On the Cosmic Obscuration of Water Megamaser Disks

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Contents

List of Tables

List of Figures

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Abstract

Within the compact central region of 3% of galaxies, there is evidence for luminous emission at 22 GHz originating in Microwaves Amplified by Stimulated Emission of Radiation (masers) from water molecules. More than 60% of these detections reveal intensities that are millions of times greater than that of the very first masers discovered in the star-forming spiral arms of our own Milky Way galaxy. A fraction of these megamasers are found in a disk-like configuration, offering thus unprecedented tools for accurate measurements of: (1) direct distances to their host galaxies, independent of assumptions about the geometry of the universe, as well as (2) the masses of the super heavy black holes that lurk in the centers of these systems, which are usually millions to billions of times more massive than our own Sun. It is therefore crucial to try to find more of these megamaser disks, and to understand their relationship with their host galaxies. Previous studies have suggested a possible association between the masing activity and the dusty, obscuring material surrounding the central black hole accretion disk in a toroidal-like geometry (i.e., the dusty torus), and we are implementing here a novel method of testing this scenario. Using observations from the Wide Field Infrared Survey Explorer (WISE) and a suite of simulated torus models, we are able to identify the range in which some key parameters of the obscuring material (e.g., viewing angle, cloud volume filling factor, cloud optical depth, disk optical depth, and inner radius) best match the detection of water megamaser disk emission. By comparisons with non-maser galaxies, we are providing new constraints

for the link between dust obscuration and the water masing process, and thus, more efficient identification of the types of galaxies that are most likely to host megamaser disks.

1. Introduction

1.1 The Cosmic Maser Emission and its Sources

Microwaves Amplification by Stimulated Emission of Radiation, or maser emission, can be found naturally within the interstellar medium located by high density gas ($n_{\mathrm{H}_2} > 10^7$ cm^{-3}) near an excitation source (i.e., photons from young hot stars or accretion disk of matter swirling around supermassive black holes, or SMBHs, that are millions to billions of time the mass of the Sun). Just like the well-known mechanisms of a laboratory laser, excited molecules in a population inversion decay radiatively, therefore amplifying the initial excitation emission as it propagates through the medium. Over large enough path lengths, like those associated with masers detected in astrophysical sources, the amplification can reach significant luminosities, sometimes many orders of magnitude larger than the luminosity of the Sun.

The first cosmic masers were found with in the spiral arms of our own Milky Way galaxy, and continue to be detected in other cold, dense, star-forming regions (i.e., near proto-stars, compact HII regions, and in molecular envelopes of evolved stars; e.g., Lo 2005). One of the most common types of cosmic masers found is the H_2O maser emitting at a frequency of 22.2 GHz, or a wavelength of 1.35 cm, respectively. Interestingly, this type of emission has been detected later on within the nuclear regions of some nearby galaxies, reaching luminosities 10^6 times more luminous than that previously found in galactic masers, earning the name "megamasers".

1.2 The Importance of Water Megamaser Emission

Because of its extremely high-surface brightness, H_2O megamaser emission can be mapped at sub-milliarcsecond resolution by Very Long Baseline Interferometry (VLBI), providing a powerful tool to probe spatial and kinematic distributions of molecular gas in distant galactic nuclei at scales of a few light years (i.e., a parsec, or about the size of an accretion disk of matter around a SMBH; Salpeter 1964, Lynden-Bell 1969).

An excellent example is the nearby galaxy NGC 4258, in which mapping of the H_2O megamaser emission has provided the first direct evidence in an extragalactic source with an active galactic nucleus (AGN) where the intense radiation coming from its center is dominated by accretion onto a SMBH. In this particular case of NGC 4258, the VLBI observations revealed the existence of a thin Keplerian accretion disk with turbulence (Herrnstein et al. 1999), highly compelling evidence for the existence of a massive black hole, along with the most precise measurement of the its mass (Miyoshi et al. 1995). Also of great importance, the high-angular resolution of VLBI has enabled a geometric distance determination of extremely high precision, which is difficult, if not impossible, to achieve by other means.

Clearly, extending measurements similar to those performed for the water maser system in the center of NGC 4258 to more galaxies and to larger distances is very important. The megamaser disks prove immensely valuable because they can (1) uniquely probe the inner works of the AGN systems or for providing the most accurate masses of the supermassive black holes, and (2) offer the most promising prospect for obtaining a highly accurate value of the Hubble Constant H_0 at $z = 0$ via direct *geometric* angular diameter distance measurements, in a single step, providing thus essential alternatives to indirect methods that use standard candles and distance ladders. A 3% or better accuracy in measuring H_0 would provide arguably the best single constraint on the nature of Dark Energy (DE) where it is most readily detected (Hu 2005; Olling 2007).

Unfortunately, megamaser disks are extremely rare, and to date, searches for additional luminous circumnuclear H_2O masers have proven to be extremely challenging.

1.3 Finding H_2O Megamaser Disks

Of more than 6000 galaxies surveyed for 22 GHz emission in their centers, only $\lesssim$3% have been found to host water maser emission ($\sim$ 190 galaxies); among these, only $\sim$ 30% (47 galaxies) show megamaser emission in a disk-like configuration (i.e., based on continuously updated results of all 22 GHz surveys of galaxies, via the Megamaser Cosmology Project, or MCP[1].)

Current water maser surveys remain relatively unsuccessful in improving the number statistics of such sources, and the main reason appears to be the generally rather blind way of selecting target galaxies. An efficient scrutiny for new such systems requires a good understanding of the special physical characteristics that nurture them in galaxy centers, and unfortunately, there are not many studies and therefore conclusions that would potentially narrow the searches. While there is some evidence that megamasers may be associated with the molecular disk or torus that surrounds and at least partially obscures an actively accreting massive black hole, the currently increasing understanding of how a dominant AGN manifests itself in galaxy centers reveals a wide dependence of the wavelength bands in which these systems are observed: i) X-rays originating in the accretion disk can be absorbed by surrounding dust, or could be contaminated by emission from X-ray binaries, ii) the optical emission and its quasar-like emission-line signatures can be obscured by surrounding dust, iii) the infrared emission from the heated circumnuclear dust reveals an AGN signature only

[1] http://wiki.gb.nrao.edu/bin/view/Main/MegamaserCosmologyProject

if the AGN is dominant as otherwise could simply reflect reprocessing of radiation by stellar light, iv) the radio emission is only helpful in $\sim 10\%$ of these systems, when they are radio loud.

Thus, for most of the nearby active galaxies, a mix of processes including emission from star-forming regions, other ionization sources (shocks, turbulence, etc.), nuclear obscuration, as well as host galaxy starlight might obfuscate their true classification. As a consequence, the true connection between the presence of mega-masers and AGN activity, or other nuclear properties of the host galaxies, is still pretty much an open question. Therefore, it may not be that surprising that simply chasing after a certain type of AGN emission has not effectively produced new megamaser disk detections.

In order to improve the rate at which we detect new megamaser disks in galaxy nuclei, we would need to be able to answer important questions such us: Are megamaser disks always related to black hole accretion? Does maser activity depend on the black hole mass, the accretion rate, the type of associated nebular emission, or the small-scale environment or the morphology of their host? Do they require dusty/molecular tori? Strong star-formation? All of the above? What is the true detection rate of disk megamaser emission?

1.4 This Thesis: An investigation into the properties of dusty tori associated with water maser disk emission

We present here a study of the key properties of the dusty tori that surround the accreting SMBHs in galaxy centers with and without water maser emission. By constraining and statistically comparing the role played by a series of parameters that characterize the obscuring material in AGNs, including the viewing angle, inner radius, cloud volume filling factor, cloud optical depth, and disk optical depth, we aim to better determine the physical conditions under which the water masing activity is most efficiently produced. In the hopes of understanding the possible relationship between masing activity and the dusty torus, we compile and compare the geometry and composition of these torii to those of AGNs that do not host megamasers. By identifying the main connections between the properties of maser disks and those of the circumnuclear dusty tori, we offer new ways to identify observational traits of galaxies hosting megamaser disks, and consequently to design more efficient searches for these exotic systems.

2. Data and Analysis Methods

2.1 The Catalogs of Maser and Non-maser Galaxies

The Megamaser Cosmology Project (MCP; Reid et al. 2009; Braatz et al. 2010) provides the largest publicly available catalog of galaxies surveyed for water maser emission with the purpose of constraining the Hubble Constant (i.e., the rate of expansion of the universe). The data are presented in the form of an atlas that contains sky positions, recession velocities, maser spectra, and the corresponding discovery reference, for known galaxies with any detection of 22 GHz emission, as well as a catalog of sky positions, recession velocities and sensitivity of observations for all of the galaxies surveyed with the Green Bank Telescope for 22 GHz emission, with or without maser detections. These data provide for the first time a sufficiently large sample of maser galaxies and a control sample of non-detections whose properties can be compared at a statistically significant level. The catalog is updated on a regular basis to include all of the new observations and associated findings. We limit our analysis to the MCP data compiled through June 2017, which includes 47 maser-disk galaxies from a total of 180 galaxies with detected maser emission, out of a sample of about 4,700 galaxies that have been surveyed in 22 GHz.

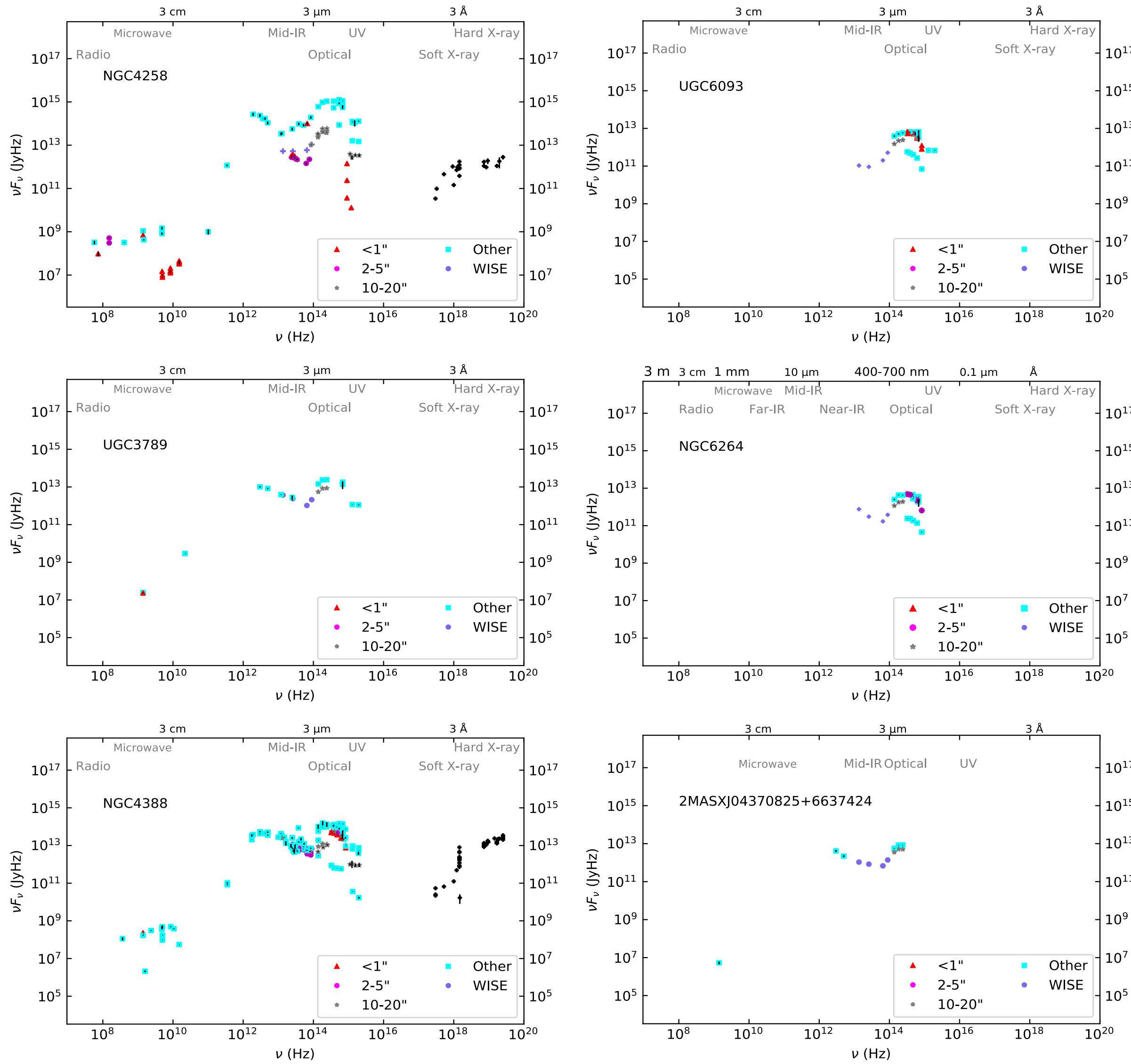

Figure 2.1: Examples of the wide availability of multi-wavelength observations needed to build spectral energy distributions, for six galaxies hosting megamaser disks. We color coded the data based on the angular resolution, and show the *WISE* measurements, which are the focus of this project, in purple.

2.2 Multi-Wavelength Measurements of Spectral Energy Distributions

Spectral energy distributions, or SEDs, illustrating the distribution of power (or flux, νF_ν) over wavelength λ (or frequency ν) over the whole electromagnetic spectrum, offer an important tool for deciphering the mechanisms that generate the emission. Specifically, by fitting the multi-wavelength measurements of the specific emitted power, we can identify and potentially quantify the fraction in each of the various energetic components (e.g., the accretion power, star formation, the host stellar component, dust obscuration and reprocessing) contribute to the total flux of a given galaxy.

Thus, through SED comparisons of host galaxies that do and do not host maser emission, along with SED fits of template models from various main emission mechanisms, SEDs can be used to determine the relationship between the 22 GHz emission and: (1) the X-ray emission associated with nuclear accretion onto the central BHs, i.e., the accretion disk; (2) the optical-UV radiation the host galaxy stellar light or light produced by hot young stars associated with central vigorous star formation; (3) the mid-infrared produced by the reprocessing of the circumnuclear surrounding dust. Ultimately, these relationships should allow for more efficient identification of the types of galaxies that are most likely to host megamaser disks, and thus increase their detection rate.

Unfortunately, the available data for such an investigation is currently lacking. We present in Figure 2.1 a selection of SED plots for six of the megamaser disk host galaxies, that illustrate the wide variety of the accessible multi-wavelength observations. The data presented here have been collected from the NASA/IPAC Extragalactic Database (NED), and we have separated the available observations in various categories to delineate the different angular apertures (and thus the different physical scales) employed in the observations; this is important as larger apertures, usually employed by ground-based telescopes, encompass larger areas, and therefore a mix of light producing mechanisms, which thus become less likely to be clearly associated with a given origin. It is clearly apparent that the radio and X-ray observations, in particular, are not abundant, and do not allow for a homogeneous investigation of the properties of the megamaser disk hosts at these wavelengths. There is also quite an apparent lack of consistency in the scales at which the optical data have been gathered, which again, reduces singificantly the sample sizes that share consistent measurements, and thus, hinders a statistically sound comparison with analog data available for the non-maser host galaxies.

Fortunately, there is one particular set of observations that is available for almost all of the host galaxies of megamaser disks, as well as for the large majority of the non-maser galaxies (as well as other types of maser galaxies: kilomasers, or megamasers that do not show a disk like configuration): the magnitude measurements from NASA's Wide-field Infrared Survey Explorer (*WISE*, shown in purple in Figure 2.1). We shall therefore restrict our SED comparisons and fitting to physical models to the mid-IR wavelength range.

2.3 The Mid-Infrared Observations from *WISE*

In order to probe the properties of the obscuring dust, we employ mid-infrared observations provided by NASA's Wide-field Infrared Survey Explorer (*WISE*; Wright et al. 2010) . *WISE* mapped the sky at 3.4, 4.6, 12, and 22 μm ($W1$, $W2$, $W3$, $W4$) with an angular resolution of 6.1", 6.4", 6.5", & 12.0" in the four bands, and achieved 5σ point source sensitivities better than 0.08, 0.11, 1 and 6 mJy in unconfused regions on the ecliptic in the four wavelength bands. The *WISE* Source Catalog contains the attributes for more than 0.5 billion point-like and resolved objects detected on the Atlas Intensity images, and provides catalog sources that are required to have a measured signal-to-noise ratio SNR $>$ 5 in at least one band. The source catalog include: J2000 positions, photometry, uncertainties, measurement quality flags and extended source and variability flags in the four WISE bands, along with association information cross-referencing WISE sources with the 2MASS Point and Extended Source Catalogs.

We have cross-matched the positions of the MCP sample of both disk-maser and non-maser galaxies with the mid-infrared detections from *WISE*, via the IRSA/GATOR general catalog query engine. After testing a range of search radii, mainly corresponding to the angular resolutions of the four *WISE* bandpasses, we have been able to extract the detections with only the smallest angular separation from the MCP source position, and removed possible duplicates. A follow up query was used to retain detections with high enough SNR (> 3). By these criteria, we have identified high quality mid-IR observations, with detections in all four *WISE* bands, for a total of 44 maser disk galaxies and 4,462 non-masers.

2.4 The Theoretical Models: A Library of Simulated AGN Tori

In an attempt to physically characterize the mid-IR light observed and measured in maser and non-maser galaxies, we are employing a library of models of the SEDs of AGNs from Siebenmorgen, Heymann, & Efstathiou (2015). These models simulate the optical and infrared emission from AGN surrounding cosmic dust, which is assumed to be formed in a torus-like geometry that may be described by a clumpy medium, a homogeneous disk, or as a combination of the two. The Siebenmorgen et al. synthetic torus emission models address both the geometry of the obscuring dust, as well as its emissivity via parameters that characterize the fluffiness, clumpiness and diffusiveness of the dusty grains, as well as the dust-photon interaction, via a fully self-consistent three-dimensional radiative transfer code. These two-phase AGN torus models consider both the formation of a clumpy and a continuous dust component, as predicted by hydrodynamical simulations (e.g., Schartman et al. 2014), where the dust extends from the dust evaporation radius at $\text{pc}/10 \leq r_{\text{in}} \leq \text{pc}/2$ up to a distance of $r_{\rm out} = 170 \times r_{\rm in}$ from the central BH; the dust from the smooth disk emerges also as a diffuse component into the polar region, while the dust clouds are pc sized with cube length of $d = 3 \times r_{\rm in}$. The dust evaporation region scales with the total AGN luminosity as $L_{\rm AGN} \propto r_{\rm in}^2$.

Parameter	Symbol	Values
Viewing angle[a]	θ (°)	86, 80, 73, 67, 60, 52, 43, 33, 19
Inner radius[b]	$r_{\rm in}$ (10^{17} cm)	3, 5.1, 7.7, 10, 15.5
Cloud volume filling factor[c]	η (%)	1.5, 7.7, 38.5, 77.7
Cloud optical depth[d]	$\tau_{V,\rm cl}$	0, 4.5, 13.5, 45
Optical depth of disk midplane[e]	$\tau_{V,\rm mid}$	0, 30, 100, 300, 1000

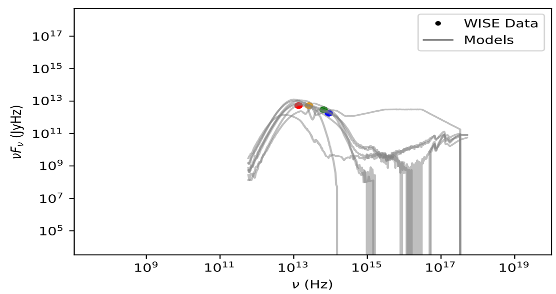

Figure 2.2: *Left:* A table of the five parameters and their value ranges used to make all 3,600 possible combinations of AGN torus models (Siebenmorgen et al. 2015). Equally binned and measured from the z-axis of the galaxy, the viewing angle ranges from 86°, edge-on, to 19°, pole-on. The inner radius is the distance from the SMBH at which dust can survive (i.e. sublimation radius). The number of clouds is associated to the cloud volume filling factor, while the optical depth of these clouds is measured along the edge of the cloud by the cloud optical depth parameter. The optical depth of the disk midplane is measured from the source to the outer edge of the disk. (See text for more detailed description of the models.) *Right:* Eight randomly chosen models over-plotted against the *WISE* data of one galaxy from our sample, exemplifying a few combinations of parameters that define the AGN torus models and how they compare to the observations.

The full library of 3,600 model SEDs account well for the observed scatter of the feature strengths and wavelengths of the peak emission of observed AGNs. The left panel of Figure 2.2 presents a summary table of the five parameters used in defining them, along with their range values. These model SEDs cover the whole mid-infrared to optical wavelengths. Figure 2 (left panel) illustrates a few examples of these models, along with the four bandbass *W*ISE measurements of one of the megamaser disk galaxy included in the sample described above.

In this study, we focused only on fitting these dusty AGN models to the the mid-IR wavelengths, with the goal to retrieve the best estimates of the five basic parameters of the AGN-related obscuring material in galaxies with and without water maser disk emission: the viewing angle (smaller to larger values indicate face-on to edge-on inclinations, respectively), the inner radius of the obscuring toroidal structure, r_{in}, the cloud volume filling factor (the could volume fraction corresponding to the number of clouds within the 3D model space), the optical depth of the clouds (τ_{cl}, measured along the edge of the cloud that has a structure of a cube), and the optical depth of the disk midplane (τ_{mid}) where both optical depths are calculated for the V band.

We utilize a chi-squared minimization fitting procedure of all models to the mid-IR observations obtained with *W*ISE, for each individual maser-disk and non-maser galaxy, in order to determine the model parameters that best fit the observed emission. These parameters can then be statistically compared for the two categories of galaxies, with and without maser disk emission in their centers, to investigate the role that these parameters, and thus their associated physical properties play in the production and detection of water maser emission.

2.5 Coding and Analysis Methods

The steps involved in the process of retrieving and manipulating the data, as well as the process of SED fitting of the *WISE* observations with the torus models via χ^2 minimization, for both megamaser disk galaxies and the control sampel of non-masers, are summarized in the flow chart presented in Figure 2.3.

To retrieve, curate, and manipulate the catalogs of MCP galaxies and their measurements we employ the Structured Query Language (SQL) and the SDSS CasJobs workbench[1]. The additional manipulation of the data, calculations of fluxes from the publicly recorded *WISE* magnitudes, χ^2 minimization SED fitting process, as well as

[1] https://skyserver.sdss.org/casjobs/

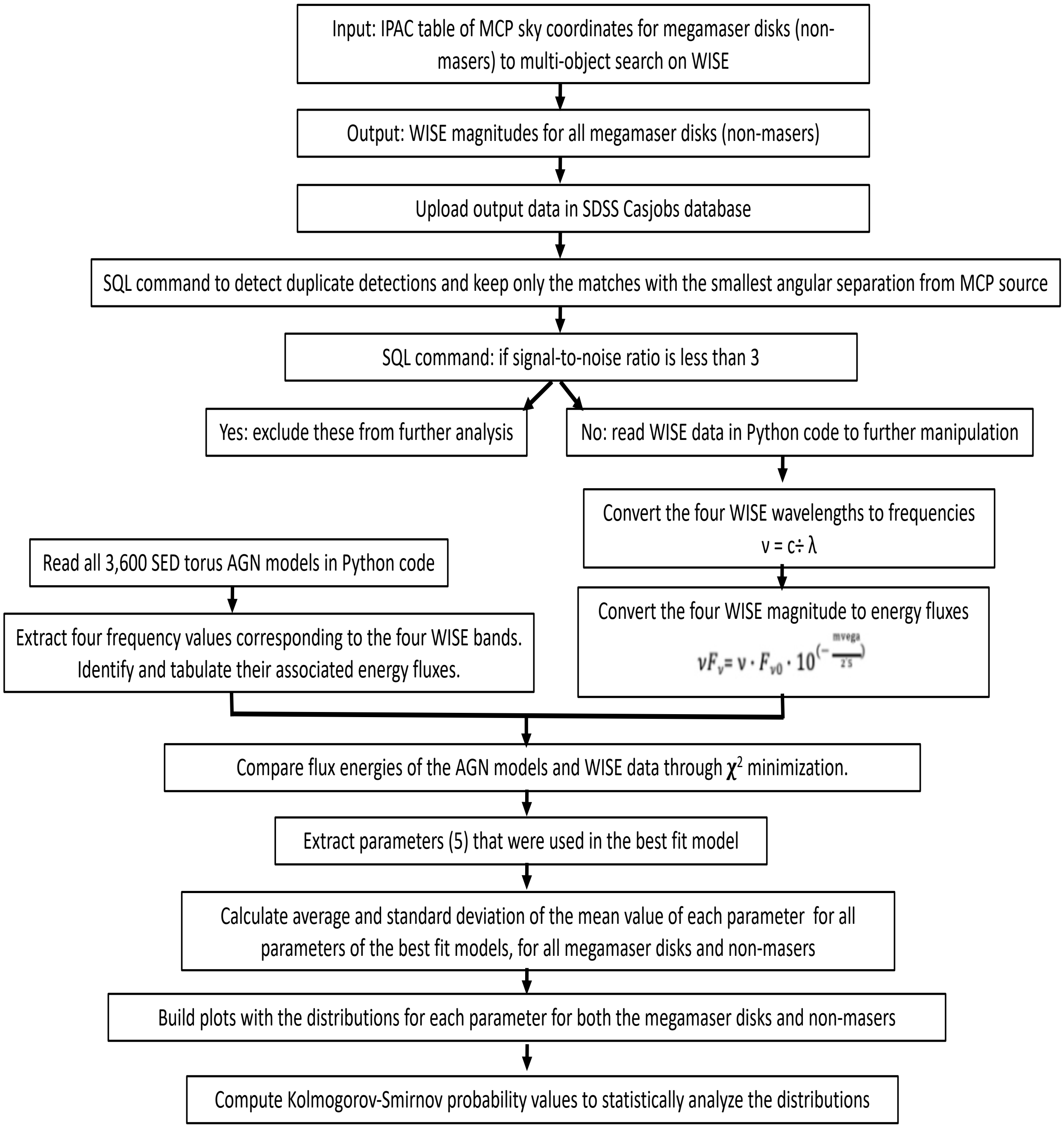

Figure 2.3: A flow chart illustrating the steps followed in the process of data acquisition, manipulation, and use in the SED-fitting technique, for both samples of megamaser disk galaxies and non-masers.

plotting and analysis of the results are performed in Python.

The following summarizes the basic steps of the data manipulation, fitting, and analysis:

1. Retrieve and manipulate the sky coordinates of galaxies with and without maser emission from public catalogs; build Infrared Processing and Analysis Center (IPAC) table formats to cross-match with the *WISE* catalogs; run search for various search radii, removing duplicate matches and matches for which SNR < 3; check by visual inspection that the matches are correct.

2. Read and format the observational measurements to match the model data: 1) convert magnitudes into fluxes, luminosities, and energy densities in the four *WISE* bands, as per Wright et al. (2010) and Jarrett et al. (2011); 2) identify and extract four frequencies from the torus model data to match the four *WISE* waveband ν values, calculate the associated νF_ν energy densities values.

3. Determine χ^2 values for fits of observational fluxes to all of the AGN SED models and identify the model corresponding to the minimum χ^2 value; the goal is to identify the element in the model library that best matches the observational set for all of the maser disk and non-maser galaxies.

4. Retrieve the five basic parameters characterizing the model associated with the best fit, and build catalogs with the best fit parameters.

5. Statistically compare the range of these parameters between the maser disks and the non-masers, and identify the probability associated with the parameters that best separate the maser host galaxies from those without maser emission (e.g., via average and median values, and Kolmogorov-Smirnov tests);

3. Results and Discussion

We present in this section the results of the χ^2 minimization fitting process of the AGN torus models to the WISE measurements, and discuss and compare the output catalogs of the physical parameters that best characterize the obscuring dusty material in samples of galaxies with and without masers.

3.1 Results of the SED best fits

We present in Figure 3.1 the best fits of the AGN torus models to the four-band WISE fluxes, for the same six galaxies we presented multiwavelength data in Figure 2.1. For each of the objects the panels list the values of the five parameters that contribute to each of the best fit curves: the viewing angle, $\theta(^\circ)$, the inner radius $r_{\rm in}$ (in 10^{17} cm), the cloud filling factor, η (%), the cloud and the disk mid-plane optical depths (τ_{cl} and τ_{mid}, respectively). It is readily apparent, and encouraging, that the fitting process yields good results, as the model SED curves are generally well within the error bars associated with the mid-IR νF_ν values, for the majority of the cases.

Maybe not as surprising, we find that there is quite an apparent range of properties associated with the parameters defining these best fits, and that there are no strong trends or apparent value ranges that separate the galaxies hosting megamaser disks from non-maser galaxies. The mid-IR SED shapes show quite a variety, which the model best fits reflect in all of their five defining parameters. Nevertheless, there are two of these parameters that show a relatively small variation: the inner (sublimation)

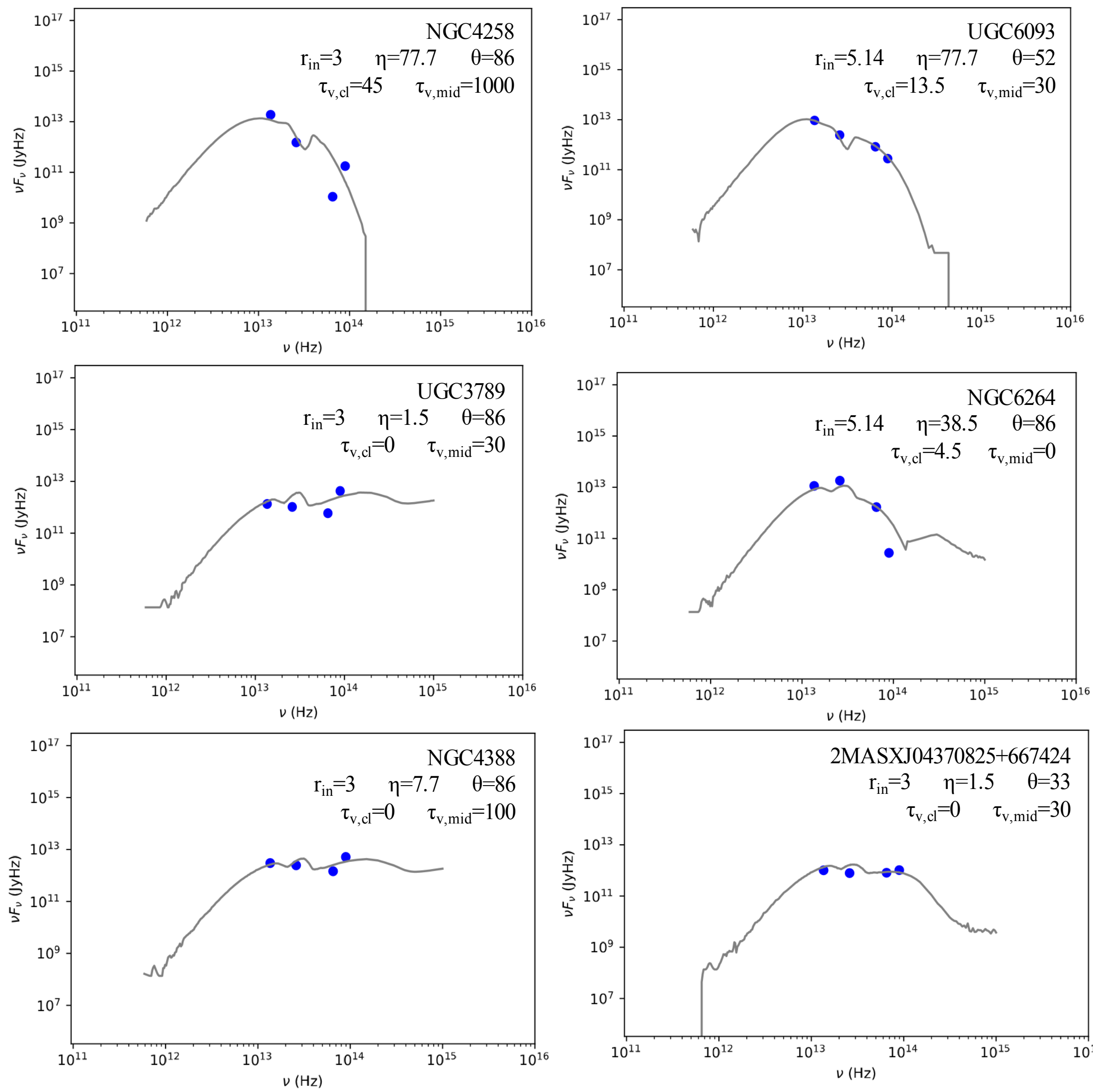

Figure 3.1: Examples of best-fit torus models with the associated $WISE$ measurements, for the six galaxies hosting megamaser disks shown in Figure 2.1. For each galaxy the best fit parameter values are indicated.

radius of the obscuring material is somewhat clustered towards the smallest values ($r_{\rm in} \approx 3 - 5 \times 10^{17}$ cm) employed by the models, and the inclination angle of the toroidal geometry suggests a more edge-on orientation relative to the line of sight ($\theta = 86°$ for four of these examples, with the other two sources showing $\theta = 52°$ and $33°$). The cloud volume filling factor (η), the cloud optical depth ($\tau_{V,cl}$) and the optical depth of the disk midplane ($\tau_{V,mid}$) span the whole range of values allowed by the entire library of torus model properties. These results remain true even if we consider only the best of these SED fits (i.e., the smallest χ^2 values). Nevertheless, a more thorough investigation of these findings in conjunction to wavelengths outside the mid-IR regime might offer additional, and potentially stronger constraints to the nature and properties of the obscuring material in these systems, and consequently, to a possible relation to the associated masing conditions.

3.2 Comparison of the dust properties

Now that we have identified a set of parameters that characterize the properties of the obscuring dust in each of the galaxies hosting megamaser disks, as well as the galaxies where no maser emission was detected, we can compare the overall distributions of these parameters, to check for any possible features that distinguish between the two types of objects, in the hope that some parameters can help single out hosts of megamasers, and thus improve the way we can hunt for these exotic systems.

Figure 3.2 illustrates the distributions of the five parameters used in building the AGN torus models that best fit the observed *W*ISE fluxes (as exemplified in Figure 3.1), for both the maser (in solid red) and the non-maser (in hashed blue) galaxies. We also indicate in each plot the average values and their corresponding standard deviation of the means for each parameter and each sample (red for the maser disks and blue for the non-masers).

Quite similar to what we found by discussing the examples presented in Figure 3.1, the comparisons of the distributions of each of the five model parameters for the whole samples of maser disks and non-masers suggest once again display that the parameters that seem to separate these two categories of galaxies are the inner (sublimation) radius, $r_{\rm in}$, and the viewing angle, θ: the average $r_{\rm in}$ is significantly smaller for the

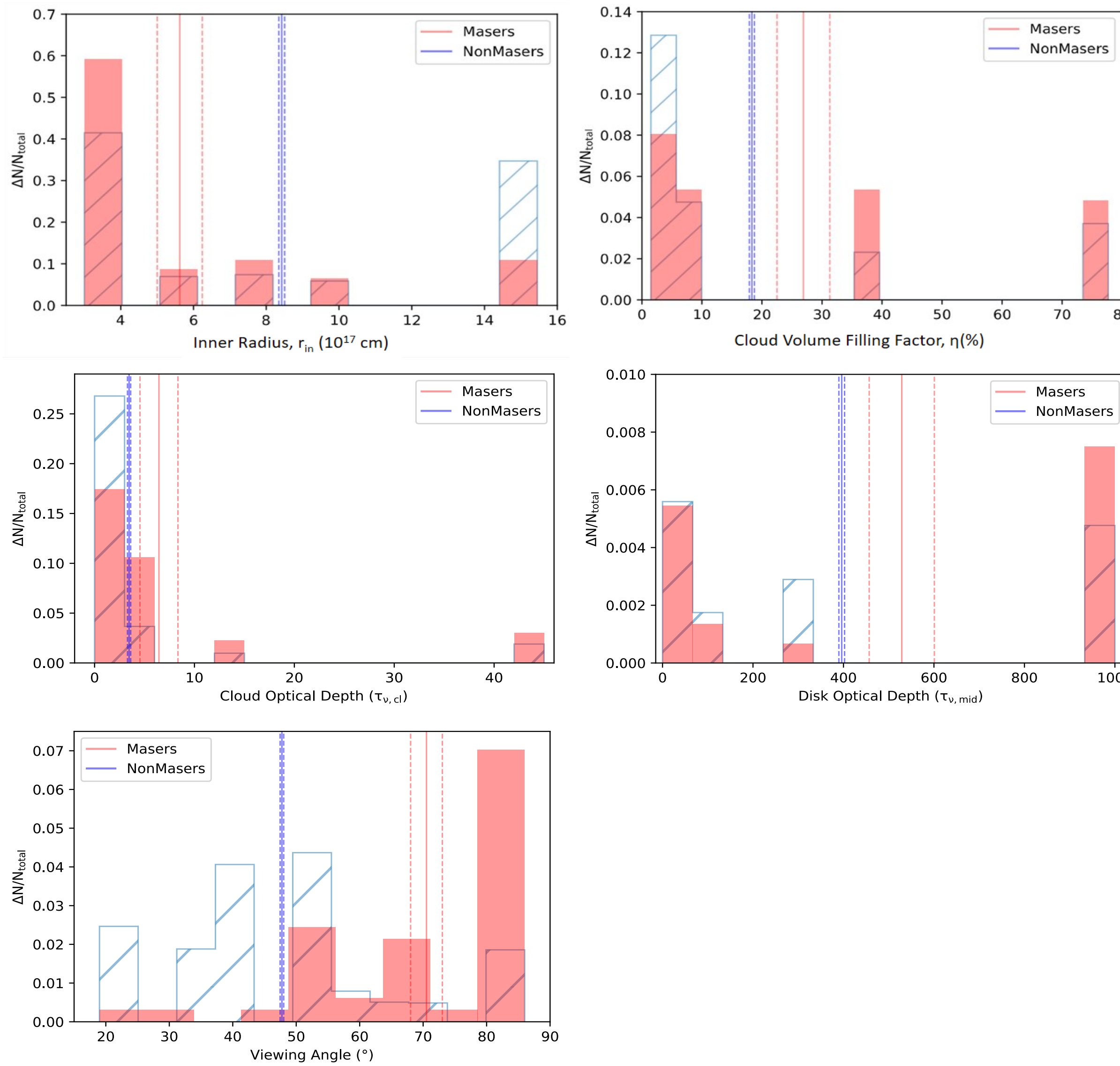

Figure 3.2: Distributions for both samples of masers (solid red) and nonmasers (hashed blue) for each of the five parameters used in building the AGN tori models. The vertical continuous lines indicate the average values for each parameter and each sample; the dotted lines indicate the standard deviation of the mean, for each average value.

maser disk systems, suggesting that maser disk emission is associated with relatively low AGN luminosities, while the average θ is significantly larger for the maser disk hosts than fro the non-masers, supporting the scenario that the masing process is associated with edge-on geometries of the circumnuclear obscuring molecular medium.

The comparisons of the parameter distributions also suggest that there might be some differences in the optical depth values of the disk component of the obscuring material, and in the cloud volume filling factor (i.e., both parameters having higher average values for the maser disks); the cloud optical depth reflects a similar trend, however, the average difference is not as substantial.

To better quantify these apparent differences between these parameters characterizing the obscuring dust in galaxy nuclei, we have employed the Kolmogorov-Smirnov (KS) statistical test. This tool is a non-parametric test of the likelihood that two different cumulative distributions are drawn from the same parent population, and it is generally useful in such sample comparisons as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples. Maybe not as surprising, the KS probabilities imply that the only statistically significant difference in these histograms is reflected by the viewing angle. These results may be due to: 1) the possibility that the maser and non-maser systems may not be intrinsically characterized by a peculiar type of circumnuclear obscuration, or 2) simply to the rather small galaxy samples available for this study. Further analysis and possibly larger samples are needed to break this possible degeneracy.

3.3 Discussion and Future Directions

With the goal to better characterize the link between circumnuclear dust obscuration and the water maser emission detected in galaxy centers, we have performed a statistical analysis of the mid-IR best matched torus parameters for the largest available samples of maser and non-maser galaxies. By employing a wide library of dusty torus models, we identified and compared the parameter values corresponding to various obscuring torus properties that best match the mid-infrared emission of these galaxies.

We found that the megamaser disk galaxies exhibit significantly more inclined torus geometries, corresponding to more edge-on orientations relative to the line-of-sight, as well as likely larger optical depths in both the individual obscuring clouds and the mid-plane disk component, while the cloud filling factor also appears to be enhanced for the maser systems. These results support further the findings of previous studies (e.g., Masini et al. 2016, Kuo et al. 2018, 2020) where, based on estimates and direct calculations of the neutral hydrogen column densities from mid-IR and X-ray emissions in these objects it was inferred that the maser disk may be intimately connected to the inner part of the torus, which needs to be of generally high densities, with nearly edge-on geometry, and a temperature range of $\sim$ 4001000 K are needed to have maser amplification. This idea was also predicted by theoretical interpretation of the galactic maser phenomenon as well (e.g., Neufeld et al. 1994, Lo 2005).

A potentially interesting finding of this study is actually that of generally lower sublimation radii for the maser disk systems than for the non-masers. Given the direct scaling of this parameter with the intrinsic AGN luminosity, this result implies that the maser disk conditions may be linked to a particularly narrow range in the AGN power, which might imply a certain "goldilocks" range in either the accretion intensity or its efficiency, and thus ultimately, of the overall range value of the $L_{\rm bolometric}/L_{\rm Edd}$ Eddington ratio parameter, which compares the bolometric power of the accreting supermassive black hole to its Eddington limit (the maximum luminosity that the black hole can achieve when the force of radiation acting outward is balanced by the gravitational force acting inward).

At first glance, this may not appear consistent with what has been found by previous calculations and comparisons of the observed $L_{\rm bol}/L_{\rm Edd}$ ratios (e.g., Constantin 2012), where values closely clustered around $L_{\rm bol}/L_{\rm Edd} \sim 10^{-2}$ were found, where non-maser galaxies exhibited lower average ratios. However, we note that the AGN torus models have only been built and tested for generally highly luminous, quasar-like AGN systems, which thus exclude the low Eddington ratio galaxy nuclei, with highly inefficient BH accretion; hence, these models do not necessarily reflect the lowest possible $L_{\rm bol}/L_{\rm Edd}$, which are rather representative of the low-redshift universe where the 22 GHz surveys target the maser galaxies. Thus, this result might need to be further investigated with a different set of models that would address more accurately the low accretion regime.

Another caveat of the results of this AGN torus model – SED fitting technique, and their interpretation relative to the current understanding of the properties of the host galaxies of maser and non-maser galaxies springs from the fact that the $L_{\rm bol}/L_{\rm Edd}$ ratios are calculated based on optical measurements mostly, which are likely biased towards unobscured AGNs. Better results and interpretation of this technique would therefore need to include optical measurements, ideally, at angular resolutions that are comparable with those from *WISE* that we have used here.

A natural extension of the study presented here would be to add to this fitting procedure photometric measurements at optical wavelengths. Nevertheless, this work requires an extensive and exhaustive process of selection and manipulation of such data as the optical observations are extremely heterogeneous in their properties (e.g., signal-to-noise, resolution), and especially their availability (see Figure 2.1 for some examples). Thus, an increased number of maser disk detections, as well as greater availability of homogeneously measured optical photometry, will likely help improving not only the number statistics associated with the results of this study but also with a more accurate determination of the physical parameters associated with the circumnuclear obscuring material in galaxy centers, and thus with the constraints leading to a more efficient linkage with the water masing phenomenon.

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