Search for H_2O maser emission toward active galaxies - New detections of 183 GHz H_2O emission

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Abstract

A preliminary analysis of the survey program data of extragalactic H_2O vapor emission in the 183 GHz transition using Atacama Large sub-Millimeter Array (ALMA) toward active galactic nuclei (AGN) is presented. The 183 GHz water emission has been detected at least seven AGN out of 18 AGN, while the spectra of three AGN indicate tentative detection of H_2O emission, which needs to be confirmed. The sample of the observed AGN is selected from known H_2O megamaser hosting galaxies (V < 16400 km s^{-1}) that can be observed from the southern hemisphere. The detected emission lines are lying near the systemic velocity (V_{sys}) of each galaxy within 100 − 300 km s^{-1} from V_{sys}. The peak flux density of the emission ranges from 10 − 50 mJy. Isotropic luminosity of the maser emission of five AGN is on the order of 10 − 100 $L_{\odot}$, which is significantly lower than that of the nearby AGN, NGC 4945 (> 1300 $L_{\odot}$) in literature. All the detected H_2O emission lines have not been spatially resolved, suggesting that they are originated from maser amplification process rather than thermal excitation. This should be confirmed by further observations at higher angular resolution together with intensity variability of the emission in future cycles of ALMA.

keywords：Radio astronomy, molecular gas : water, maser, sub-millimeter, active galactic nuclei

1 Introduction

Water molecules are seen in natural environment in three different states, solid, liquid and gaseous. On the surface of the earth, water vapor is one of the most important contents in the earth's atmosphere. In the Universe, the H_2O molecules have been detected as water vapor around in stars and galaxies. In 1968 H_2O molecule was first detected at the star-forming site in Orion-KL [6], and then extragalactic H_2O was detected in the spiral arm in galaxy M 33 in 1977 [3] as water vapor maser (a

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microwave version of laser at optical wavelength) whose emission radiates at 22.235 GHz (wavelength λ = 1.3 cm). The H_2O maser whose isotropic luminosity is a million times larger than that in typical Galactic star forming sites is named megamaser, which has been detected toward the nuclear regions of active galactic nuclei (AGN) [18] for which they are often called nuclear maser [10]. The H_2O megamasers detected at 22 GHz have been well studied and they are exclusively found toward active galactic nuclei (AGN) [1, 2, 10], while some of them show maser emission in the different transitions as well as that at 22 GHz [14]. It is important that we will search for H_2O emission or maser in the different transitions toward AGN to find a new probe for the nuclear region of AGN. As a strategy, to increase the number of detection, it would be reasonable to begin a search for new H_2O maser or emission among known megamaser galaxies rather than conducting a blind survey toward AGN. Particularly, the excitation condition of H_2O maser in the 183 GHz transition is not so different from that of 22 GHz [15], thus it is likely that 22 GHz H_2O megamasers also host H_2O maser at 183 GHz.

In this short article, the preliminary analysis of archived data of 183 GHz H_2O maser survey from the known 22 GHz H_2O megamaser galaxies using Atacama Large sub-Millimeter Array (ALMA) is presented.

2 Data analysis and results

The data used in this research are obtained from ALMA Science Archive. The data (project dode: 2018.1.00321.S) were obtained with the Band 5 ALMA observations from October to December in 2018 and data analysis is conducted with CASA (https://casa.nrao.edu). H_2O emission in the transition of $3_{13} - 2_{20}$ at rest frequency of 183.308 GHz was observed toward 18 AGN at angular resolutions of ~ 0.3" – 0.9".

A list of the observed AGN and observing parameters is shown in table 1. The systemic velocities of the AGN range from V = 2925 km s^{-1} to 16369 km s^{-1}. Line sensitivity per one spectral channel is about 5–10 mJy $beam^{-1}$, depending on a target source. The bandwidths of each spectral window are about 800 km s^{-1} with a spectral resolution of about 0.4 km s^{-1}. In this data, the H_2O emission lines are detected in seven AGN, and they are noted at the last column in table1, while the three AGN show marginal features ($\lesssim \sim 2\sigma$). In total, the 10 AGN out of 18 contain H_2O emission. These tentatively detected features should be confirmed by further observations. If the detected emission is maser, the flux intensity is likely to be very variable and the intensity of the marginal features might be increased strong enough to be detected in future observations. The newly detected 183 GHz H_2O maser spectra of the five AGN out of seven AGN are presented in figures 1-5, the rest of which will be reported in a later publication. The spectrum of no H_2O emission toward the nucleus of the type 2

Seyfert NGC 1068 is shown in figure 6. The detected H_2O emission in figures 1-5 is obtained toward a nuclear continuum source in the center of each AGN. The H_2O emission in each AGN remains unresolved and compact at the given angular resolutions.

3 Discussion

From our analysis of the archived ALMA data originally observed in late 2018, the 183 GHz water maser lines are newly detected toward the 7 AGN that host 22 GHz water megamaser. Given the fact that H_2O line-widths of each emission in the figures are narrow (< 1 km s^{-1}) and the emission is unresolved at the angular resolution of < ~0.6", it is likely that the detected H_2O lines are maser rather than thermally excited molecular gas emission. Hereafter, we proceed discussion, assuming that the detected H_2O features are maser.

3.1 ESO 269-G012

ESO 269-G012 exhibits highly Doppler-shifted (high-velocity) emission at 22 GHz, nearly symmetrically offset by about 650 km s^{-1} from the systemic velocity. The high-velocity emission may come from radial part of a rotating gas disc in the galaxy [5]. Figure 2 displays 183 GHz H_2O maser spectra detected toward the center of the galaxy, with the systemic features (V ≃5000–5015 km s^{-1}) near at the systemic velocity of Vsys = 4950 km s^{-1}. The velocity ranges of the known high-velocity features at 22 GHz peaked at V = 4350 km s^{-1} and V = 5550 km s^{-1} seem not to be covered by the spectral windows. It is therefore not certain that high-velocity emission at 183 GHz is present or not like that at 22 GHz.

3.2 Mrk 1419

Figure 3 shows spectrum of the maser in type 2 Seyfert Mrk 1419 (NGC 2960) with distinct maser features having a broad line-width at V ≃ 4900 − 4930 km s^{-1}. Also minor features are seen at V ≃ 4770 − 4780 km s^{-1}. The velocity ranges of these features are similar to those of 22 GHz maser detected in the galaxy [13]. The spectra of the 22 GHz water maser of the galaxy show Doppler-shifted (high-velocity) emission on either sides of the systemic velocity (V_{sys} = 4932 km s^{-1}) [13], suggestive of a rotating disc around a central super massive black hole (SMBH). The maser spectrum in the data does not cover the high-velocity ranges of the 22 GHz maser.

3.3 NGC 5765b

Gao et al. (2016) revealed the 22 GHz maser spectrum that displays high-velocity

Table 1. A list of 18 active galactic nuclei (AGN) observed with ALMA is presented. Of all the 18 AGN, 183 GHz water maser emission is detected toward 10 AGN, including tentative detection.

List of galaxies, observed with ALMA

Source name	Vsys (optical, LSR, km/s)	Frequency (GHz)	Angular resolution(arcsecond)	Minimum velocity resolution (m/s)	Integration time (sec)	Observation date (year-month-date)	Detection/note
NGC 1386	868	180.192	0.393	398.930	1360.8	2018-11-16	Distinct emission lines at V=964-999.3 km/s in spw25
NGC 1068	1137	180.026	0.357	399.287	2479.68	2018-11-09	
IC 2560	2925	178.959	0.391	401.599	2721.6	2018-10-30	
NGC 3393	3750	178.471	0.356	402.682	2903.04	2018-10-30	
NGC 1194	4076	178.277	0.326	403.157	1330.56	2018-11-16	Faint emission at V=4087 km/s
Mrk 1419	4932	177.772	0.383	404.243	1874.88	2018-11-14	Distinct emission peaked at Vsys = 4915 km/s
ESO 269-G012	4950	177.719	0.785	404.379	1360.8	2018-12-01	Weak lines at V=4840, 5010, 5170 km/s in spw25, 27, 29
J0126-0417	5639	177.357	0.322	405.243	1814.4	2018-11-16	
NGC 5495	6737	176.712	0.934	406.653	1330.56	2018-12-06	
CGCG 074-064	6886	176.622	0.588	406.842	1451.52	2018-12-06	Weak emission at 6919 km/s in spw25
ESO 558-G009	7674	176.184	0.406	407.889	1421.28	2018-10-31	Faint emission at V = 7559 km/s
NGC 5765b	8333	175.786	0.586	408.767	1421.28	2018-12-06	Emission lines at V=8273 km/s (nearVsys) in spw25
IC 485	8338	175.796	0.374	408.757	2963.52	2018-10-31	Emission lines at V=8353 km/s in spw25
CGCG 165-035	9649	175.048	0.681	410.479	1602.72	2018-12-06	
NGC 6264	10177	174.730	0.374	411.238	2358.72	2018-11-18	
UGC 6093	10828	174.388	0.371	412.031	1451.52	2018-10-31	A signature of emission at V=10847 km/s in spw25
J0847-0022	15275	171.893	0.349	417.948	1179.36	2018-11-08	Emission at V=15273 km/s (spw25)
J0109-0332	16369	171.313	0.340	419.457	1391.04	2018-11-06	

emission that is symmettically offset w.r.t. the systemic velocity [4], implying the presence of a rotating disc around a SMBH. The maser features show relatively strong flux density of > 200 mJy. The high-velocity features show a linear structure extending from 0.3 to 1.2 pc [4]. The 183 GHz spectrum in figure 4 shows maser features at V ≃ 8250–8280 km s^{-1}, which are blue-shifted about 50–70 km s^{-1} w.r.t. the systemic velocity (V_{sys} = 8333 km s^{-1}). The spectrum displays only features near the systemic velocity that are weaker about 10 mJy than those at 22 GHz. The obtained 183 GHz spectrum does not cover the high-velocity ranges of the 22 GHz maser spectrum.

3.4 NGC 1386

Type 2 Seyfert galaxy NGC 1386 hosts intense 22 GHz water maser features, one of them lies near at the systemic velocity (V_{sys} = 868 km s^{-1}) with broader line-width and two narrow lines are red- and blue-shifted about 100 km s^{-1} respectively from the systemic velocity [1]. The VLBA observations revealed that the distribution of the maser shows a roughly linear structure extending over 1.2 pc [e.g. 1]. The spectrum in figure 5 exhibits the maser features at V ≃ 960–1000 km s^{-1}, which probably correspond to red-shifted emission detected at the 22 GHz maser spectra [1].
It should be noted that no maser in the 321 GHz transition was detected toward the galaxy in the earlier ALMA observation [11].

3.5 NGC 1068

The galaxy NGC 1068 is known to be a prototypical type 2 Seyfert galaxy, from which the well-known AGN unified theory is established. The galaxy hosts bright 22 GHz H_2O maser emission that shows high-velocity blue- and red-shifted features relative to the systemic velocity (V_{sys} = 1137 km s^{-1}), and the maser traces a sub-parsec scale maser disc around a SMBH [7]. The rotating gas torus with a radius of~5pc has been detected in HCN (J=3-2) and HCO^+ (J=3-2) line emission toward the nucleus of the galaxy [16]. Very recently, the detection of an inner counter rotating disc inside the torus has been detected at the angular resolution of 0".02 (1.6 pc at a distance of 16 Mpc) also in HCN and HCO^+ [17]. There is no detection of 183 GHz water emission in the spectrum (figure 6). Note that no water maser in the transition of 321 GHz is detected with the earlier ALMA observation [11].
In this 183 GHz extragalactic H_2O search toward the known 22 GHz megamaser host galaxies, the detection rate of the new maser is about 7/18=0.39, about 40 per cents, which is a particularly high value for the H_2O maser detection rate, compared with any of the past extragalactic 22 GHz H_2O maser surveys using single dish telescopes [2, 8]. This indicates that the exciting conditions of 183 GHz H_2O maser may be similar to that of 22 GHz H_2O maser and therefore the 183 GHz maser could trace similar regions and gas dynamics of inner sub-parsecs of AGN like the cases probed by 22 GHz H_2O masers.

Isotropic luminosity of the 183 GHz water maser can be estimated by using a formula below [15]:

$$L = 1.04 \times 10^{-3}\ \nu\ (\mathrm{GHz})\ D^2\ (\mathrm{Mpc}) \int S\ dv\ (Jy\ kms^{-1})\ L_{\odot} \qquad (1)$$

, in which ν is rest frequency of 183.310 GHz, D is a distance to a galaxy in Mpc, and $\int S\,dv$ is integrated intensity in Jy km s^{-1}.
Using the distance of 15.3 Mpc to NGC 1386 and the emission between V = ~980 − 990 km s^{-1} giving the integrated intensity of 70 mJy km s^{-1}, the luminosity of the maser is estimated to be 3.1 $L_{\odot}$. For NGC 5765b, with D=126 Mpc and the integrated intensity of 62.3 mJy km s^{-1} of the maser between V = ~8265 − 8280 km s^{-1}, the luminosity of the maser is about 189 $L_{\odot}$. For ESO 269-G012, with D=77.7 Mpc and the integrated intensity of 78 mJy km s^{-1} of the maser between V = ~ 4990 − 5020 km s^{-1}, the luminosity of the maser is about 178 $L_{\odot}$. For IC 485, with D=125 Mpc and the integrated intensity of 142 mJy km s^{-1}, the luminosity is estimated to be 422 $L_{\odot}$. Likewise, the luminosity of Mrk 1419 is calculated to be 135 $L_{\odot}$.
The known 183 GHz H_2O maser in NGC 4945 has the luminosity of > 1300 $L_{\odot}$ [15]. In comparison of the estimated 183 GHz maser luminosity of NGC 4945 [15], the luminosities of these galaxies are lower by factors of ~3 − 400, depending on a distance to each galaxy.

The interpretation of the H_2O maser obtained from the galaxies is not straightforward. All the H_2O masers in the five AGN are detected toward 183 GHz continuum sources in the center. The luminosity of the maser in NGC 1386 is very weak and it can be interpreted as maser or thermally excited emission from star-forming region, while those other four AGN are larger than 100 $L_{\odot}$, similar to 22 GHz H_2O megamasers. It is likely that the origins of the maser in the other four AGN are due to AGN-activity. For NGC 1386, if evidence of intensity variability is found in future observations, which will be evidence for the emission being the result of maser amplification. It should be noted that velocity ranges of the 183 GHz H_2O features are not exactly same as that of 22 GHz H_2O masers, which indicates that the regions that the 183 GHz maser arises from are different from those of 22 GHz H_2O masers. It is interesting to explore what the 183 GHz maser probes in the nuclear regions of AGN, which is a subject to be pursued in further studies with ALMA.

The maser detection rate is about 40%, very high, which supports the earlier study: the excitation conditions of the both 183 GHz and 22 GHz transition are similar. This suggests that we ought to search for more water masers with bias toward 22 GHz megamaser galaxies, which may result in increasing more 183 GHz H_2O maser detections.

According to theoretical studies, the upper state energy (Eu/k=1862 K) of H_2O maser in the 321 GHz transition is significantly higher than that in the 22 GHz transition (Eu/k=644 K), while the energy in the 183 GHz transition (Eu/k= 205 K) is lower than that of the 22 GHz maser. This explains that the number of extragalactic 321 GHz H_2O maser detected up to date is much fewer than that of the 22 and 183 GHz H_2O masers [9, 12].

4 Summary

The preliminary result of search for H_2O emission in the 183 GHz transition toward 22 GHz megamaser host galaxies with the ALMA Science Archive data is presented. In our analysis at least seven 183 GHz H_2O maser sources are newly detected out of 18 AGN at high detection rate of about 40%, while the masers in three sources are marginally detected in our preliminary analysis, which needs to be confirmed. The flux densities of the detected maser emission are weaker, compared with that at 22 GHz, and the luminosity of the maser ranges from about 3 − 400 $L_\odot$, assuming isotropic radiation of the maser. Most of the detected emission is likely the result of maser excitation, however one of them could be thermally excited emission or maser in a star-forming region in the galaxy. With evidence of intensity variability, whether or not the detected emission is maser will be clarified. We need to observe more AGN to understand the properties of the extragalactic 183 GHz H_2O emission since it could be a new probe of gas dynamics in the nuclear regions of AGN.

This article makes use of the following ALMA data: ADS/JAO.ALMA #2018.1.00321.S. ALMA is a partnership of ESO, NSF and NINS, together with NRC, MOST and ASIAA, and KASI, in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is funded by the National

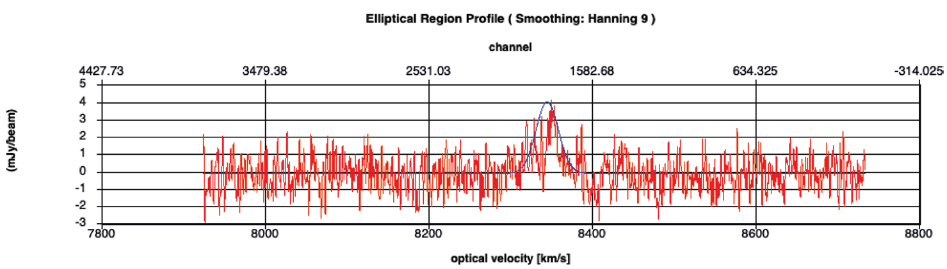

Figure 1: Spectrum of 183 GHz H_2O emission in galaxy IC 485, obtained with ALMA. A vertical axis denotes line flux density scaled in milli-Jansky, and a horizontal axis at the bottom shows LSR velocity (optical definition), covering from V = 7924.58–8733.77 km s^{-1} and observing frequency (GHz) is displayed at the top. A solid line indicates a Gaussian-fitted result, assuming a single emission peak.

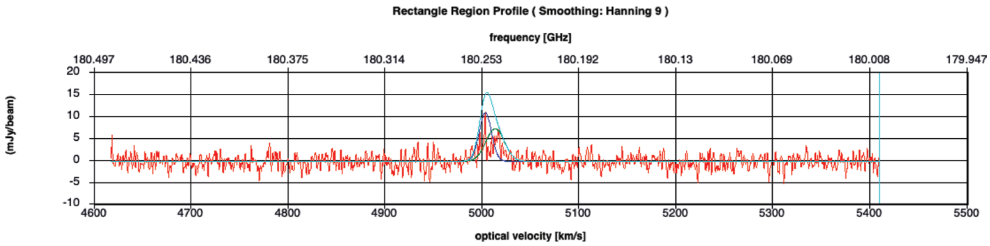

Figure 2: Spectrum of 183 GHz H_2O emission in galaxy ESO 269-G012, obtained with ALMA. The axes are same as shown in figure 1, with velocity coverage of V = 4617.87 – 5409.72 km s^{-1}. Solid lines are Gaussian-fitting result.

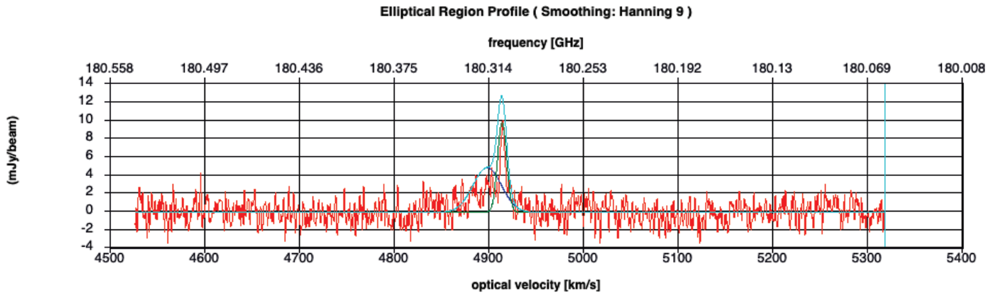

Figure 3: Spectrum of 183 GHz H_2O emission in galaxy Mrk 1419, obtained with ALMA. The axes are same as shown in figure 1, with velocity coverage of V = 4257.13 – 5318.51 km s^{-1}. Solid lines indicate Gaussian-fitting result.

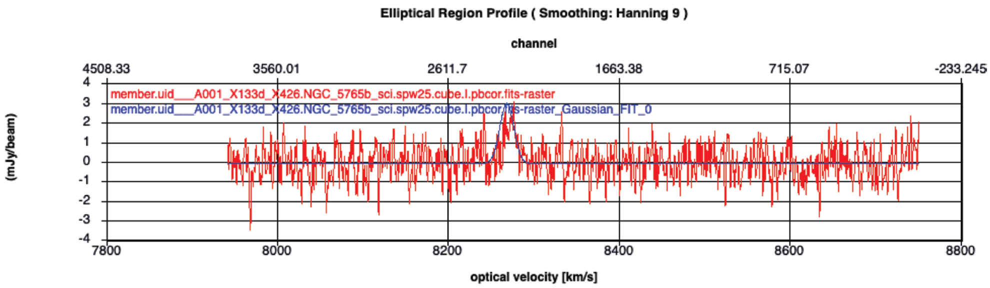

Figure 4: Spectrum of 183 GHz H_2O emission in galaxy NGC 5765b, obtained with ALMA. The axes are same as shown in figure 1. A solid line indicates Gaussian-fitting result.

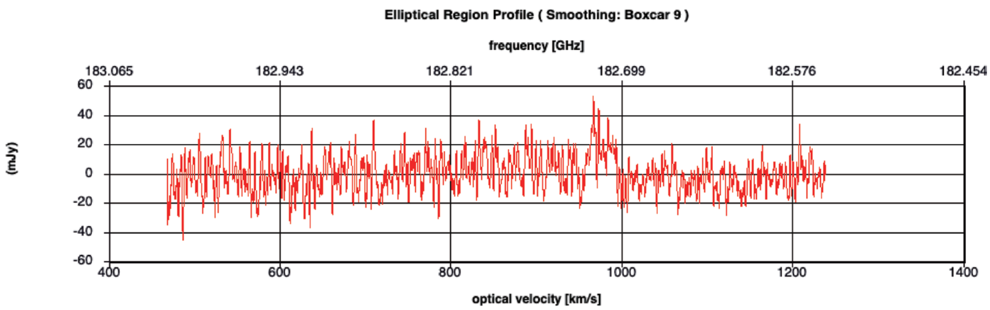

Figure 5: Spectrum of 183 GHz H_2O emission in galaxy NGC 1386, obtained with ALMA. The axes are same as shown in figure 1.

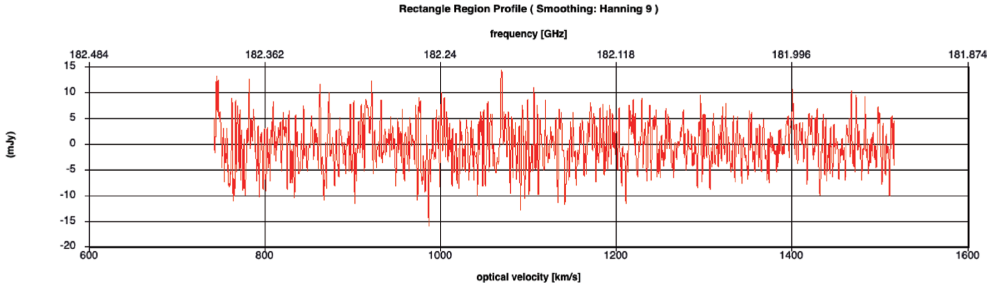

Figure 6: Spectrum obtained for 183 GHz H_2O emission toward galaxy NGC 1068 with ALMA in which no H_2O emission is detected. The axes are same as shown in figure 1.

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和文摘要

活動銀河における水蒸気メーザーの探査 - 183 GHz帯水メーザーの新たな検出

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アタカマサブミリ波干渉計（ALMA：アルマ）のアーカイブデータの解析結果により、183 GHz（ギガヘルツ）帯水蒸気メーザーが、活動銀河核(AGN)に新たに検出されたことを報告する。探査された18のAGNのうち、7個のAGNから183 GHz帯の水メーザーが新たに検出された。また3AGNから、微弱な水分子の放射を検出したが、今後の観測で確認を要する。観測されたAGNには、22 GHz帯での水メーザーが既に検出されており、銀河の系統速度はおよそ16400 km/s以下で、いずれも南天から観測可能な天体である。メーザー輝線の速度は、銀河の系統速度から約200-300 km/s以内の速度範囲に検出されている。輝線強度は、ピークフラックス密度で約10-50ミリジャンスキーである。また等方的放射を仮定した光度はオーダーでおおよそ10-100太陽光度であり、先行研究による近傍AGNのNGC 4945の光度（1300太陽光度以上）より、かなり低い値を示している。検出された水分子輝線放射の特徴や、放射源が空間的に分解されないことを考慮すると、検出された放射は熱的に励起された輝線ではなく、非熱的励起のメーザー増幅によると考えられる。今後のALMAによる高空間分解能観測で、強度変動と共に、メーザー源の空間分布や運動学的な情報を得ることが重要である。

keywords：電波天文学、分子ガス、水、メーザー、サブミリ波、活動銀河核