東洋大学学術情報リポジトリ　Toyo University Repository for Academic Resources

Search for H2O Maser Emission towards active galaxies II　New detections of 183 GHz H2O Emission

著者	Yoshiaki HAGIWARA
journal or publication title	JOURNAL OF TOYO UNIVERSITY NATURAL SCIENCE
volume	66
page range	55-65
year	2022-03
URL	http://doi.org/10.34428/00013469

Creative Commons : 表示 - 非営利 - 改変禁止
http://creativecommons.org/licenses/by-nc-nd/3.0/deed.ja

Search for H_2O Maser Emission towards active galaxies II – New detections of 183 GHz H_2O Emission

Yoshiaki HAGIWARA*

Abstract

The preliminary result of our archival data analysis of the searches for extragalactic 183 GHz H_2O maser emission towards 18 active galactic nuclei (AGN) using Band 5 Atacama Large sub-Millimeter Array (ALMA) was presented in the previous article (Paper I). Here in this article, adding to the 18 AGN, a new data analysis for 183 GHz H_2O emission in the nearby AGN, Circinus galaxy is presented. The spectrum of the emission in the galaxy shows several prominent H_2O maser features that are Doppler-shifted with respect to the systemic velocity of the galaxy. The velocities of these features identified in the spectrum are similar to those in the 22 and 321 GHz transitions. The peak flux density of the emission is as strong as that of the 321 GHz H_2O maser emission detected in the center of the galaxy, but significantly weaker than that of 22 GHz H_2O maser. The isotropic luminosity of the 183 GHz emission of the Circinus is estimated to be $\approx$ 100 $L_\odot$, which is as large as that of H_2O megamasers. The detected H_2O emission has not been spatially resolved at angular resolution of 0.76 arcsec ($\simeq$16 parsecs). These results support the fact that 183 GHz emission in the galaxy is maser that is originated from AGN-activity but not in star-forming site. A clear velocity gradient nearly along axis of the sub-parsec scale maser disk probed by 22 GHz H_2O maser using VLBI at milliarcssecond resolution and a weak velocity dispersion are detected, which is also consistent with the earlier results obtained from 321 GHz H_2O masers.

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

1 Introduction

The H_2O vapour maser is a natural phenomenon that occurs in interstellar medium in young massive stars, evolved stars, and external galaxies. The basic knowledges on maser are described in literatures [8, 7]. Since H_2O maser emission pinpoints dynamical

*) 5-28-20, Hakusan, Bunkyo-ku, Natural Science Laboratory, Toyo University, Tokyo, 112-8606, Japan

structures in galaxies, it is worth utilizing the maser as a direct tool for probing inner part of active nuclei in galaxies.

The H_2O maser excited at frequency of 22.236 GHz (wavelength : 1.3 cm) has been well studied in our Galaxy, while the known H_2O maser in external galaxies, known in active galactic nuclei (AGN) that is also known as megamaser, is a relatively rare phenomenon [1, 2], compared with those observed in Galactic star-forming regions. Some H_2O megamasers excited at sub-millimeter wavelengths are known in the different transitions as well as those at 22 GHz [e.g.,] [11] : They are in 183.308 GHz (1.2 mm) and 321.226 GHz (0.7 mm) transitions. It is worth searching for H_2O maser in such different transitions toward AGN to find new probes for the nuclear region of AGN. Increasing the number of detected sub-millimeter H_2O maser or maser from other molecules would be necessary for that purpose. So, we should be able to conduct more searches for new sub-millimeter H_2O masers, exclusively toward known 22 GHz megamaser galaxies rather than taking a large sample toward active galaxies without biasing.

Since the excitation condition of H_2O maser in the 183 GHz transition is similar to that in the 22 GHz transition [12], it is likely that the maser excitation in the both transitions occurs in the same materials in a galaxy. The detections of the 183 GHz H_2O masers are already seen in the nearby AGN, NGC 4945 and the type 2 Seyfert galaxy NGC 3079 [11, 12]. Very recently, the bright 183 GHz H_2O maser has been detected toward the Superantennae galaxy (IRAS 19254-7245) at $z = 0.0617$, which will enable us to study a mass-accretion phenomenon onto a super massive black hole (SMBH) beyond the local Universe [15].

In this article, we focus on a report on the detection of 183 GHz H_2O maser towards the nearby AGN, Circinus galaxy using Atacama Large sub-Millimeter Array (ALMA).

2 Observations and Data analysis

We utilized the ALMA Science Archive, from which the data (#2018.1.00321.S) including Circinus galaxy was obtained. In this data of a mini-survey in nearby AGN, one can find searches for H_2O maser in the transition of $3_{13} - 2_{20}$ (183.308 GHz) that are towards other 18 AGN at angular resolutions of ~ 0.3" - 0.9". After having a preliminary analysis of the data, it turns out that the data contain more new detections of 183 GHz H_2O maser towards at least 7 AGN, which was reported in the earlier paper (Paper I) [6]. Data reduction due to pipeline analysis and imaging of the data were conducted with the standard software for ALMA data analysis, CASA (https://casa.nrao.edu) [16].

A list of the observed AGN revised from Paper I is shown in table 1. An rms sensitivity per one spectral channel is smaller than 25 mJy/beam, which was required in this survey. In total, 183 GHz H_2O emission lines are detected in eight AGN of 19 AGN sample, including Circinus galaxy, that constituted of known 22 GHz H_2O megamaser galaxies exhibiting spectra with Doppler-shifted features that imply the presence of a rotating disk around a central SMBH. All the detected emission lines are not spatially resolved at the given synthesized beam sizes of ALMA, and they are detected towards central continuum emission at centers of each galaxy. A summary of the observation of Circinus galaxy is shown in table 2.

3 Results

H_2O emission in the 183 GHz transition has been detected towards the center of Circinus galaxy. Given the fact that H_2O line-widths of each emission in figure 2 are narrow (<1 km s^{-1}) and emission is unresolved at the angular resolution of < ~0.76", corresponding to about 16 pc at a distance of 4.2 Mpc, thus we interpret that the detected H_2O emission resulted from maser amplification, but not thermally excited molecular emission. Hereafter in this article, we proceed discussion, by assuming that the detected 183 GHz H_2O emission is maser.

Figure 1 displays a 183 GHz continuum map of the Circinus galaxy that remains unresolved at 0.76 arcsecond resolution given by ALMA Band 5 observation and a velocity-integrated line intensity (0th moment) map.

Figure 2 (upper and lower figures) compares two maser spectra in the 321 GHz and 183 GHz transitions. Most prominent H_2O maser emission is peaked at VLSR = 556.3 km s^{-1} with a peak flux density of ~ 2 Jy in a signal-to-noise ratio (SNR) of > 100. Other prominent features are seen at V_{LSR} = 569.9, 560.3, 515.0, 389.6, and 360.6 km s^{-1} with a peak flux density of ~0.3 - 1.2 Jy.

Figure 3 shows a mean velocity (first moment) map and a velocity dispersion (second moment) map in the Circinus galaxy. One can see that there found a weak velocity gradient and dispersion in the maps, which are discussed in later section.

Table 1：List of galaxies searched for 183 GHz H_2O masers

Galaxy	V[a] (km/s)	Epoch[b] (yyyy-mm-dd)	Detection[c]
Circiunus galaxy	560	2018-12-01	○
NGC 1386	868	2018-11-16	○
NGC 1068	1137	2018-11-09	
IC 2560	2925	2018-10-30	
NGC 3393	3750	2018-10-30	
NGC 1194	4076	2018-11-16	△
Mrk 1419	4932	2018-11-14	○
ESO 269-G012	4950	2018-12-01	○
J 0126-0417	5639	2018-11-16	
NGC 5495	6737	2018-12-06	
CSCG 074-064	6886	2018-12-06	○
ESO 558-G009	7674	2018-10-31	△
NGC 5765b	8333	2018-12-06	○
IC 485	8338	2018-10-31	○
CSCG 165-035	9649	2018-12-06	
NGC 6264	10177	2018-11-18	
UGC 6093	10828	2018-10-31	△
J 0847-0022	15275	2018-11-08	○
J 0109-0332	16369	2018-11-06	

[a] Systemic velocity of galaxies that is primarily obtained from NED
[b] Date of observations in yyyy-mm-dd format
[c] Detection of 183 GHz H_2O maser :○, marginal detection ($< 3\sigma$): △

Table 2：Observations of Circinus galaxy

R.A.[a] (J2000)	Dec.[a] (J2000)	N_{Ant}[b]	t_{obs}[c] (sec)	θ_b(P.A.)[d] arcsec^2	$\Delta\nu$[e] (km/s)	σ_I[f] mJy/b
14:13:09.950	-65:20:21.20	43	2750	0.761" ×0.468"(-37.0°)	0.19	18

[a] Interferometry phase-tracking center position
[b] The number of 12-m antenna used in the observation
[c] Total observing time
[d] Synthesized beam size (beam position angle)
[e] Spectral velocity resolution
[f] An rms sensitivity of one channel with line emission

4 Discussion

4.1 Origin of the 183 GHz maser in the Circinus galaxy

What is the origin of the maser in the galaxy? The isotropic luminosity of the 183 GHz H_2O line can be estimated by using a formula : $L = 1.04 \times 10^{-3} \nu$ (GHz) D^2 (Mpc) $\int S dv$ (Jy km s^{-1}) $L_\odot$ (Sun's luminosity), in which ν is a rest frequency of 183.310 GHz, D is a distance to a galaxy in Mpc, and $\int Sdv$ is integrated intensity in Jy km s^{-1}. Given the distance of 4.2 Mpc to the galaxy and the total integrated intensity estimated from the spectrum of the 183 GHz H_2O emission of $\sim$ 30 Jy km s^{-1}, the luminosity of the maser is estimated to be $\approx$ 100 $L_\odot$.

The estimated luminosity is similar to that of 22 GHz H_2O megamasers that are associated to AGN-activity, strongly suggesting that the 183 GHz maser in the galaxy is not the maser that occurs in star-forming site but that is associated with the active nucleus of the galaxy. If the variability of flux density of the emission is found in future observations, that will confirm that the 183 GHz emission is maser like the 321 GHz maser.

4.2 Comparison of the 183 GHz maser with 22 GHz and 321 GHz maser

It is found that velocity range of the detected 183 GHz H_2O maser emission is very similar to those of 22 GHz and 321 GHz H_2O masers [3, 10], which indicates that in our line of sight the materials or gases which the 183 GHz maser arises from could be similar to that of 22 GHz H_2O masers. It would be interesting to explore what the 183 GHz maser will probe in the nuclear regions of AGN, which ought to be pursued in further observations with ALMA.

It is known that the upper state energy ($E_u/k = 1862$ K) of H_2O maser in the 321 GHz transition is significantly higher than that in the 22 GHz transition ($E_u/k = 644$ K), while the energy in the 183 GHz transition ($E_u/k = 205$ K) is even lower that in the 22 GHz maser. This might indicate that the known 321 GHz maser emission including the Circinus might not be sufficiently excited but part of the emission is inverted and most of the emission is thermalized. This explains that the 321 GHz H_2O maser is weaker than 183 GHz in the galaxy. The same trend is seen in the nearby AGN, NGC 4945, in which the flux density of the 183 GHz maser is approximately two orders of magnitude larger than that of the 321 GHz maser [12, 5].

4.3 Velocity gradient and dispersion

It is interesting to note that a weak but distinct velocity gradient of the 183 GHz maser has been detected in the center of the galaxy. The velocity gradient is seen nearly along the axis of a molecular gas disk identified on sub-parsec scales with 22 GHz

maser [4]. This is also consistent with earlier results obtained by 321 GHz H_2O maser [5]. A value of the detected velocity gradient is 40 km s^{-1} over $\sim$ 1", corresponding to about 20 pc, which results in the gradient of 2 km s^{-1} per one parsec, very small. The fact that overall direction of the gradient is not inconsistent with that of the sub-pc scale disk indicates that the 183 GHz and 22 GHz masers trace the same gas in our line of sight.
Moreover, the velocity dispersion is seen in part of the nuclear region and the value of the dispersion is about 20 km s^{-1}, which indicates a presence of turbulent of gas nearby an edge of the emission. The high-dispersion region is seen at near the edge, which is clearly offset from the center of the H_2O emission and its trend is similar to that of 321 GHz H_2O maser [5].
There is no straightforward interpretation of the detected velocity fields from the present data.

5 Summary

H_2O maser in the 183 GHz transition in Circinus galaxy is detected at the first time. The spectrum of the emission exhibits several Doppler-shifted features within about 300 km s^{-1} w.r.t. the systemic velocity. The estimated luminosity of the maser is about 100 $L_\odot$, assuming isotropic radiaion. Adding to the previous analysis in Paper I, at least eight 183 GHz H_2O masers are detected out of 19 AGN hosting 22 GHz megamasers, and the masers in three more AGN are tentatively detected in our preliminary analysis. Adding to the detection of the emission, the properties of these emissions like brightness temperatures or variability should be studied in further observations at higher angular resolution. The weak velocity gradient of the 183 GHz maser is distinctly found nearly along the axis of the molecular gas disk identified by VLBI mapping of the 22 GHz H_2O maser. Moveover, the velocity dispersion of the maser is barely detected at the northern edge of the H_2O emission. At this moment we have no clear interpretation of the detected velocity gradient and dispersion, however we speculate that the masers in the both 22 GHz and 183 GHz transitions trace same gas or materials, although the excitation energy of the 321 GHz maser is significantly higher than the 22 and 183 GHz maser. It should be also noted that the detected velocity gradient of the 183 GHzmaser is similar to that of the 321 GHz.

Further observations at a higher angular resolution would be necessary to reveal the gradient and dispersion. Comparison of the spectra in the both transitions show that the velocity ranges and velocities of Doppler-shifted components of the masers are very similar, which might support our speculation mentioned above.

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 Aeronautics and Space Administration and operated by the California Institute of Technology.

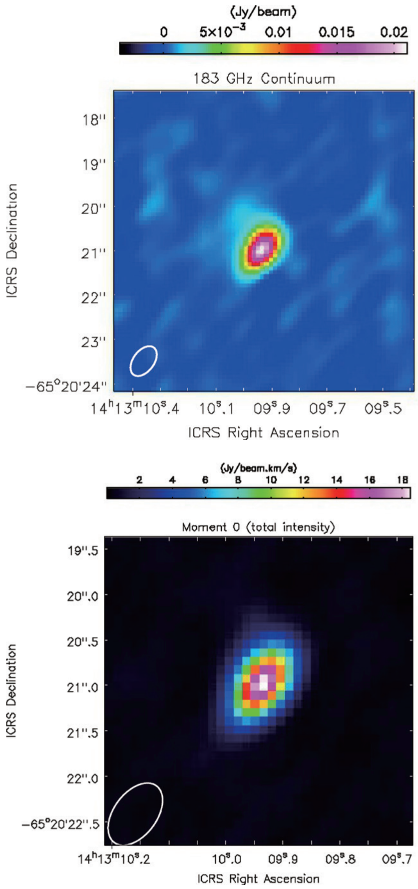

Figure 1 : (Upper) : 183 GHz continuum color-scale map in the Circinus galaxy. (lower) : Integrated line intensity map (zeroth moment). The synthesized beams are plotted in the bottom left corner in each map.

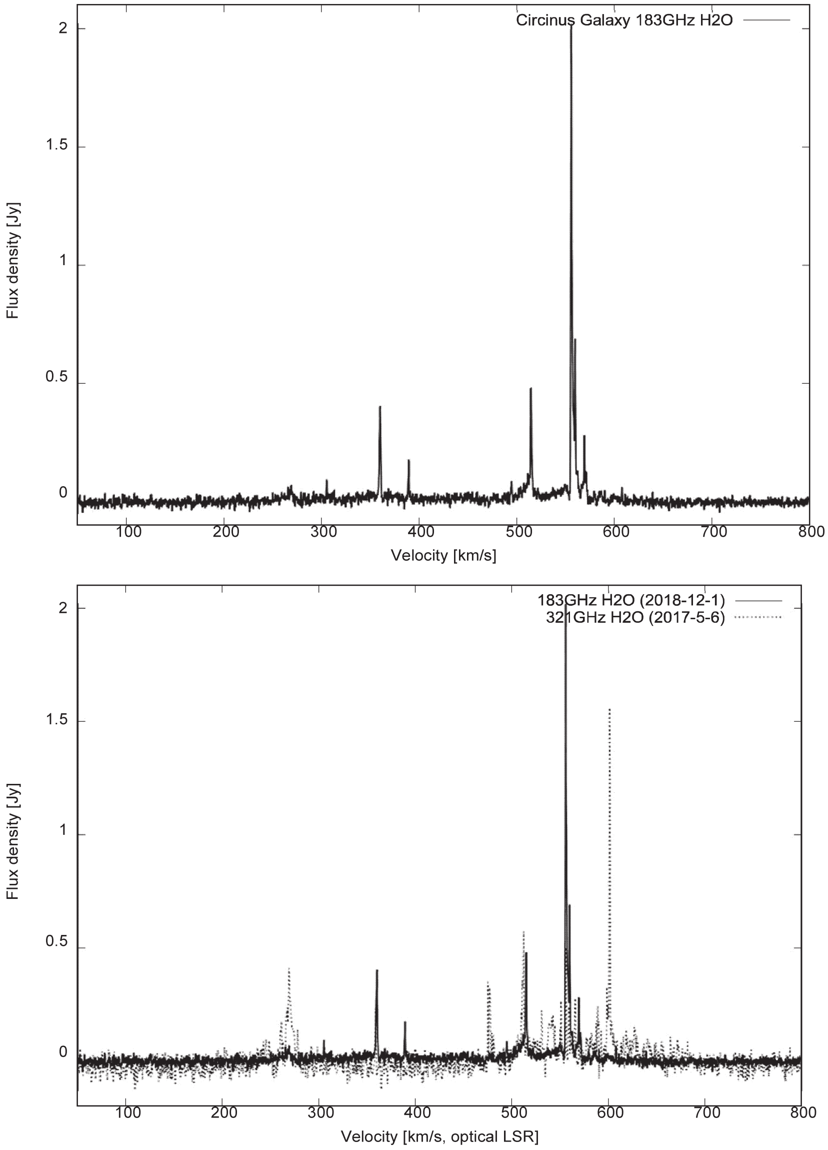

Figure 2 : (Upper) : Spectrum of 183 GHz H_2O maser emission toward the nucleus of the Circinus galaxy. (lower) : Comparison of 183 GHz and 321 GHz (dashed lines) H_2O maser spectra toward the nucleus of Circinus galaxy. The 321 GHz spectrum is from [5]. The systemic velocity of the galaxy is V_{LSR} = 433 km s^{-1}.

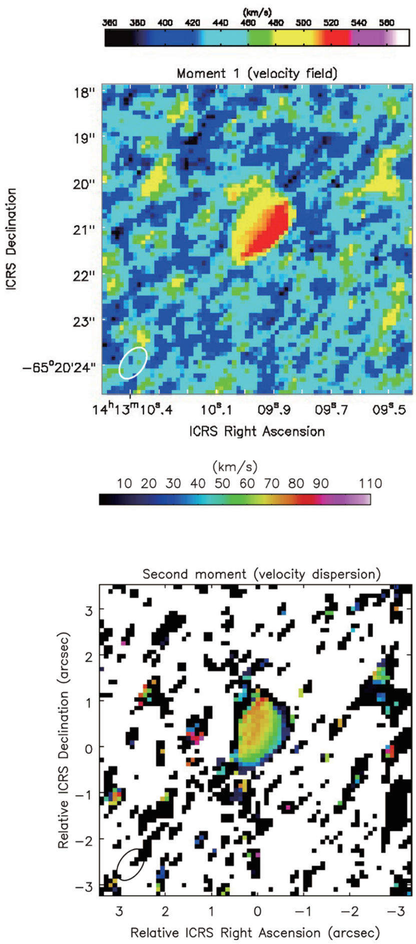

Figure 3 : Moment maps of the 183 GHz H_2O maser toward the center of Circinus galaxy. (Upper) : A mean velocity (first moment) map and (lower) : a velocity dispersion map (second moment). The synthesized beams are plotted in the bottom left in each map.

References

[1] Braatz, J. A., et al., 2003, *The Astrophysical Journal Supplement Series*, 146, 249
[2] Braatz, J. A., et al., 1997, *The Astrophysical Journal Supplement Series*, 110, 321
[3] Greenhill, L. J., Ellingsen, S. P., Norris, R. P., et al. 1997, *The Astrophysical Journal*, 474, L103
[4] Greenhill, L. J., Booth, R. S., Ellingsen, S. P., et al. 2003, *The Astrophysical Journal*, 590, 162
[5] Hagiwara, Y., Horiuchi, S., Imanishi, M., Edwards, P. 2021, *The Astrophysical*

Journal, 923, 251
[6] Hagiwara, Y. 2021, *Journal of Toyo University Natural Science*, 65, 53 (Paper I)
[7] Hagiwara, Y. 2017, Dialogos, Proceedings of the Department of English Communication, Faculty of Letters, Toyo University, 17, 105-114
[8] Hagiwara, Y. 2016a, Dialogos, Proceedings of the Department of English Communication, Faculty of Letters, Toyo University, 16, 71-80
[9] Hagiwara, Y., Horiuchi, S., Doi, A., Miyoshi, M., & Edwards, P. G., 2016b, *the Astrophysical Journal*, 827, 69
[10] Hagiwara, Y., Miyoshi, M., Doi, A., Horiuchi, S., 2013, *The Astrophysical Journal*, 768, L38
[11] Humphreys, E. M. L., Greenhill, L. J., Reid, M. J., Beuther, H., Moran, J. M., Gurwell, M., Wilner, D. J., Kondratko, P. T., 2005, *The Astrophysical Journal*, 634, L133
[12] Humphreys, E. M. L., Vlemmings, W. H. T., Impellizzeri, C. M. V., et al. 2018, *Astronomy & Astrophysics*, 592, L13
[13] Imanishi, M., Nakanishi, K., Izumi, T., Wada, K. 2018, *The Astrophysical Journal Letters*, 853, L25
[14] Imanishi, M., Nguyen, D. D., Wada, K., Hagiwara, Y. et al. 2020, *The Astrophysical Journal*, 902, 99
[15] Imanishi, M., Hagiwara, Y., Horiuchi, S., et al. 2021, *Monthly Notices of the Royal Astronomical Society*, 502, L79
[16] McMullin, J. P., Waters, B., Schiebel, D., et al. 2007, Astronomical Data Analysis Software and Systems XVI, 376, 127
[17] The Megamaser Cosmology Project Home page (J.Braatz):https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject (2020/11/10)
[18] Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., Inoue, M. 1995, *Nature*, 373, 127

和文摘要

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

Abstract

ALMA望遠鏡のアーカイブデータを利用して、18個の活動銀河核(AGN)に対して実施された183 GHz帯で励起される水(蒸気)メーザー探査のデータ解析結果については前拙著で報告した。本論文では上記18個のAGNに加えて、同アーカイブデータに含まれる近傍の代表的なAGNであるコンパス座のシルシナス銀河における183 GHz帯の水分子輝線観

測の成果を報告する。初期解析の結果、水分子輝線スペクトルは、銀河の系統速度に関してドップラー偏移する輝線速度成分の存在を示すことがわかった。検出された輝線の速度範囲は、22 GHzおよび321 GHz帯の水メーザーの速度範囲と同様なことがわかった。183 GHz水分子輝線のフラックス強度は、321 GHz 水メーザーと概ね同等であるが、22 GHz水メーザーよりは有意に弱い。また、等方性を仮定した183 GHz水分子輝線の光度は、約100太陽光度であると計算された。この値は22 GHz帯の水メガメーザーの光度に匹敵し、かつ検出されたメーザー源がコンパクトで、0.76秒（約16パーセクに相当）の角分解能で空間的に分解されていないことから、183 GHz帯の水分子輝線は熱的に励起された放射ではなく、AGNの活動性に付随するメーザーである事実を支持する。183 GHz水メーザーの速度構造を調べたところ、弱い速度勾配が検出され。その速度場の方向は、22 GHz水メーザーを利用してVLBIのミリ秒分解能でマッピングされたサブパーセクスケールのガス円盤の方向と矛盾しない。これは最近発表された321 GHzの水メーザーで得られた速度勾配の方向とも一致している。