DUSTY TORI OF SEYFERT NUCLEI PROBED BY THE WATER VAPOR MASER EMISSION: HOW LARGE ARE THE DUSTY TORI?

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ABSTRACT

Geometrical and physical properties of dusty tori of Seyfert nuclei probed by the water vapor maser emission at 22 GHz are discussed. We assume that the dusty torus has a simple cylindrical form and the maser emission can be detected only when we observe the torus from almost edge-on views. The observed low frequency of occurrence of the water vapor maser emission (less than 10 percent) suggests that the torus is a vertically thin cylinder whose outer radius between a few pc and \( \sim 10 \) pc. However, the observed masing regions are concentrated in the inner 1 pc regions of the torus. This property can be explained by that only the inner a few pc regions have physical conditions enough to cause the maser emission; the temperature is as high as several hundred K and the density is as high as \( \sim 10^{10} \) cm\(^{-3}\).

Subject headings: galaxies: active - galaxies: Seyfert - ISM: molecules - masers - radio lines: galaxies - infrared: emission

1. INTRODUCTION

The current unified models of active galactic nuclei (AGN) have introduced a dusty torus which surrounds the central engine. Since the torus is considered to be optically very thick, the visibility of the central engine is significantly affected by viewing angles toward AGN (Antonucci & Miller 1985; Krolik & Begelman 1988; see for a review Antonucci 1993). The dusty tori emit their energy mostly in mid- and far-infrared wavelengths. Therefore, infrared spectral energy distributions of AGN have been often utilized to study physical properties of the dusty tori [Pier & Krolik 1992b, 1993 (hereafter PK92 and PK93, respectively); Heckman, Chambers, & Postman 1992; Heckman 1995; Granato, Danese, & Franceschini 1997; Taniguchi et al. 1997; Murayama, Mouri, & Taniguchi 1998]. However, geometrical properties of the dusty tori have not yet been studied directly because the dusty tori are too compact to be resolved spatially at mid- and far-infrared wavelengths.

On the other hand, for these several years, we have learned that the water vapor maser emission at 22 GHz can be used to probe dusty tori directly (Nakai, Inoue, & Miyoshi 1993; Miyoshi et al. 1995; Greenhill et al. 1995a, 1995b, 1996; Gallimore et al. 1996; Greenhill & Gwinn 1997). In particular, the recent VLBA or VLA measurements of the \( \text{H}_2\text{O} \) maser emission of the nearby AGNs, NGC 1068 (Gallimore et al. 1996; Greenhill et al. 1996; Greenhill & Gwinn 1997), NGC 4258 (Miyoshi et al. 1995; Greenhill et al. 1995a, 1995b), and NGC 4945 (Greenhill, Moran, & Herrnstein 1997a), have shown that the masing clouds are located at distances of \( \sim 0.1 \) - 1 pc from the nuclei. Since these distances are almost comparable to those of the dusty tori, it is suggested that the masing clouds reside in the tori themselves (e.g., Greenhill et al. 1996). Therefore, the \( \text{H}_2\text{O} \) maser emission provides a useful tool to study physical properties of dusty tori as well as dynamical ones (e.g., Murayama & Taniguchi 1997 and references therein). The recent \( \text{H}_2\text{O} \) maser searches [Braatz, Wilson, & Henkel 1996, 1997 (hereafter BWH97); Greenhill et al. 1997b] also
provides important information. Although the microphysics of the maser emission has been investigated in detail (Krolik & Lepp 1989; Neufeld, Maloney, & Conger 1994), the H$_2$O maser data have not yet fully utilized to study geometrical properties of the dusty tori. Therefore, in this Letter, incorporating all the above observational results on the H$_2$O maser emission, we discuss the geometrical properties of the dusty tori.

2. DUSTY TORI OF SEYFERT NUCLEI PROBED BY THE WATER VAPOR MASER EMISSION

2.1. Dusty Torus Models

Several dusty torus models for AGN have been proposed up to now (Efstathiou & Rowan-Robinson 1990; PK92, PK93; Granato & Danese 1994; Granato, Danese, & Franceschini 1997). Among them, models of PK92 are quite simple and thus are very useful for investigations of statistical properties of dusty tori (PK93). Therefore, we adopt the simple torus models of PK92 who investigated the thermally reradiated infrared spectra of the compact dusty tori surrounding the central engine of AGNs by using a two-dimensional radiative transfer algorithm. The torus is a cylinder of dust with a uniform density, characterized by the inner radius (a), the outer radius (b), and the full height (h). A half opening angle of the torus is thus given as $\theta_{\text{open}} = \tan^{-1}(2a/h)$. The important parameters describing models are; 1) the inner aspect ratio, (a/h), which is coupled with the covering factor, $f = 1 - \Omega/4\pi$, where $\Omega$ is the solid angle subtended at the source not covered by dust, 2) the effective temperature of the torus, $T_{\text{eff}}$, which is roughly equal to the hottest dust temperature in the torus, and 3) the radial and the vertical Thomson optical depth, $\tau_r = n_H \sigma_T (b-a)$ and $\tau_z = n_H \sigma_T h$, where $n_H$ is the hydrogen number density and $\sigma_T$ is the Thomson cross section.

Comparing the observed infrared spectra with the model spectra, PK93 showed that the tori of Seyfert nuclei have $T_{\text{eff}} \simeq 600 - 800$ K and a/h $\simeq 0.3$. Such geometrically thick tori may be supported by the radiation pressure from the central engines (Pier & Krolik 1992a). PK93 also made a case study for a dusty torus of the archetypical type 2 Seyfert nucleus of NGC 1068 in detail and found that a model with $T_{\text{eff}} = 800$ K, a/h $= 0.3$, and $\tau_r = \tau_z = 1$, can explain the observed spectral energy distribution of NGC 1068. The inner radius of the torus can be given by $a = 0.59(T_{\text{eff}}/800 \text{ K})^{-2} (L_{\text{bol}}/2.4 \times 10^{11} L_{\odot})^{-0.5} \text{ pc}$ where $L_{\text{bol}}$ is the bolometric luminosity of the central engine of NGC 1068. The most reliable estimate of $L_{\text{bol}}$ of NGC 1068 is given by Pier et al. (1994); $L_{\text{bol}} = 2.2 \times 10^{11} (f_{\text{refl}}/0.01)^{-1} (D/22 \text{ Mpc})^2$ where $f_{\text{refl}}$ is the fraction of nuclear flux reflected into our line of sight and $D$ is the distance to NGC 1068. Thus we obtain $a \simeq 0.56$ pc which is just comparable to the observed inner radius of the H$_2$O masering region (Greenhill et al. 1996). The gas mass of the torus of NGC 1068 can be estimated as $M_{\text{gas}} \simeq 560 (T_{\text{eff}}/800 \text{ K})^{-4} \tau_r (a/h)^{-1} [(\tau_r/\tau_z)(a/h)^{-1} + 2] L_{44} M_{\odot} \simeq 4.9 \times 10^4 M_{\odot}$ where $L_{44}$ is the bolometric luminosity of the central engine in units of $10^{44}$ erg s$^{-1}$ (PK92).

One remaining problem is how to estimate the outer radius of the torus. Since most of the energy in the torus is radiated through the top to bottom surfaces within $r < a + h$, it is difficult to constrain b using the infrared spectral energy distribution. For example, if we adopt a dusty torus with $a = 1 \text{ pc}$, $b = 10 \text{ pc}$, $h = 2 \text{ pc}$, and $M_{\text{gas}} = 10^5 M_{\odot}$ (e.g., Murayama, Taniguchi, & Iwasawa 1998), this torus gives an average hydrogen number density, $n_H \simeq 6.6 \times 10^3 \text{ cm}^{-3}$ and an HI column density for an edge-on view toward the torus, $N_{\text{HI}} = \pi h (b-a) \simeq 1.8 \times 10^23 (M_{\text{gas}}/10^5 M_{\odot})(b/10 \text{ pc})^{-1} (h/2 \text{ pc})^{-1} \text{ cm}^{-2}$.

The inner aspect ratio of this torus, $a/h = 0.5$, gives a semi-opening angle of the torus, $\theta_{\text{open}} = 45^\circ$, being consistent with the typical
half opening angle of narrow-line regions, $\sim 30^\circ - 45^\circ$ (Pogge 1989; Wilson & Tsvetanov 1994; Schmitt & Kinney 1996; see also Osterbrock & Shaw 1988; Miller & Goodrich 1990; Lawrence 1991). Further, hard X-ray observations have shown that typical Seyfert 2 galaxies have the HI column density of of the order of $10^{23}$ cm$^{-2}$ (e.g., Awaki et al. 1997). Here it is remembered that the H$_2$O maser emission tends to be detected in AGNs with higher HI column densities, e.g., $N_{HI} > 10^{23}$ cm$^{-2}$ (BWH97). It is thus suggested that the H$_2$O maser emission can be observed only when we see the dusty torus from an almost edge-on view. If we adopt this hypothesis, we are able to estimate a typical outer radius statistically using the observed frequency of occurrence of the maser emission in AGNs.

### 2.2. A Statistical Size of the Dusty Tori inferred from the Frequency of Occurrence of H$_2$O Maser

First we give a brief summary of the recent comprehensive survey of the H$_2$O maser emission for $\sim 350$ AGNs by BWH97. (1) The detection rate of the H$_2$O maser emission is $\sim 5\%$ at most. (2) No H$_2$O maser emission has been detected in type 1 Seyferts (hereafter S1s). (3) Therefore, the H$_2$O maser emission can be seen only in type 2 Seyferts (hereafter S2s) and LINERs.$^1$ The detection rate of the H$_2$O maser emission is still low, $\sim 7\%$, even only for the S2s. And, (4) the AGN with the H$_2$O maser emission tends to have a higher HI column density, $N_{HI} \sim 10^{23}$–$24$ cm$^{-2}$, inferred from the hard X-ray observations. In Table 1, the observed detection rates of the H$_2$O maser emission are summarized for some AGN samples studied by BWH97. The observations show that the detection rates of the H$_2$O maser emission are $\simeq 5\%$ among the observed Seyfert nuclei for both the distance-limited and the magnitude-limited samples.

The important observational properties are both that the H$_2$O maser emission has not yet been observed in S1s and that the S2s with the H$_2$O maser emission have the higher HI column densities toward the central engine (BWH97). It is hence suggested strongly that the maser emission can be detected only when the dusty torus is viewed from almost edge-on views. This is advocated by the ubiquitous presence of so-called the main maser component whose velocity is close to the systemic one whenever the maser emission is observed because this component arises from dense molecular gas clouds along the line of sight between the background amplifier (the central engine) and us (e.g., Miyoshi et al. 1995; Greenhill et al. 1995a).

Since the high HI column density is achieved only when we see the torus within the aspect angle, $\phi = \tan^{-1}(h/2b)$ (see Figure 1), we are able to estimate $b$ because the detection rate of H$_2$O maser, $P_{\text{maser}}$, emission can be related to the aspect angle as, $P_{\text{maser}} = N_{\text{maser}}/(N_{\text{maser}} + N_{\text{non-maser}}) = \cos(90^\circ - \phi)$ where $N_{\text{maser}}$ and $N_{\text{non-maser}}$ are the numbers of AGN with the H$_2$O maser emission and without the H$_2$O maser emission, respectively. This relation gives $b = h \left[2\tan(90^\circ - \cos^{-1}P_{\text{maser}})\right]^{-1}$. Table 1 shows that a typical detection rate is $P_{\text{maser}} \simeq 0.05$. However, this value should be regarded as a lower limit because some special properties of may be necessary to cause the maser emission (Wilson 1998). If we take account of new detections of H$_2$O maser emission from NGC 5793 (Hagiwara et al. 1997) and NGC 3735 (Greenhill et al. 1997b) which were discovered by two other maser surveys independent from BWH97, the detection rate may be as high as $\simeq 0.1$ (Wilson 1998). Therefore, we estimate $b$ values for the two cases; 1) $P_{\text{maser}} = 0.05$, and $P_{\text{maser}} = 0.1$. These two rates correspond to the aspect angles, $\phi \simeq 2.5\degree$ and $\phi \simeq 5.7\degree$, respectively. In Table 2, we give the estimates of $b$ for three cases, $a = 0.1$, 0.5, and 1 pc. If $a > 1$ pc, the HI column density becomes lower than $10^{23}$ cm$^{-2}$ given $M_{\text{gas}} = 10^6 M_\odot$. Therefore, it is suggested that the inner radius may

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$^1$LINER = Low Ionization Nuclear Emission-line Region (Heckman 1980).
be in a range between 0.1 pc and 0.5 pc for typical Seyfert nuclei. The inner radii of the H$_2$O masering regions in NGC 1068, NGC 4258, and NGC 4945 are indeed in this range (Greenhill et al. 1996; Miyoshi et al. 1995; Greenhill et al. 1997a). We thus obtain possible sizes of the dusty tori; (a, b, h) = (0.1 - 0.5 pc, 1.67 - 8.35 pc, 0.33 - 1.67 pc) for $\phi \simeq 5^\circ.7$, and (a, b, h) = (0.1 - 0.5 pc, 3.29 - 16.5 pc, 0.33 - 1.67 pc) for $\phi \simeq 2^\circ.9$. All the cases can achieve $N_{\text{HI}} > 10^{23} \text{cm}^{-2}$, being consistent with the observations (BWH97).

We have shown that the most probable outer radii of the dusty tori are from a few pc to 10 pc. On the other hand, the observed outer radii of the H$_2$O masering regions are between 0.25 pc (NGC 4258: Miyoshi et al. 1995) and 1 pc (NGC 1068: Greenhill et al. 1996). In Table 3, we give a summary of the observations. We can regard that the inner radius of the H$_2$O maser is almost equal to the inner radius of the torus in each case. However, it is worth noting that the outer radius of the torus is much larger than that of the H$_2$O masering region. Another important aspect is that the masing regions can be observed in an area of $r < r_{\text{hot}}$ for all the objects. This implies that the H$_2$O maser emission can arise only from the inner hot (several hundred K), dense ($\sim 10^{10} \text{cm}^{-3}$) region of the torus (cf. Eltur 1992). The thermal equilibrium cannot be attained in the torus and thus the temperature of H$_2$O molecules may not necessarily be the same as that of the dust. However, it is unlikely that the molecule temperature is quite different from that of dust. In other words, we may conclude that the H$_2$O maser emission can be generated only in dense, hot molecular clouds in the inner parts of the dusty tori.

In this Letter, we assumed for simplicity that sufficient optical depth for maser emission occurs only if the torus is seen edge-on. However, we should remind that the same effect could be produced if tori exhibit a range of intrinsic (e.g. vertical) column densities. This point shall also be taken into account in future investigations.

### 2.3. A Case for Warped Dusty Tori

Finally we mention about a case for warped dusty tori. Even if the dusty torus is warped significantly like that of NGC 1068 (Begelman & Bland-Hawthorn 1997), the HI column density is still high, $N_{\text{HI}} \simeq (l/b)\bar{n}_{\text{HI}}(b - a) \simeq 8 \times 10^{22}(M_{\text{gas}}/10^5M_\odot)(b/10 \text{ pc})^{-2}(\sin\xi/0.5)^{-1} \text{ cm}^{-2}$ where $l$ is the path length of the line of sight within the torus and $\xi$ is the intersecting angle between the torus plane and the line of sight (see Figure 2). In this estimate, we adopt $\xi = 30^\circ$ as a fiducial value. If the masing condition could be achieved in any parts of the torus, the detection rate of the H$_2$O maser emission would be higher significantly than the observed one. For example, if the aspect angle were $\phi \simeq 30^\circ$, the detection rate of the H$_2$O maser emission would be $P_{\text{maser}} \sim 0.5/2 \sim 0.25$, being much higher than the observed rates (see Table 1). We can reconcile this dilemma if we take account of the inadequate physical conditions of the outer parts of the tori; i.e., the gas density may be too low (e.g., $\bar{n}_{\text{H}} \sim 10^4 \text{ cm}^{-3}$) to cause the maser emission and the temperature should be also too low (e.g., $\sim 50 \text{ K}$: PK92).

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Table 1: A summary of the detection rates of the H$_2$O maser in active galactic nuclei studied by Braatz, Wilson, & Henkel (1997) for the various samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{maser}}$</th>
<th>$N_{\text{total}}$</th>
<th>$P_{\text{maser}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance-limited</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All (S1+S2+L)</td>
<td>15</td>
<td>278</td>
<td>5.4</td>
</tr>
<tr>
<td>Seyfert (S1+S2)</td>
<td>10</td>
<td>198</td>
<td>5.1</td>
</tr>
<tr>
<td>S2</td>
<td>10</td>
<td>141</td>
<td>7.1</td>
</tr>
<tr>
<td><strong>Magnitude-limited</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All (S1+S2+L)</td>
<td>13</td>
<td>241</td>
<td>5.4</td>
</tr>
<tr>
<td>Seyfert (S1+S2)</td>
<td>8</td>
<td>166</td>
<td>4.8</td>
</tr>
<tr>
<td>S2</td>
<td>8</td>
<td>112</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Table 2: Geometrical properties of the dusty tori inferred from the statistics of the H$_2$O maser emission

<table>
<thead>
<tr>
<th>$a$ (pc)</th>
<th>$h$ (pc)</th>
<th>$r_{\text{hot}}$ (pc)</th>
<th>$b$ (pc)</th>
<th>$N_{\text{HI}}$ (cm$^{-2}$)</th>
<th>$b$ (pc)</th>
<th>$N_{\text{HI}}$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.33</td>
<td>0.43</td>
<td>3.29</td>
<td>$3.3 \times 10^{24}$</td>
<td>1.67</td>
<td>$6.5 \times 10^{24}$</td>
</tr>
<tr>
<td>0.5</td>
<td>1.67</td>
<td>2.17</td>
<td>16.5</td>
<td>$1.3 \times 10^{23}$</td>
<td>8.35</td>
<td>$2.6 \times 10^{23}$</td>
</tr>
<tr>
<td>1</td>
<td>3.30</td>
<td>4.30</td>
<td>32.9</td>
<td>$3.3 \times 10^{22}$</td>
<td>16.7</td>
<td>$6.5 \times 10^{22}$</td>
</tr>
</tbody>
</table>

$P_{\text{maser}} = 0.05$, $\phi = 2.59$

$P_{\text{maser}} = 0.1$, $\phi = 5.7$

$^a$The radius of the hot part in the torus; $r_{\text{hot}} = a + h$. 
REFERENCES

Awaki, H., Ueno, S., Koyama, K., Iwasawa, K., & Kunieda, H. 1997, Advances in Space Research, 9, 95
Elitur, M. 1992, Astrophysical Masers (Dordrecht, KIewer), Chap. 10
Murayama, T., & Taniguchi, Y. 1997, PASJ, 49, L13

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Fig. 1.— A section of the dusty torus adopted in this paper.

Fig. 2.— A section of the warped dusty torus.
Table 3: Active galactic nuclei with spatially-resolved \textit{H}_2\textit{O} masing regions

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>( D ) (Mpc)</th>
<th>( a = r_{\text{in}}(\text{H}_2\text{O}) ) (pc)</th>
<th>( h^a ) (pc)</th>
<th>( r_{\text{out}}(\text{H}_2\text{O}) ) (pc)</th>
<th>( r_{\text{hot}} ) (pc)</th>
<th>( b^e ) (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1068</td>
<td>S2</td>
<td>22</td>
<td>0.56(^b)</td>
<td>1.87</td>
<td>1.0(^b)</td>
<td>2.43</td>
<td>9.35</td>
</tr>
<tr>
<td>NGC 4258</td>
<td>L</td>
<td>6.4</td>
<td>0.13(^c)</td>
<td>0.43</td>
<td>0.25(^c)</td>
<td>0.56</td>
<td>2.17</td>
</tr>
<tr>
<td>NGC 4945</td>
<td>S2/L</td>
<td>3.7</td>
<td>0.18(^d)</td>
<td>0.60</td>
<td>0.45(^d)</td>
<td>0.78</td>
<td>3.01</td>
</tr>
</tbody>
</table>

\(^a\)We assume \( a/h = 0.3 \).

\(^b\)Greenhill et al. (1996)

\(^c\)Miyoshi et al. (1995)

\(^d\)Greenhill et al. (1997a)

\(^e\)The outer radius of the torus for the case of \( P_{\text{masing}} = 0.1 \).
Warped Torus