Water Masers: An Unobscured Probe of Obscured AGN

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**H₂O Maser Emission**

Unique location
0.1-1.0 pc from SMBH
10⁴ - 10⁶ R₉

- Microwave Amplification by Stimulated Emission of Radiation (MASER)
  - Power Source
  - Column density along line of sight => type 2 AGN
  - Velocity cohesion (~1 km/s)

- J = 6₁₆ → J = 5₂₃: 22.235 GHz (λ = 1.35 cm)

- Traces warm (~400-1000 K), dense (~10⁷ - 10¹¹ cm⁻³) gas

**Molecular Energy Levels**
In order of precedence, we adopt results from Maiolino et al. (1998) (NGC 3081), and Pounds et al. (2003) (NGC 17, and NGC 591), Reeves et al. (2004) (NGC 3783), et al. 2005], this work (5 objects), Guainazzi et al. (2005) (Mrk ), and Cappi et al. (2006) (31 objects, except NGC 5256 [see Guainazzi et 2007], and NGC 3081, NGC 4253, and NGC 3783 [J. A. Braatz et al. (2008)]).

BeppoSAX

1.—

The current sample of 42, a greater fraction of recognized disk-masers, suggests that maser disks are not only common, but also often obscured. A distribution of maser AGNs in AGNs that host masers and where X-ray data are available. Shaded bars indicate lower limits.

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance</th>
<th>$N_H$</th>
<th>Ref.</th>
<th>Log($L_{2-10}$)</th>
<th>Ref.</th>
<th>log($M_{BH}$)</th>
<th>Disk size</th>
<th>Ref.</th>
<th>Log($L_{H2O}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1068</td>
<td>16</td>
<td>$\gtrsim$100</td>
<td>Mat97</td>
<td>43.4</td>
<td>Til08</td>
<td>7.3</td>
<td>0.65–1.1</td>
<td>Til08</td>
<td>1.7</td>
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<tr>
<td>NGC 1194</td>
<td>53</td>
<td>10.6$^{+3.6}_{-2.4}$</td>
<td>Gre08</td>
<td>42.6</td>
<td>Gre08</td>
<td>7.8</td>
<td>0.54–1.33</td>
<td>Kuo11</td>
<td>2.0</td>
</tr>
<tr>
<td>NGC 1386</td>
<td>12</td>
<td>20$^{+3}_{-3}$</td>
<td>Fuk11</td>
<td>43.0</td>
<td>Til08</td>
<td>6.1</td>
<td>0.44–0.94</td>
<td>Til08</td>
<td>2.1</td>
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<tr>
<td>NGC 2273</td>
<td>26</td>
<td>15$^{+4}_{-4}$</td>
<td>Awa09</td>
<td>42.2</td>
<td>Awa09</td>
<td>6.9</td>
<td>0.028–0.084</td>
<td>Kuo11</td>
<td>0.9</td>
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<tr>
<td>UGC 3789</td>
<td>46</td>
<td>$\gtrsim$10</td>
<td>this work</td>
<td>42.3</td>
<td>this work</td>
<td>7.0</td>
<td>0.084–0.30</td>
<td>Kuo11</td>
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<td>$\gtrsim$10</td>
<td>Gre08</td>
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<td>Gre08</td>
<td>7.1</td>
<td>0.13–0.37</td>
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<td>2.7</td>
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<td>NGC 3079</td>
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<td>54.0$^{+6.1}_{-6.5}$</td>
<td>Bur11</td>
<td>42.8</td>
<td>Til08</td>
<td>6.3</td>
<td>$\sim$0.4</td>
<td>Til08</td>
<td>2.6</td>
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<tr>
<td>IC 2560</td>
<td>40</td>
<td>$\gtrsim$10</td>
<td>Til08</td>
<td>41.8</td>
<td>Til08</td>
<td>6.5</td>
<td>0.08–0.27</td>
<td>Gre09</td>
<td>2.1</td>
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<td>NGC 3393</td>
<td>51</td>
<td>45.0$^{+6.2}_{-3.6}$</td>
<td>Bur11</td>
<td>41.6</td>
<td>Til08</td>
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<td>0.17</td>
<td>Til08</td>
<td>2.5</td>
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<td>NGC 4258</td>
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<td>0.87$^{+0.03}_{-0.07}$</td>
<td>Cap06</td>
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<td>0.12–0.28</td>
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<td>Fuk11</td>
<td>41.9</td>
<td>Cap06</td>
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<td>0.24–0.29</td>
<td>Kuo11</td>
<td>0.6</td>
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<td>NGC 4945</td>
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<td>Don03</td>
<td>42.5</td>
<td>Til08</td>
<td>6.1</td>
<td>$\sim$0.3</td>
<td>Til08</td>
<td>1.7</td>
</tr>
<tr>
<td>Circinus</td>
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<td>43$^{+4}_{-7}$</td>
<td>Mat99</td>
<td>42.1</td>
<td>Til08</td>
<td>6.2</td>
<td>0.11–0.4</td>
<td>Til08</td>
<td>1.2</td>
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<tr>
<td>NGC 6264</td>
<td>139</td>
<td>$\gtrsim$10</td>
<td>this work</td>
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<td>this work</td>
<td>7.5</td>
<td>0.24–0.80</td>
<td>Kuo11</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Figure 5.

Table 6. X-ray properties of confirmed disk-masers.

Greenhill et al. (2008)

Highly Obscured

Zhu, IZ, Blanton, & Greenhill (2011)
Resolved in position (~millarcsec) and velocity (~km/s)
Maps (VLBI)
Spectra (Single Dish)

Claussen et al., 1998 (map),
http://www.gb.nrao.edu/~jbraatz/masergifs/ngc1052.gif (spectrum)

Circinus, disk+outflow

Miyoshi et al. (1995)
Herrnstein et al. (1999)

Greenhill et al. (2003)

H₂O masers live here.
Distances and Masses from “clean” disk systems

Figure 8. Relation between BH mass and bulge velocity dispersion for the maser galaxies presented here (open circles) and those from the literature (gray stars). IC 2560 is indicated with a cross and the BH mass error bar is heuristic only. For reference, we show the $M_{BH}$–$\sigma^*$ relation of elliptical galaxies from Gultekin et al. (2009, red dashed line). The maser galaxies trace a population of low-mass systems whose BHs lie below the $M_{BH}$–$\sigma^*$ relation defined by elliptical galaxies. The largest outlier galaxies are (from highest to lowest $M_{BH}$) NGC 2960, NGC 6323, and NGC 2273.

Sérsic index, see Section 5.1). These authors also show that the average $B/T$ of pseudobulges (0.16) is lower than that of classical bulges (0.4) with a large spread. Gadotti (2009), on the other hand, advocates use of the Kormendy (1977) relation as a discriminator, since pseudobulges tend to have lower central surface brightnesses at a fixed radius (see also Carollo 1999; Fisher & Drory 2008). Finally, while classical bulges are typified by old stellar populations, pseudobulges tend to have ongoing star formation (e.g., Kormendy & Kennicutt 2004; Drory & Fisher 2007; Gadotti 2009). Since deriving robust velocity measurements is beyond the scope of this paper, and in the absence of more robust structural information, we rely on morphology and stellar population properties at the present time.

The nearest, well-studied targets in our sample (NGC 4388, and NGC 2273) probably contain pseudobulges. In the case of NGC 2273, this classification is based on both the young stellar populations and the rings and nuclear disk. NGC 4388 is less certain, but there is clear evidence for recent star formation and dust. We suspect that NGC 6264 contains a pseudobulge, given its morphological similarities with NGC 2273 (namely the outer ring and inner bar) and the evidence for young stars. The same goes for NGC 3393 and IC 2560, which each contain an outer ring, a bar, and an inner ring. On the other hand, NGC 1194, with both evolved stellar populations and a large bulge, probably contains a classical bulge. NGC 2960 has some of the clearest evidence for ongoing star formation, and so we tentatively put it into the pseudobulge category. Finally, we remain agnostic about NGC 6323, which is one of the most distant targets. Thus, of the nine targets we consider, at least seven likely contain pseudobulges.

6. SCALING BETWEEN $M_{BH}$ AND $\sigma^*$

In Figure 8, we present the location of the megamaser galaxies in the $M_{BH}$–$\sigma^*$ plane. The maser galaxies do not follow the extrapolation of the $M_{BH}$–$\sigma^*$ relation defined by the elliptical galaxies. Instead, they scatter towards smaller BH masses at a given velocity dispersion. Quantitatively, taking $\Delta M_{BH} \equiv \log(M_{BH}) - \log[M(\sigma^*)]$, where $\log[M(\sigma^*)]$ is the expected $M_{BH}$ given $\sigma^*$, we find $\langle \Delta M_{BH} \rangle = 0.24 \pm 0.10$ dex. There are many hints in the literature that the $M_{BH}$–$\sigma^*$ relation does not extend to low-mass and late-type galaxies in a straightforward manner (e.g., Hu 2008; Greene et al. 2008; Gadotti & Kauffmann 2009). However, the precision BH masses afforded by the maser galaxies make a much stronger case. The $M_{BH}$–$\sigma^*$ relation is not universal. Neither the shape nor the scatter of the elliptical galaxy $M_{BH}$–$\sigma^*$ relation provides a good description of the maser galaxies in this plane.

We now add the maser galaxies to the larger sample of local galaxies with dynamical BH masses to show that indeed a single, low-scatter power-law does not provide an adequate description of all galaxies in the $M_{BH}$–$\sigma^*$ plane. For convenience and to facilitate comparison with previous work, we assume a power-law for all fits, although that form may not provide the best description of the sample as a whole.

Greene et al. (2010)

NGC 6264: $H_0 = 68 \pm 9$ km/s/Mpc, Kuo et al. (2013)

Reid et al. (2008)

Ade et al. 2013

Greene et al. (2010)
Accretion and Outflow Physics from “messy” systems
NGC4945($\text{H}_2\text{O}$)
(Parkes-Tidbinbilla-Hobart-Mopra 6-97)

Accretion and Outflow Physics from “messy” systems
Accretion and Outflow Physics from “messy” systems

NGC4945(H₂O)
(Parkes-Tidbinbilla-Hobart-Mopra 6-97)

North-South Offset (mas)

CO Major Axis

East-West Offset (mas)

Heliocentric Radio Velocity (km s⁻¹)

Flux (Jy)

Velocity (km/s)

Systemic

X-ray Wind

IR Wind

Done et al. (2003)

Greenhill, IZ, & Zhang, in prep
Traces warm, dense gas
Test temperature gradient

Temperature required: ~400-1000 K

\[
R_{\text{out}}/R_{\text{in}} = (400/1000)^{-4/3} = 3.39
\]

\[
T = 8.6 \times 10^7 \alpha^{-1/5} m^{3/10} m^{-1/5} r^{-3/4} (1 - z^{-1/2})^{3/10}
\]

Shakura & Sunyaev (1973)
IZ, Greenhill, & Gruzinov, in prep
Preliminary maps from Megamaser Cosmology Group
https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject
NuSTAR spectroscopic fitting of AGN which host disk masers

Model torus as extension of maser disk, exploit maser density condition to predict torus dimensions

Torus dimensions agree roughly with available IR interferometry (NGC 1068 and Circinus)

Density required: $\sim 10^7 - 10^{11}$ cm$^{-3}$

- NuSTAR spectroscopic fitting of AGN which host disk masers
- Model torus as extension of maser disk, exploit maser density condition to predict torus dimensions
- Torus dimensions agree roughly with available IR interferometry (NGC 1068 and Circinus)

Masini et al. (2016)
Maser Host AGN

- Systems (~150 currently known):
  - Mostly local (z < ~0.067)
  - Most distant known maser at z = 2.64
  - Rare, only ~few % of Sy2’s host masers

What is special about maser hosts?

Zhu, IZ, Blanton, & Greenhill (2011)
• Maser detections and non-detections cross-matched with SDSS

• Overall detection rate \(~3\%, \sim4.5\%\) in Sy 2's

• Detection rates higher at higher \(L_{[\text{OIII}]5007}\) and velocity dispersion, \(\sigma\)

Zhu, IZ, Blanton, & Greenhill (2011)
Is Maser Luminosity an unobscured proxy for AGN activity and SMBH mass?

- Maser emission beamed and variable
- Data from different surveys with different sensitivities
- SDSS data supplemented with values from literature

\[ R_{cr} \propto L_{AGN}^{0.38} M_{BH}^{0.62} \]

Assuming \( \alpha, \eta_x, \mu \) similar to NGC 4258

Zhu, IZ, Blanton, & Greenhill (2011)
Is Maser Luminosity an unobscured proxy for AGN activity and SMBH mass?

- Large scatter but appears to be correlated, defying expectations
- Fit (dashed line), large errors: \( L_{H_2O} \propto L_{[OIII]}^{0.3} \), \( L_{H_2O} \propto \sigma^{2.7} \)
- Dotted line assuming \( L_{H_2O} \) proportional to \( L_{[OIII]} \) and \( M_{BH} (\sigma^4) \)

Zhu, IZ, Blanton, & Greenhill (2011)
Eddington Ratios

IZ, Mei, & Greenhill, in prep

Maser Types

Disk

Jet

Other

https://safe.nrao.edu/wiki/bin/view/Main/PrivateWaterMaserList
Is Maser Luminosity an unobscured proxy for AGN activity and SMBH mass?

\[ R_{cr} \propto L_{AGN}^{0.38} M_{BH}^{0.62} \]

\[ L_{H_2O} \propto L_{AGN}^{0.06\pm0.08} M_{BH}^{0.59\pm0.14} \]

IZ, Mei, & Greenhill, in prep
Search for New Masers

- **Northern Sky: Megamaser Cosmology Project (MCP)**
  - ~3000 Type 2 AGN from SDSS surveyed with the Green Bank Telescope, completed in 2015 (Braatz et al. 2016)
  - Follow-up systems suitable for distance measurements

- **Southern Sky: Tidbinbilla AGN Maser Survey (TAMS)**
  - Co-PIs: Ingyin Zaw, Lincoln Greenhill (CfA),
    Team: Shinji Horiuchi (CDSCC), Tom Kuiper (JPL), Frank Briggs (ANU)
  - ~900 Type 2 AGN identified from 6dF spectra, $\delta < -30^\circ$
  - 1200 hrs at the 70 m Tidbinbilla telescope (NASA DSN, near Canberra, Australia)
  - Expect ~38 new masers, ~16 disks
  - Combine with multi-wavelength data to understand AGN physics
Summary

- Masers offer a direct view of region ~0.1-1.0 pc from the SMBH in highly obscured systems, combine with multi-wavelength data
- Single systems: detailed study of disk and outflow geometry
- Population studies:
  - Masers are probes of disk temperature and density which can be used to test models of accretion and obscuration
  - Maser luminosity could be a proxy for SMBH mass and AGN activity
- Conducting a large survey in the Southern hemisphere