHz
- Emission detectable from back of disk
- Blueshifted masers extend further

Additionally, 183 GHz masers may probe material above and below the 22GHz disk
### Some H₂O Masers

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>Transition</th>
<th>Vib. State</th>
<th>Ortho/Para</th>
<th>(E_u/k) (K)</th>
<th>CSE</th>
<th>SFR</th>
<th>EXG</th>
<th>Primary Reference</th>
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<tr>
<td>22.235</td>
<td>6_{16}-5_{23}</td>
<td>G</td>
<td>O</td>
<td>644</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Cheung et al. (1969)</td>
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<tr>
<td>96.261</td>
<td>4_{40}-5_{33}</td>
<td>(v_2=1)</td>
<td>P</td>
<td>3065</td>
<td>Y</td>
<td></td>
<td></td>
<td>Menten &amp; Melnick (1989)</td>
</tr>
<tr>
<td>183.308</td>
<td>3_{13}-2_{20}</td>
<td>G</td>
<td>P</td>
<td>205</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Waters et al. (1980)</td>
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<td>232.687</td>
<td>5_{50}-6_{43}</td>
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<td>O</td>
<td>3463</td>
<td></td>
<td></td>
<td></td>
<td>Menten et al. (1989)</td>
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<td>293.439</td>
<td>6_{61}-7_{52}</td>
<td>(v_2=1)</td>
<td>O</td>
<td>3935</td>
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<td></td>
<td>Y</td>
<td>Menten et al. (2006)</td>
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<tr>
<td>321.226</td>
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<td>G</td>
<td>O</td>
<td>1862</td>
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<td>Y</td>
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<td>P</td>
<td>470</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Menten &amp; Melnick (1991)</td>
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<tr>
<td>336.228</td>
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<td>(v_2=1)</td>
<td>O</td>
<td>2956</td>
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<td></td>
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<td>Feldman et al. (1992)</td>
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<td>354.885</td>
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<td>G</td>
<td>O</td>
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<td>Feldman et al. (1992)</td>
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<td>380.194</td>
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<td>Phillips et al. (1980)</td>
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<td>439.151</td>
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<td>Y</td>
<td>T</td>
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<td>2361</td>
<td></td>
<td></td>
<td>Y</td>
<td>Menten &amp; Melnick (1989)</td>
</tr>
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</table>
$H_2O$ Energy Levels

Data from Tennyson et al. (2001)
What we know so far

- 183 GHz emission - detected
  - AGN NGC 3079 (Humphreys et al. 2005)
  - starburst galaxy Arp 220 (Cernicharo et al. 2006)
  - No evidence of supermaser, ratio ~20%

- 439 GHz maser emission – tentative detection
  - NGC 3079 (Humphreys et al. 2005)

- ALMA Cycle 0: Search for Submillimeter H$_2$O Maser Towards Active Galactic Nuclei
  - 321 /325 GHz extragalactic maser search
  - Previous unsuccessful searches
NGC 3079: blue shows X-rays (Chandra), gold is H-alpha+[N II] (HST). Insert: X-rays are purple

22 GHz H$_2$O maser disk at apex of superbubble (Kondratko et al. 2005)

NGC 3079 Seyfert 2/ LINER at 16 Mpc

Well-known host of 22 GHz H$_2$O maser emission (3 – 12 Jy)

Cecil et al. 2001
Models indicate that the 183 GHz line is pumped at:
- High T, high $n(H_2)$: $T=400 - 1000\ K$, $n(H_2)=10^8-10^{10}\ cm^{-3}$
- Low T, low $n(H_2)$: $T= 200\ K$, $n(H_2)=10^7\ cm^{-3}$ (Yates et al. 1997), as low as $10^5\ cm^{-3}$ (Cernicharo et al. 1999, 2006)

Expect to find it in same regions as 22 GHz masers and out to lower densities and T

183 GHz emission less time-variable than the other well-studied $H_2O$ masers
SMA Observations of NGC 3079

- 1 track at the SMA with six antennas
  - compact configuration (projected baselines 8 – 72 m)
  - zenith opacity (225 GHz) 0.03 to 0.05 throughout

- Redshift of the galaxy reduced line frequency by 0.7 GHz, lowering corresponding atmospheric opacity

- Amplitude calibration was performed as a function of frequency to reduce the effect of variation in terrestrial H₂O across the 2 GHz sideband
Results

Maser and dust Continuum

0.55 Jy, 7σ detection

Humphreys, Greenhill, Reid, Beuther, Moran, Gurwell, Wilner, Kondratko (2005)

22 GHz Maser Peak Position
22 GHz and 183 GHz emission occur at overlapping velocities
mmVLBI and Starbursts: Arp 220 183 GHz

Cernicharo, Pardo & Weiss (2006)

The detection of the $3_{1,3} - 2_{2,0}$ line of H$_2$O with a luminosity of $\sim 2.5 \times 10^8$ K km s$^{-1}$ pc$^2$ toward Arp 220 has been interpreted as being due to a starburst in the central kiloparsec or so, triggered by the merging nature of this object, with $\sim 10^6$ sources similar to the Galactic condensations Sgr B2(M) and Sgr B2(N). The luminosities of HCN and HNC in the $J = 1-0$ and $J = 3-2$ transitions further support this scenario.
Site/redshift Considerations

$pwv = 0.5\text{mm}$

**183 GHz**

Redshift out of the lines

Stronger masers - gravitational lensing?

In terms of site:
- local: 321 GHz
- distant: 183, 325 GHz
Prospects: Local AGN

Local AGN (< 30 Mpc)

- Water Maser Cosmology Project has \(~30\) sources, some of which accessible to the Southern sky
- Survey for 183 GHz emission:
  - NGC 3079 at 30 Mpc: 0.16 Jy
  - Taking 182.5 GHz, 0.5 \(\text{km s}^{-1}\) channels, a 5\(\sigma\) detection
    - 6 antennas: 10 hours per source on source in best weather octile (0.5 mm pwv), goes up to >60 hours for 0.9 mm pwv
    - 50 antennas: 7 minutes (0.5 mm pwv), 40 minutes (0.9 mm)
- Maximum angular resolution \((B=14 \text{ km,} \lambda=1.6\text{mm})\): 24 mas
  - but can get position accuracy of beam/2*SNR, so could get \(~2.5\) mas spatial scale information i.e. < 0.4 pc at 30 Mpc

Science

- AGN unified model – is there a puffed up torus? Disk-torus connection
- AGN accretion disk physics: warps, spiral structure, local distances, disk thickness, accretion mechanism

Schinnerer et al. 2001, NGC 1068, CO
Prospects: Maser Cosmology

- Band 5 will allow observation of the 183 GHz line out to $z \sim 0.1$ or $v=30,000$ kms$^{-1}$, $D \sim 400$ Mpc
- At $D=400$ Mpc, the NGC 3079 maser would be 0.8 mJy (0.5 kms$^{-1}$) (166.6 GHz)
  - 6 antennas: $>10,000$ hrs (5σ)
  - 50 antennas: $\sim130$ hrs (5σ)
- At $D=50$ Mpc, maser would be 56 mJy (181.2 GHz)
  - 6 antennas: 13 hrs (5σ), 184 hr (20σ)
  - 50 antennas: 10 minutes (5σ), 2.3 hrs (20σ)
- If resolution $\sim25$ mas, SNR=20, can have 0.6 mas position accuracy. Rivals VLBA at 22 GHz....
- But, maser cosmology will require good imaging - mmVLBI
(sub-)mmVLBI & ALMA:
  • High spectral resolution
  • High angular resolution
  • High sensitivity

• Local AGN < 30 pc
  • Test unified model for AGN
  • AGN accretion physics
  • 321 GHz maser may be best

• Distant AGN > 50 Mpc
  • Maser Cosmology, high accuracy Hubble constant, Dark energy....
  • 183, 321 & 325 GHz masers
  • Gravitationally-lensed masers

• ALMA pre-surveys: find out if we can populate the black hole mass range in the M-σ diagram
<table>
<thead>
<tr>
<th>ALMA BAND (Freq Range GHz)</th>
<th>H$_2$O (GHz)</th>
<th>SIO &amp; Isotop. (v=0 – 4) (GHz)</th>
<th>CH$_3$OH (GHz)</th>
<th>HCN (GHz)</th>
<th>H (GHz)</th>
<th>SiS (GHz)</th>
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<tbody>
<tr>
<td>1</td>
<td>31.3-45</td>
<td>~43</td>
<td>36,44</td>
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<tr>
<td>2</td>
<td>69 - 90</td>
<td>~86</td>
<td>85</td>
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<tr>
<td>4</td>
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<tr>
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<td>9</td>
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<td>662</td>
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<tr>
<td>10</td>
<td>787-950</td>
<td>906</td>
<td>more</td>
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<td>804,891</td>
<td>After Wootten (2007)</td>
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