Extragalactic Astronomical Masers II —Submillimeter maser and maser in narrow-line Seyfert 1 galaxies

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Abstract

Recent observational studies of the basic properties of MASER (Microwave Amplication by Stimulated Emission of Radiation) phenomena that naturally occurs in astronomical objects were briefly reviewed in Paper I, in which I focused on centimeter water maser in active galaxies. It has been demonstrated that extragalactic water vapor masers at centimeter wavelength (λ =1.35 cm or 22.23508 GHz) are a powerful tool for imaging the inner few parsecs of active galactic nuclei (AGN) using radio interferometry with exceptionally fine angular resolution, such as very long baseline interferometry (VLBI). Here I review recent observational results of extragalactic water vapor masers in AGN at (sub-)millimeter wavelength, and the future prospects of observational studies of millimeter and sub-millimeter extragalactic masers. Extragalactic (sub-)millimeter maser is a potentially promising tool for studying the inner part of AGN, closer to a central engine or a super massive black hole. It is thus expected that studies of the (sub-)millimeter maser at high spatial resolution attained by using radio interferometry will give us much insight into the structure and dynamics of dense molecular gas in AGN. In addition, recent studies of water masers in narrow-line Seyfert 1 galaxies are summarized.

keywords: Interstellar medium, molecular gas, maser, active galaxies, galactic nuclei

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1 Introduction

Astronomical maser that naturally occurs in star-forming sites and evolved stars in our Galaxy under peculiar physical conditions has been extensively studied (e.g., Elitzur 1992). Maser has been observed in extragalactic objects: masers with very intense radiation that is 6 orders of magnitude larger than that in star-forming sites in our Galaxy are called "megamaser". Some water megamasers are known to exist near the active nuclei of galaxies. They are sub-categorized as "nuclear maser". Very long baseline interferometry (VLBI) with exceptionally fine angular resolution of about 0.2 milliarcseconds (or 200 microarcseconds) is one of the most important tools for exploring angular structure, distribution, and the kinematics of maser emission since the physical size of the maser is estimated to be smaller than 10 AU (astronomical unit)*, typically, or even smaller.

For example, an approximate angular size (θ) of a celestial object is expressed as the following, where D is a physical size and d is the distance to the object.

$$\theta = D/d \tag{1.1}$$

Assuming that D = 1 AU (1.49×10^8 km) and d = 1 mega parsecs (Mpc) (3×10^{19} km), the angular size is estimated to be as follows;

$$\begin{aligned} \theta &= 1(\mathrm{AU})/1(\mathrm{Mpc}) \\ &= 1.49 \times 10^8\ [\mathrm{km}]/3 \times 10^{19}\ [\mathrm{km}] \\ &= 0.50 \times 10^{-11}\ [\mathrm{rad}] \\ &= 1.0 \times 10^{-6}\quad [\mathrm{arcsecond}] \\ &= 1.0 \times 10^{-3}\quad [\mathrm{milliarcsecond\ (mas)}] \end{aligned}$$

It is known that the maser emission is even smaller than 1 AU and in fact the distance to masers in external galaxies is farther than 1 Mpc. So, the angular size

*1 AU corresponds to a mean distance between the earth and the sun, which is about 1.49×10^8 km, or 150 million km.

of the maser can be smaller than 0.001 milliarcseconds (mas) for distant galaxies (> 10 Mpc). Accordingly, interferometry with angular resolution of less than one milliarcsecond (mas) would be necessary for studying extragalactic masers in order to map the spatial distribution of maser emission in stars or galaxies. Thus, milliarcsec VLBI mapping of maser spots (when we observe masers, emission from maser is often observed in clusters, and each of the emission looks very compact and remains unresolved by a single-dish telescope measurement) has proved that extragalactic masers are very useful for understanding the gas dynamics within the central few parsecs of active galaxies.

In this article, recent studies of extragalactic masers at (sub-)millimeter wavelength are reviewed with an emphasis on H_2O masers at sub-millimeter wavelength. In addition, recent research for masers in narrow-line Seyfert 1 galaxies (NLS1s) is presented.

2 Extragalactic sub-millimeter H_2O Masers

In Hagiwara (2016a), hereafter Paper I, recent research and future prospects of extragalactic H_2O masers observed at 1.35 cm were presented since the 1.35 cm (or 22 GHz) H_2O maser is one of the best-studied extragalactic masers. (Sub-) millimeter H_2O maser has been known to arise in star-forming sites, towards the Galactic Center in our Galaxy, and many of external galaxies as well. Recent research of extragalactic maser has shown that (sub-)millimeter masers (maser emission with wavelengths of approximately from 1 to 0.1 millimeter) are present in the central regions of AGN. Extragalactic sub-millimeter H_2O masers in the transitions of 183.308 GHz (1.6 mm) and 321.226 GHz (0.9 mm) have been discovered in AGN, such as NGC 3079, Circinus galaxy, and NGC 4945 (Humphreys et al. 2005, 2016; Hagiwara et al. 2013, 2016b); the extragalactic H_2O maser at mm-wave was first discovered in the active galaxy, NGC 3079

(Humphreys et al. 2005).

Figure 1 displays the spectrum of sub-millimeter H_2O maser that was first detected at sub-mm wave and radio continuum emission at 321 GHz using Atacama Large (Sub-)Millimeter Array (ALMA) (Hagiwara et al. 2013). ALMA has thus enabled us to observe such sub-millimeter masers since around 2011, which resulted in detections of new AGN masers at 183 and 321 GHz. From figure 1, we can see that the compact maser emission resides in the center of the Circinus galaxy at this angular resolution of about 0.6 arcsecond and Doppler-shifted velocity components spanning from V = 250 to 700 km s^{-1}. The velocity range of the maser is similar to that of the 22 GHz H_2O maser reported in the literature (e.g., Hagiwara et al. 2013). These facts suggest that sub-mm H_2O maser probes kinematics of dense molecular gas around the circumnuclear region of AGN like the cases of 22 GHz H_2O maser (Miyoshi et al. 1995).

It is expected that H_2O masers will be detected in other transitions, like 325, 439, and 658 GHz as these maser transitions were strongly inverted in the stellar sites in our Galaxy. The 183 GHz maser traces star-forming sites but also seems to trace the circumnuclear region of AGN (Humphreys et al. 2007, 2016). Using ALMA with down to ≈ 40 mas angular resolution, corresponding to a few parsecs for nearby AGNs, one can aim to map out maser spots that would reveal angular distribution of dense molecular gas around the circumnuclear regions of AGNs.

3 The 183 and 321 GHz H_2O Masers in AGN

The 321 GHz H_2O masers have been detected towards two AGNs, Circinus galaxy (Figure 1), and NGC 4945. Figure 1 shows that the 321 GHz maser spectrum and continuum emission from Circinus galaxy, in which the maser pin-points the center of the galaxy and remains unresolved. Observations of these galaxies demonstrate that the maser emission remains unresolved at about 0.54 — 0.66 arcseconds resolution that corresponds to about 15 — 30 parsecs at the distances of these galaxies. It is generally understood that the distribution of the 1.35 cm H_2O maser emission begins to be resolved on the scales of a few parsecs. If this applies to the 321 GHz maser, the detected maser in these galaxies would require, at least, the angular resolution of ≈ 0.01 arcseconds (or 10 mas), which can be nearly attained by the long-baseline ALMA observation at 321 GHz (ALMA Partnership et al. 2015).

It should be remarked that the isotropic luminosity of the 321 GHz maser emission (~ 1 $L_\odot$) is of 2 − 3 orders of magnitude weaker than that of the 22 GHz maser found in these galaxies (Hagiwara et al. 2013, 2016b). On the contrary, it is surprising that the luminosity of the 183 GHz maser (~ 10 $L_\odot$) is approximately one order of magnitude higher than the 321 GHz maser in NCC 4945 (Humphreys et al. 2016). This might be due to the fact that the energy level of the 183 GHz transition (E_u/k = 205 K) is lower than that of 321 GHz (E_u/k = 1862 K). The energy level of the 321 GHz emission at E_u/k = 1862 K is very high so that the physical conditions needed to invert the 321 GHz water maser are not sufficient enough in the galaxy, compared with the conditions needed for pumping the 183 and 22 GHz maser emission (see table 1).

4 H_2O Masers in narrow-line Seyfert 1 Galaxies

Narrow-line Seyfert 1 galaxies (NLS1s) are a very particular type of AGN, and their origin is still mostly unknown. It is known that most of extragalactic masers are found in Type 2 active galaxies (see figure 2 and Paper I), however most of the exceptions are NLS1s. NLS1s are characterized by a higher mass accretion rate onto a central engine of a galaxy, rapid X-ray variability, and a smaller black hole mass. Interferometric observations of H_2O masers using VLBI are of great

Table 1: Transitions and energy level (E_u/k) of H_2O maser

Frequency (GHz)	Transition	E_u/k	Extragalactic detection
22.235	$6_{16} - 5_{23}$	644	YES
183.308	$3_{13} - 2_{20}$	205	YES
321.226	$10_{29} - 9_{36}$	1862	YES
325.153	$5_{15} - 4_{22}$	470	YES

interest to understanding nuclear processes in NLS1s. After the first discovery of H_2O maser in the narrow-line Seyfert 1 galaxy, NGC 4051 (Hagiwara et al., 2003), only a handful of NLS1s have been identified (Tarchi et al. 2011, Hagiwara et al., submitted). It is thus important to increase the number of known detections. Single-dish observations would be a first step towards identifying new H_2O maser for follow-up the VLBI observations. By studying the maser in NLS1 it is expected that we can learn the processes of how maser is inverted in a particular situation in which an obscuring medium surrounding an active nucleus is misaligned in the line of sight (Figure 2). It is interesting to note that the H_2O maser has been detected to the type I AGN, NGC 4151 whose optical classification is type 1.5 Seyfert rather than the type 1 or 2 (Braatz et al. 2004). This can be explained by the obscuring medium or clouds moving across an active nucleus, which causes apparent variation between type 1 and 2 nuclei. To understand maser excitation from this extreme type of AGN, it is crucial to image maser emission, at least, on scales of a few parsecs. Finally, more NLS1 H_2O masers are expected to be found with sensitive single-dish telescope surveys.

5 Summary and future prospects

MASER is a natural phenomenon occurring both in Galactic and extragalactic objects. In this article I focused on extragalactic maser emission, particularly

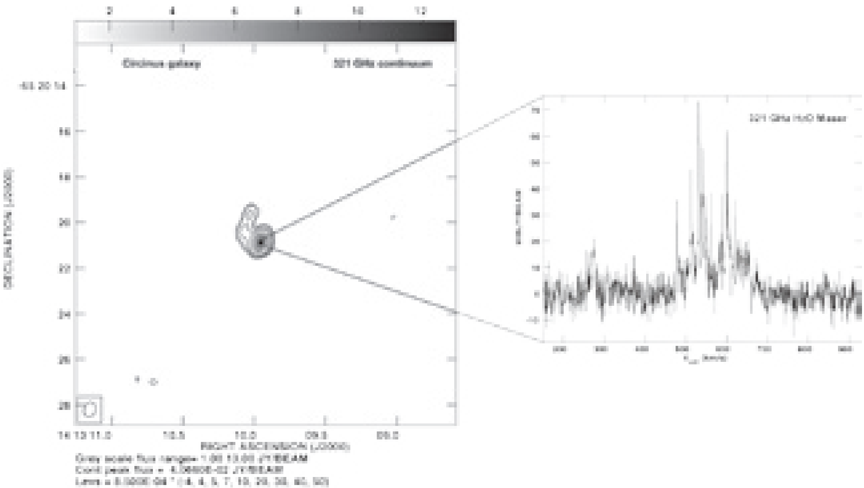

Fig. 1: Spectrum of sub-millimeter H_2O maser in the 321 GHz transition and 321 GHz continuum emission towards the Circinus galaxy, obtained in 2012 June (Hagiwara et al. 2013). The maser emission is not spatially resolved and its position looks to coincide with the nucleus of the galaxy at 0.6" resolution.

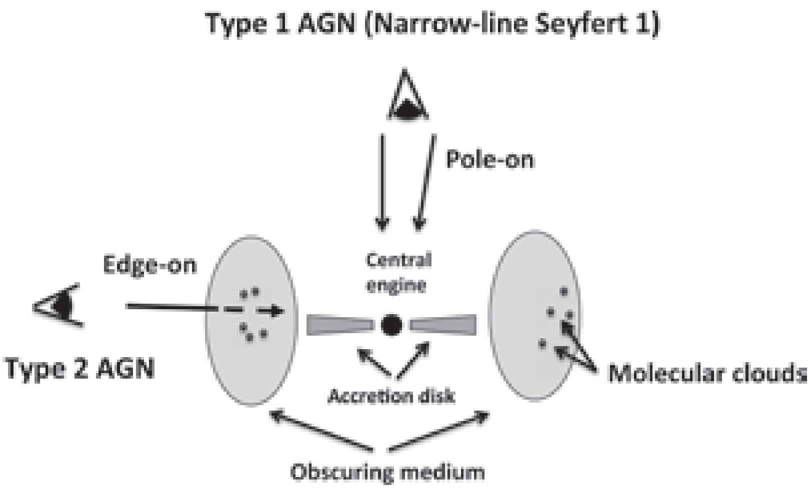

Fig. 2: Schematic view of the central region of active galactic nuclei (Antonucci & Miller 1985), which consists of a central engine, an accretion disk, and an obscuring medium surrounding the nuclear region. When an active nucleus is obscured from observers by obscuring medium, a type 2 AGN spectrum is observed. Maser emission is observed enhanced by long gain path of molecular materials in the obscuring medium in the line of sight. Some viewing angles of observers are not obscured, and a type 1 AGN spectrum is observed. Water maser in narrow-line Seyfert 1 galaxies (NLS1s), a peculiar type of Type 1 AGN is identified towards an active nucleus when an obscuring disk or torus is seen misaligned between the nucleus and observers, while maser in type 2 AGN is observed in edge-on view.

sub-mm H_2O masers and NLS1 H_2O masers. The study of maser emission from distant active galaxies (d ~ 100 Mpc) requires telescopes with higher angular resolution and sensitivities. The most important tool for studying the 1.35 cm maser is definitely VLBI with unique angular resolution that can pin-point the relative locations of each maser spot in AGN. On the other hand, future progress of the study of the sub-mm H_2O masers will depend on sub-mm radio telescopes, such as ALMA. These instruments will enable us to reveal the structure and dynamics of circumnuclear gas in the center of AGN. This work will benefit from currently on-going (sub-)millimeter VLBI at 230 GHz, which is expected to be extended to 320 GHz bands.

The study of these sub-mm masers in different transitions is of interest in that masers that need higher energy level might be able to probe inner regions of active galaxies, where cm-wave masers are not inverted. It is also clear that the study of different species of (sub-)millimeter maser is important to trace the circumnuclear region.

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