Publ. Astron. Soc. Japan (2018) 70 (3), 54 (1–8)
doi: 10.1093/pasj/psy046
Advance Access Publication Date: 2018 May 4

Searches for H_2O masers toward narrow-line Seyfert 1 galaxies

Yoshiaki HAGIWARA,[1,2,*] Akihiro DOI,[3] Kazuya HACHISUKA,[2,4] and Shinji HORIUCHI[5]

[1]Natural Science Laboratory, Toyo University, 5-28-20 Hakusan, Bunkyo-ku, Tokyo 112-8606, Japan
[2]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, 181-8588 Tokyo, Japan
[3]The Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuou-ku, Sagamihara, Kanagawa 252-5210, Japan
[4]Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, Hoshigaoka 2-12, Mizusawa, Oshu, Iwate 023-0861, Japan
[5]CSIRO Astronomy and Space Science, Canberra Deep Space Communications Complex, PO Box 1035, Tuggeranong, ACT 2901, Australia

*E-mail:yhagiwara@toyo.jp

Received 2017 January 10; Accepted 2018 March 28

Abstract

We present searches for 22 GHz H_2O masers toward 36 narrow-line Seyfert 1 galaxies (NLS1s), selected from known NLS1s with $v_{\rm sys} \lesssim 41000\,\rm km\,s^{-1}$. Out of the 36 NLS1s in our sample, 11 have been first surveyed in our observations, while the observations of other NLS1s were previously reported in literature. In our survey, no new water maser source from NLS1s was detected at the 3σ rms level of 8.4 mJy to 144 mJy, which depends on different observing conditions or inhomogeneous sensitivities of each observation using three different telescopes. It is likely that the non-detection of new masers in our NLS1 sample is primarily due to insufficient sensitivities of our observations. Including the five known NLS1 masers, the total detection rate of the H_2O maser in NLS1s is not remarkably different from that of type 2 Seyfert galaxies or LINERs. However, more extensive and systematic searches of NLS1 would be required for a statistical discussion of the detection rate of the NLS1 maser, compared with that of type 2 Seyferts or LINERs.

Key words: galaxies: active — galaxies: nuclei — galaxies: Seyfert — masers — radio lines: ISM

1 Introduction

Luminous extragalactic H_2O masers in the transition of 6_{16}–5_{23} (rest frequency: 22.23508 GHz) are known to exist in central regions of active galactic nuclei (AGN). Many attempts at finding extragalactic H_2O masers have been made, with the result that detections of these masers are largely in type 2 Seyfert galaxies and LINERs (e.g., Claussen & Lo 1986; Braatz et al. 1996; Hagiwara et al. 2002; Kondratko et al. 2006; Wagner 2013). Some fraction of these H_2O masers associated with AGN-activity ("nuclear masers") have proven themselves to be useful in tracing the angular distribution of the maser spots within about one parsec from a central engine. The velocity range of highly Doppler-shifted (high-velocity) maser emission in the nuclear masers is offset by up to $\sim\pm 1000\,\rm km\,s^{-1}$ from a galaxy's systemic velocity, which indicates the presence of a rotating disc around a supermassive black hole in host galaxies (Miyoshi et al. 1995; Greenhill et al. 1996, 2003a; Herrnstein et al. 1999; Hagiwara et al.

2001; Ishihara et al. 2001; Kondratko et al. 2005, 2008; Mamyoda et al. 2009; Reid et al. 2009; Kuo et al. 2011; Gao et al. 2017).

Narrow-line Seyfert 1 galaxies (NLS1s) were first studied by Osterbrock and Pogge (1985). These galaxies show the following optical spectral properties: (1) The full width half maximum (FWHM) of the Hβ lines is less than 2000 km s^{-1}, (2) the permitted lines are somewhat broader than the forbidden lines, and (3) the relative weakness of the forbidden lines, such as [O III]λ5007/Hβ < 3 (Osterbrock & Pogge 1985; Goodrich 1989). There is evidence that NLS1s have mass accretion rates much closer to the Eddington limit than normal broad-line Seyfert galaxies, and the NLS1s accreting near the Eddington limit could have smaller black hole masses ($\sim 10^6\,M_\odot$) (Boroson & Green 1992; Boller et al. 1996; Mineshige et al. 2000; Peterson et al. 2000). The smaller masses of NLS1s are still under debate; their significantly smaller masses than expected from the $M_{\rm BH}$–σ relation have been shown compared to broad-line AGN and quiescent galaxies (e.g., Mathur et al. 2001; Grupe & Mathur 2004), while no strong evidence of such a deviation has been presented (e.g., Wang & Lu 2001; Komossa et al. 2008; Woo et al. 2015). It is essential to understand the structure of an NLS1's central engine via some different approaches.

Hagiwara et al. (2003) first discovered a bright H_2O maser toward the NLS1 NGC 4051. Stimulated by this discovery, single-dish observations searching for new extragalactic H_2O masers toward NLS1s were conducted, and these observations yielded the detections of new H_2O masers in three NLS1s; Mrk 766, IRAS 03450+0055, and IGR J16385−2057 (Tarchi et al. 2011). The detection of H_2O maser emission toward a Seyfert 1.5 galaxy, NGC 4151 was reported by Braatz et al. (2004). The galaxy is known to host a well-studied broad-line region and shows intermediate optical properties between type 1 and type 2 Seyferts (e.g., Mundell et al. 1995). These results show that H_2O masers in active galaxies (a.k.a. "megamasers") have been found in type 2 Seyfert, LINER, NLS1s, and other types of Seyfert nuclei. Some fraction of the megamasers are considered to be associated with ejecta from AGN, such as jets or winds (e.g., Claussen et al. 1998; Greenhill et al. 2003a). The recent study of radio-quiet NLS1s (e.g., Mrk 1239, Mrk 766) using very long baseline interferometry (VLBI) revealed that some NLS1s exhibit parsec-scale radio jets within 300 pc of the central engine (Doi et al. 2013, 2015; Doi 2015). The results would imply that H_2O masers in NLS1s are a potential tracer of the circumnuclear regionsof AGN by analogy with the masers in type 2 Seyferts with (sub)parsec-scale non-thermal jets.

The H_2O masers in NLS1s provide important information about the geometry and kinematics of a disc or disc-like structure, jets and winds around the central engine of AGN, like the cases of the H_2O masers in type 2 Seyferts, LINERs, and radio galaxies (e.g., Miyoshi et al. 1995; Hagiwara et al. 2001; Greenhill et al. 2003a; Kuo et al. 2011; Ott et al. 2013). However, the origin of H_2O masers in NLS1s has not been well understood, because most of them are not bright enough to be imaged at milliarcsecond (mas) angular resolution using VLBI.

This article presents studies of H_2O maser in NLS1s, based on observations using the 45 m telescope at Nobeyama Radio Observatory (NRO), the 100 m telescope of the Max-Planck-Institut für Radioastronomy (MPIfR), and the NASA Deep Space Network 70 m telescope at Tidbinbilla (DSS-43). The studies of many H_2O maser sources in NLS1s will uncover radio properties of this class of AGN, and provide clues for solving problems in the unified theory (e.g., Antonucci & Miller 1985; Urry & Padovani 1995). This article also uses results from other searches for statistics on maser detection. Throughout this article, cosmological parameters of $H_0 = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.73$, and $\Omega_M = 0.27$ are adopted.

2 Sample selection

In our survey, 36 relatively nearby NLS1s ($\upsilon_{\rm sys} \lesssim$ 41000 km s^{-1}) from NLS1 galaxy samples in literature (Mathur et al. 2001; Véron-Cetty et al. 2001; Deo et al. 2006; Whalen et al. 2006) were programmed to search for new H_2O maser sources. Two NLS1s known to host H_2O maser emission, NGC 4051 and NGC 5506 were selected to search for new high-velocity components; NGC 5506 has been identified as an obscured NLS1 by near-IR spectroscopy (Nagar et al. 2002), but not by the definition based on optical spectral properties as summarized in the previous section. The 26 NLS1s were observed in 2005–2006 at Nobeyama or Effelsberg. In addition, 14 NLS1s with relatively larger systemic velocities or lower declinations, of which four were also observed at Nobeyama or Effelsberg, were observed in 2012 at Tidbinbilla (table 1). In all, 36 NLS1s were observed in our program. Mrk 766, which appears to provide evidence for an accretion disc around the central black hole from X-ray observations (Turner et al. 2006), was included in our list without knowing the fact that the galaxy was observed in other surveys. Coordinates and systemic velocities of galaxies observed in our program, 1σ sensitivities, and velocity resolutions at each telescope are listed in table 2.

3 Observations

Single-dish searches for 22 GHz H_2O maser emission toward NLS1s were made during the periods of 2005 May

Table 1. Summary of observations.

Telescope	Date	Number of sources*	Sensitivity (1σ) (mJy)	Note
Nobeyama	2005 May 25–June 3	20	8.7–48	AOS spectrometer used
	2012 March 12–14	3	15–24	SAM45 spectrometer used
Effelsberg	2006 February 3–6	19	2.8–8.5	
Tidbinbilla	2012 July 23–October 23	14	4.3–27	Sources below $+20^{\circ}$ Declinations included

*The total number of targeted NLS1 galaxies is 36 as listed in table 2, while some of them were observed multiple times.

Table 2. Summary of observations of narrow-line Seyfert 1 galaxies.

Source*	$\alpha_{J2000.0}$†	$\delta_{J2000.0}$†	V‡ (km s^{-1})	σ_{45}§ (mJy)	σ_{100}§ (mJy)	σ_{70}§ (mJy)	$\Delta\nu_{45}$‖ (km s^{-1})	$\Delta\nu_{100}$‖ (km s^{-1})	$\Delta\nu_{70}$‖ (km s^{-1})
MRK 335	$00^{h}06^{m}19.^{s}5$	$+20^{\circ}12'10''$	7730	21	4.0		1.5	1.1	
I Zw 1	$00^{h}53^{m}34.^{s}9$	$+12^{\circ}41'36''$	18330	9.8		6	1.5		1.6
MRK 359	$01^{h}27^{m}32.^{s}5$	$+19^{\circ}10'44''$	5212	17			1.5		
MRK 1044	$02^{h}30^{m}05.^{s}5$	$-08^{\circ}59'53''$	4932	15		9	1.5		1.6
MRK 618	$04^{h}36^{m}22.^{s}2$	$-10^{\circ}22'34''$	10658			4.3			1.6
PKS 0558–504	$05^{h}59^{m}47.^{s}4$	$-50^{\circ}26'52''$	41132			6.5			1.6
J 07084153–4933066	$07^{h}08^{m}41.^{s}5$	$-49^{\circ}33'07''$	12162			5.5			1.6
MRK 382	$07^{h}55^{m}25.^{s}3$	$+39^{\circ}11'10''$	10139	16	3.6		1.5	1.1	
				15			1.6		
MRK 0110	$09^{h}25^{m}12.^{s}8$	$+52^{\circ}17'10''$	10580	17	5.3		1.5	1.1	
MRK 705	$09^{h}26^{m}03.^{s}3$	$+12^{\circ}44'04''$	8739	8.7	3.3	12	1.5	1.1	1.6
MRK 0124	$09^{h}48^{m}42.^{s}6$	$+50^{\circ}29'31''$	16878	15	2.9		1.5	1.1	
MRK 1239	$09^{h}52^{m}19.^{s}0$	$-01^{\circ}36'43''$	5974	14	8.5	5.5	1.5	1.1	1.6
KUG 1031+398	$10^{h}34^{m}38.^{s}6$	$+39^{\circ}38'28''$	12724	16	3.8		1.5	1.1	
MRK 734	$11^{h}21^{m}47.^{s}0$	$+11^{\circ}44'18''$	15050		3.1			1.1	
MRK 42	$11^{h}53^{m}41.^{s}8$	$+46^{\circ}12'43''$	7385	17			1.5		
NGC 4051	$12^{h}03^{m}09.^{s}6$	$+44^{\circ}31'53''$	700	16	5.9		1.5	1.1	
				24			1.6		
MRK 766	$12^{h}18^{m}26.^{s}5$	$+29^{\circ}48'46''$	3876	12	7.3		1.5	1.1	
				15			1.6		
WAS 61	$12^{h}42^{m}10.^{s}6$	$+33^{\circ}17'03''$	13045		3.2			1.1	
J 12431152–0053442	$12^{h}43^{m}11.^{s}5$	$-00^{\circ}53'45''$	24546			31			1.6
NGC 4748	$12^{h}52^{m}12.^{s}4$	$-13^{\circ}24'53''$	4386			5.0			1.6
MRK 783	$13^{h}02^{m}58.^{s}9$	$+16^{\circ}24'27''$	20146	21	2.9		1.5	1.1	
IRAS 13224–3809	$13^{h}25^{m}19.^{s}4$	$-38^{\circ}24'53''$	19726			22			1.6
PG 1404+226	$14^{h}06^{m}21.^{s}8$	$+22^{\circ}23'46''$	29380	17			1.5		
NGC 5506	$14^{h}13^{m}14.^{s}8$	$-03^{\circ}12'27''$	1853		5.6			1.1	
MRK 478	$14^{h}42^{m}07.^{s}4$	$+35^{\circ}26'23''$	23700		3.4			1.1	
PG 1448+273	$14^{h}51^{m}08.^{s}8$	$+27^{\circ}09'27''$	19487	18	6.5		1.5	1.1	
IRAS 15091−2107	$15^{h}11^{m}59.^{s}8$	$-21^{\circ}19'02''$	13373			12			1.6
15480−051	$15^{h}48^{m}56.^{s}8$	$-04^{\circ}59'34''$	29917		2.9			1.1	
MRK 493	$15^{h}59^{m}09.^{s}6$	$+35^{\circ}01'48''$	9392	12			1.5		
IRAS 17020+4544	$17^{h}03^{m}30.^{s}4$	$+45^{\circ}40'47''$	18107	48	3.0		1.5	1.1	
MRK 507	$17^{h}48^{m}38.^{s}4$	$+68^{\circ}42'16''$	16758	14			1.5		
1927+654	$19^{h}27^{m}19.^{s}5$	$+65^{\circ}33'54''$	5096		2.8			1.1	
1H 1934−063 A	$19^{h}37^{m}33.^{s}0$	$-06^{\circ}13'05''$	3074			27			1.6
2159+0113	$21^{h}59^{m}24.^{s}0$	$+01^{\circ}13'05''$	30041			5.0			1.6
AKN 564	$22^{h}42^{m}39.^{s}3$	$+29^{\circ}43'31''$	7400	9.8	4.3		1.5	1.1	
2327–1023	$23^{h}26^{m}56.^{s}1$	$-10^{\circ}21'43''$	19557			4.6			1.6

*NLS1s hosting 22 GHz H_2O maser are indicated in bold type.
†Right ascension ($\alpha_{J2000.0}$) and declination ($\delta_{J2000.0}$). Source coordinates are taken from NED.
‡Systemic velocity (heliocentric definition from NED).
§σ_{45}, σ_{100}, and σ_{70} are 1σ noise per velocity resolution.
‖$\Delta\nu_{45}$, $\Delta\nu_{100}$, and $\Delta\nu_{70}$ are velocity resolutions at Nobeyema, Effelsberg, and Tidbinbilla.

25 to June 3, 2006 February 3 to 6, 2012 March 12 to 14, and 2012 July 23 to October 23. The observations in the first and third periods were carried out using the Nobeyama 45 m telescope (NRO 45 m), those in the second period were conducted using the Effelsberg 100 m telescope, and those in the fourth period were made using the Deep Space Network 70 m telescope at Tidbinbilla. All the observations in this program were made in the position-switching mode. These observations are summarized in table 1. Originally, all 26 sources were scheduled at both the NRO 45 m and Effelsberg 100 m telescopes, however some sources were observed once and some twice due to technical problems of telescope back-end at Effelsberg or weather conditions. In addition, 10 new sources at declination below $+20^{\circ}$ were scheduled at Tidbinbilla.

3.1 Nobeyama 45 m

The half-power beam width (HPBW) of the NRO 45 m was $\sim 74''$ at 22 GHz and the system noise temperature was about 90 K to 160 K. The pointing calibration of each galaxy was conducted every 1 hr to 2 hr by observing 43 GHz SiO maser stars near galaxies, which resulted in a pointing accuracy of $\sim 5''$–$10''$, typically. A conversion factor of the antenna temperature to the flux density is estimated to be 2.63 Jy K^{-1}, adopting the aperture efficiency value of 66% (T. Umemoto 2011 private communication), and a flux density accuracy of $\sim 10\%$ is estimated. In the NRO 45 m observations in 2005, the acousto-optical spectrometer (AOS) was configured to record 2048 frequency points over a 40 MHz bandwidth for both left and right circularly polarized signals. We used an array of eight AOSs, resulting in a total velocity coverage of $\sim 2100\,\mathrm{km\,s^{-1}}$ for each polarization, nearly centred on the systemic velocity and having a frequency resolution of 39 kHz ($\sim 0.5\,\mathrm{km\,s^{-1}}$). In the 2012 observations the new FX-type SAM45 spectrometer was used for the telescope back-end, in which an array of eight IFs, subdivided into 250 MHz bandwidths, was employed, each of which has 4096 spectral points, providing 61 kHz frequency resolution. The total velocity coverage and velocity resolution are $26000\,\mathrm{km\,s^{-1}}$ and $0.83\,\mathrm{km\,s^{-1}}$, respectively. In our analysis of the SAM45 data, two frequency channels were smoothed, which resulted in a velocity resolution of $\sim 1.6\,\mathrm{km\,s^{-1}}$. (Note that in table 2 the sources listed with a $0.5\,\mathrm{km\,s^{-1}}$ velocity resolution were observed using the AOS spectrometer, and those with the $1.6\,\mathrm{km\,s^{-1}}$ resolution were observed using the SAM45.)

3.2 Effelsberg 100 m

The system temperatures and HPBW beam size were about 70 K to 120 K and $\sim 40''$, respectively, in 22 GHz observations of the Effelsberg 100 m. At Effelsberg, eight-channel autocorrelators (AK90) were employed, each of them having a 40 MHz IF bandwidth and 512 spectral points, which yielded a 78 kHz frequency resolution. In our observations, four IF bands for each circular polarization were being used, which resulted in a total velocity coverage of $\sim 2100\,\mathrm{km\,s^{-1}}$, nearly centered on the systemic velocity, and a velocity resolution of $\sim 1.1\,\mathrm{km\,s^{-1}}$. The pointing calibration was made by observing nearby strong continuum sources every 1 hr to 1.5 hr, yielding a pointing accuracy of better than $\sim 5''$. The telescope sensitivity of 3.1 Jy K^{-1} is estimated, based on the standard gain curve formula of the Effelsberg 100 m (Gallimore et al. 2001). The accuracy of the flux density is estimated to be $\sim 10\%$.

3.3 Tidbinbilla 70 m

The system temperatures and HPBW beam size were about 25 K to 160 K and $\sim 48''$, respectively. Pointing errors were measured and corrected using nearby bright quasars before observations, resulting in a pointing accuracy of $\sim 7''$. The Australian Telescope National Facility (ATNF) Correlator was configured to record 2048 spectral channels per polarization over a 64 MHz bandwidth for both left and right circularly polarized signals (e.g., Surcis et al. 2009; Breen et al. 2013), yielding a total velocity coverage of $\sim 860\,\mathrm{km\,s^{-1}}$ and spectral resolution of 31.25 kHz or $0.42\,\mathrm{km\,s^{-1}}$. The telescope sensitivity of 1.5 Jy K^{-1} is adopted (Greenhill et al. 2003b), and the accuracy of flux density is estimated to be $\sim 10\%$.

Data reduction was conducted using the software packages NEWSTAR for NRO 45 m data, CLASS for Effelsberg 100 m data, and ATNF Spectral Analysis Package (ASAP) for Tidbinbilla 70 m data. Some data flagging was required due to spurious-like peaks or noises appearing in the band edges.

In this article, the velocities are calculated with respect to the Local Standard of Rest (LSR), and at Effelsberg and Tidbinbilla the optical convention is adopted, while the radio velocity definition is used at Nobeyama.

4 Results

In this program, no new H_2O maser source was detected at the 3σ detection level of ~ 8 mJy–90 mJy per spectral channel, as a result of the exclusion of the NRO 45 m observation of IRAS 17020+4544 that shows a very high rms value. This implies that no strong H_2O maser was in the observed NLS1s during the observing periods. In our observations, the maser from Mrk 766 was not detected, which is likely due to the intensity variability of the maser. The maser in Mrk 766 should have been marginally detected in 2σ at Effelsberg, if its peak flux density was as bright

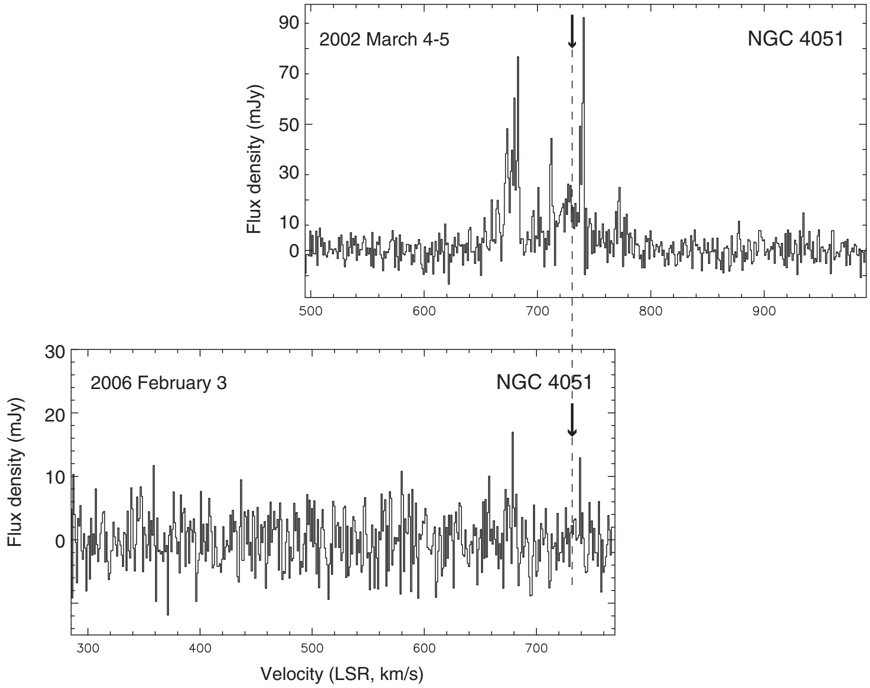

Fig. 1. Spectra of H_2O maser ($\Delta v = 2.1\,\mathrm{km\,s^{-1}}$) between 275–775 $\mathrm{km\,s^{-1}}$ toward the centre of NGC 4051, obtained with the Effelsberg 100 m in 2002 and 2006. The vertical dotted line and arrows denote the systemic velocity of the galaxy (730 $\mathrm{km\,s^{-1}}$). The vertical axis denotes flux density scaled in Jansky, and the horizontal axis LSR velocity.

as that observed at the NRAO Green Bank Telescope (GBT) in 2008 ($\sim$15 mJy) (Tarchi et al. 2011). The H_2O maser spectra of NGC 4051 in figure 1 show the flux variability between two epochs of the two known features at $V = 679$ and 738–741 $\mathrm{km\,s^{-1}}$, which were reported in earlier observations (Hagiwara et al. 2003; Hagiwara 2007). No new H_2O maser features were found in the observed bands toward the galaxy. The maser emission in the NLS1s was searched in the velocity range of $\sim\pm$400–800 $\mathrm{km\,s^{-1}}$ with respect to the systemic velocities of galaxies. Measured rms noises were $\sim$9 mJy to 48 mJy per smoothed two or three channels (SAM45 or AOS) at Nobeyama, $\sim$3 mJy to $\sim$9 mJy at Effelsberg, and $\sim$4 mJy to $\sim$30 mJy at Tidbinbilla (table 2). We targeted 36 NLS1s (Ulvestad et al. 1995; Véron-Cetty et al. 2001; Komossa et al. 2006; Mullaney & Ward 2008), out of which 26 NLS1s overlap those observed in the survey using the GBT (Tarchi et al. 2011). In Tarchi et al. 2011, new detections of the masers in two NLS1s, IGR J16385−2057 and IRAS 03450+0055, were reported. These two known NLS1 maser galaxies are not included in our sample.

5 Discussion

5.1 No detection of new H_2O maser in NLS1

Of the 36 sources observed in our observations, Mrk 766 is included. However, the maser in that galaxy was not detected in 2005 nor 2006 in our observations. After our observations, the maser was detected in the NLS1 survey in 2008 with the GBT (Tarchi et al. 2011). It should be noted that the survey was more sensitive ($1\,\sigma \lesssim 3$ mJy per spectral channel of 0.33 $\mathrm{km\,s^{-1}}$) than ours ($1\sigma \sim$3–48 mJy per channel, or 7.3/12 mJy for Mrk 766).

Including the five known NLS1 masers, 71 NLS1s were surveyed with the GBT by Tarchi et al. and in our survey and 11 NLS1s were surveyed only in our survey, as a result of which the total detection rate of the H_2O maser in NLS1s is estimated to be $\sim$6% (5/82). It is shown that the nominal detection rates of the past H_2O megamaser surveys of type 2 Seyferts and LINERs are $\sim$3% (Braatz et al. 1997; van den Bosch et al. 2016), and in a survey of 40 AGNs with the GBT (Greenhill et al. 2009), the detection rate was $3/40 = 7.5\%$ in the $v_{\mathrm{sys}} < 20000\,\mathrm{km\,s^{-1}}$ sample. The GBT "snapshot" survey of nearby galaxies ($v_{\mathrm{sys}} < 5000\,\mathrm{km\,s^{-1}}$) by Braatz et al. (2008) has a detection rate of 1.3%, however the survey detected eight new masers. Thus, the detection rate of the NLS1 maser is not remarkably different from that in previous extragalactic H_2O maser surveys that have detection rates of, at most, several percent. Moreover, a recent systematic study that compiled the results of past megamaser surveys revealed that the detection rate will be improved from $\sim$3% to $\sim$16% with the bias of higher extinction and higher optical luminosity, that is, the luminosity of [O III] λ5007 (Zhu et al. 2011). Finally, we

Table 3. Column density of the known NLS1 masers.

Source	N_H* (10^{22} cm^{-2})	Reference
IRAS 03450+0055	—[†]	Rush et al. (1996)
NGC 4051	8–37	Madejski et al. (2006)
Mrk 766	20–30[‡] >	Risaliti et al. (2011)
NGC 5506	3.40	Molina et al. (2013)
IGR J16385−2057	0.12	Molina et al. (2013)

*N_H are adopted from published X-ray data from IRAS 03450+0055 (ROSAT), Mrk 766 (BeppoSAX), NGC 5506 and IGR J16385−2057 (INTEGRAL), and NGC 4051 (Chandra).
[†]Galactic N_H(soft X-ray) from the ROSAT All-Sky Survey is 5.89×10^{20} cm^{-2}.
[‡]Lower limit value.

speculate that there is no evidence that an incidence of an H_2O maser in NLS1s is either more or less probable than in other AGN masers in type 2 Seyferts or LINERs.

One of the most critical problems in our programme lies in the insufficient sensitivities of our survey, which makes it difficult to have a statistical discussion, compared to past surveys. This is, for example, consistent with our non-detection of the Mrk 766 maser.

5.2 Column density and X-ray properties of H_2O megamasers

In earlier studies, correlation between the incidence of H_2O maser emission and high column density (N_H) in type 2 Seyferts and LINERs was demonstrated (Kondratko et al. 2006; Zhang et al. 2006; Greenhill et al. 2008; Castangia et al. 2013). Of 42 AGN megamasers that have column densities available from published hard X-ray data, 95% have $N_H \gtrsim 10^{23}$ cm^{-2}, or, alternatively, 60% are Compton-thick, with $N_H \gtrsim 10^{24}$ cm^{-2} (Greenhill et al. 2008). Moreover, of 21 disc masers in which masers originate in subparsec- or parsec-scale discs, 76% are Compton-thick and the others are 10^{23} cm^{-2} $\lesssim N_H \lesssim 10^{24}$ cm^{-2} (Greenhill et al. 2008). According to the recent study with the X-ray observatory NuSTAR (Nuclear Spectroscopic Telescope Array) in the high-energy X-ray range (3–79 keV), of 14 disc masers in type 2 Seyferts, 79% of masers are Compton-thick, and 21% are Compton-thin (Masini et al. 2016), which is largely consistent with the earlier study by Greenhill, Tilak, and Madejski (2008). In contrast, the column densities of NLS1s are no higher than 10^{24} cm^{-2} (e.g., Panessa et al. 2011). The summary of column density (N_H) for the known NLS1 H_2O maser is shown in table 3, in which there is no NLS1 showing column densities in excess of $N_H \sim 10^{24}$ cm^{-2}, showing that nuclear obscuration in NLS1s, including those hosting the maser, is smaller than those in type 2 Seyferts or LINERs.

Column densities toward active nuclei are obtained from Madejski et al. (2006) (NGC 4051), Risaliti et al. (2011) (Mrk 766), and Molina et al. (2013) (NGC 5506 and IGR J16385−2057), except for IRAS 03450+0055, the column density of which was measured by hard X-ray toward a nucleus and is not available in the literature (table 3). It is interesting to note that one of the best-studied disc masers, NGC 4258 ($N_H = 0.6$–1.3×10^{23} cm^{-2}) and a known disc maser NGC 4388 ($N_H = 0.02$–4.8×10^{23} cm^{-2}) are Compton-thin (Madejski et al. 2006), hence the occurrence of the maser cannot be explained simply by high column density.

5.3 Origin of H_2O masers in NLS1s

The small number of the detection of NLS1 masers demonstrates that masers are seen less enhanced because the masing discs are viewed less edge-on in the line of sight, which is consistent with a picture of type 1 Seyfert nuclei in the AGN unified model (Antonucci & Miller 1985; Urry & Padovani 1995). The masers in NLS1s are associated with AGN-activity like other AGN masers. However, their averaged apparent maser luminosity [$10\,L_\odot \lesssim L(H_2O) \lesssim 100\,L_\odot$] is one order of magnitude lower than that of high-luminosity masers with $L(H_2O) \gtrsim 100\,L_\odot$ (Hagiwara 2007). According to Zhang et al. (2006), comparison between kilomasers [$L(H_2O) \lesssim 10\,L_\odot$] and high-luminosity masers shows that high-luminosity masers have higher N_H. Thus, it is less likely that a number of NLS1 masers with high luminosity will be detected in future single-dish surveys. However, we expect to find as many NLS1 masers with luminosities as low [$10\,L_\odot \lesssim L(H_2O) \lesssim 100\,L_\odot$] as in other AGN masers. Figure 2 shows the spectra of the three NLS1 masers, obtained by Tarchi et al. (2011). The velocity ranges of the observed maser emission in these galaxies and NGC 4051 are smaller than $\sim$100 km s^{-1}, which could be explained by the lower disc inclination angle of NLS1s: the apparent line-of-sight velocities (v_{los}) are expressed as $v_{los} = v_{rad} \sin i$, where i is a disc inclination angle, and v_{los} with $i = 30^\circ$–40° is calculated to be about 30%–50% smaller than those in a more edge-on disc ($i > 70^\circ$). Alternatively, there is the possibility that these masers are associated with jets or winds in nuclear regions. We need a larger sample of the masers in NLS1s to examine these possibilities.

5.4 NGC 4051

Figure 1 demonstrates that the maser flux density in NGC 4051 is weaker than that in earlier observations by a factor of $\sim$3, due to variability. The maser in that galaxy was first detected in 2002 by Hagiwara et al. (2003). They

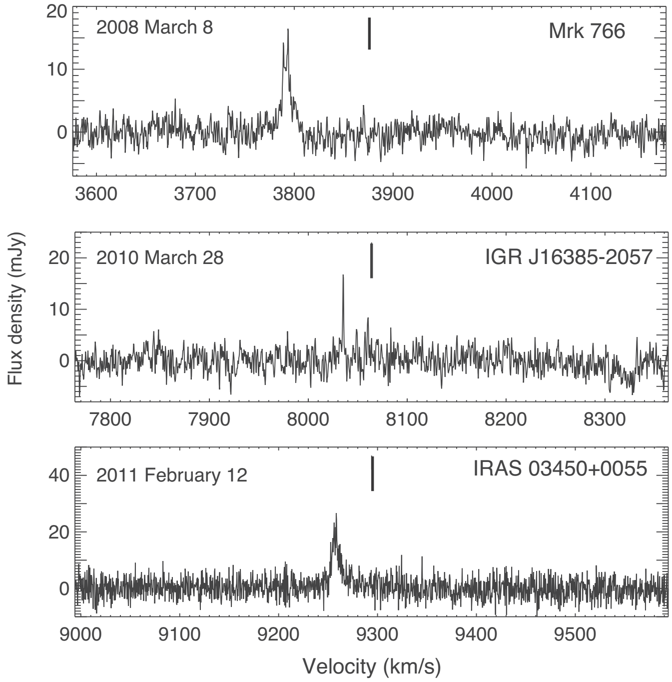

Fig. 2. Published GBT spectra of H_2O masers in the three NLS1 galaxies Mrk 766, IGR J16385–2057, and IRAS 03450+0055 (Tarchi et al. 2011). In these figures, heliocentric velocity definition is adopted and vertical bars denote the systemic velocity of the galaxies.

argued that it was a disc maser associated with an active nucleus. However, to date there has been no direct evidence that the maser originates in a parsec or sub-parsec scale disc around the nucleus in the galaxy. Madejski et al. (2006) explains that the broadly distributed narrow line emission in the galaxy is consistent with a wind maser associated with nuclear galactic winds related to the formation of narrow-line Seyfert 1 spectra (Greenhill et al. 2003a). The galaxy exhibits significant variability in column density caused by the ionized absorbing medium (McHardy et al. 1995), which should be physically separated from the molecular medium giving a rise to the maser, so the variability of the maser is not due to the variability of the column density. Similarly, Mrk 766 shows N_H variability that originates from ionized gas (Risaliti et al. 2011) and not from the masing medium. The significant variability of the maser may be explained by the variability of the background continuum in the nuclear region as in NGC 6240 (Hagiwara & Edwards 2015), whereas 22 GHz nuclear continuum from NGC 4051 has not been detected.

6 Summary

We searched for 22 GHz H_2O masers toward 36 narrow-line Seyfert 1 galaxies (NLS1s) using the NRO 45 m, Effelsberg 100 m, and Tidbinbilla 70 m telescopes. We did not detect any new maser sources toward these NLS1s. We discussed possible causes of the non-detection, one of which is small number statistics by considering the overall detection rate of 3% in previous extragalactic maser surveys, and the other is the insufficient sensitivities of our survey. There is no evidence for the occurrence of masers in NLS1s being higher or lower than in type 2 Seyferts or LINERs, although the higher detection rate of NLS1 masers is claimed in Tarchi et al. (2011).

More detections of new maser sources in NLS1s would be necessary to establish the overall nature of NLS1 masers. However, the number of detections of the maser sources in NLS1s could be small due to their low maser luminosity. We note that no high-velocity maser features in NGC 4051 have been detected since the first detection in 2002. This might imply that the maser in the galaxy is not a disc maser but a wind maser associated with nuclear winds.

Acknowledgments

This research was supported by the Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (B) (Grant Number: JP15H03644). The Nobeyama Radio Observatory is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences. Based on observations with the 100 m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg. The Tidbinbilla 70 m DSS-43 telescope is part of the Canberra Deep Space Communication Complex (CDSCC), which is operated by CSIRO Astronomy and Space Science on behalf of NASA. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. YH thanks Koichiro Sugiyama and Teppei Tamaki for their help in observations at Nobeyama, and Alan Roy for useful comments to improve the initial draft of this article. YH also thanks Toshihiro Kawaguchi for valuable comments and suggestions.

References

Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Boller, Th., Brandt, W. N., & Fink, H. 1996, A&A, 305, 53
Boroson, T. A., & Green, R. F. 1992, ApJS, 80, 109
Braatz, J. A., & Gugliucci, N. E. 2008, ApJ, 678, 96
Braatz, J. A., Henkel, C., Greenhill, L. J., Moran, J. M., & Wilson, A. S. 2004, ApJ, 617, L29
Braatz, J. A., Wilson, A. S., & Henkel, C. 1996, ApJS, 106, 51
Braatz, J. A., Wilson, A. S., & Henkel, C. 1997, ApJS, 110, 321
Breen, S. L., Lovell, J. E. J., Ellingsen, S. P., Horiuchi, S., Beasley, A. J., & Marvel, K. 2013, MNRAS, 432, 1382
Castangia, P., Panessa, F., Henkel, C., Kadler, M., & Tarchi, A. 2013, MNRAS, 436, 3388
Claussen, M. J., Diamond, P. J., Braatz, J. A., Wilson, A. S., & Henkel, C. 1998, ApJ, 500, L129
Claussen, M. J., & Lo, K.-Y. 1986, ApJ, 308, 592
Deo, R. P., Crenshaw, D. M., & Kraemer, S. B. 2006, AJ, 132, 321
Doi, A. 2015, PASJ, 67, 15
Doi, A., Asada, K., Fujisawa, K., Nagai, H., Hagiwara, Y., Wajima, K., & Inoue, M. 2013, ApJ, 765, 69
Doi, A., Wajima, K., Hagiwara, Y., & Inoue, M. 2015, ApJ, 798, L30
Gallimore, J. F., Henkel, C., Baum, S. A., Glass, I. S., Claussen, M. J., Prieto, M. A., & Von, Kap-herr A. 2001, ApJ, 556, 694
Gao, F., et al. 2017, ApJ, 834, 52
Goodrich, R. W. 1989, ApJ, 342, 224
Greenhill, L. J., et al. 2003a, ApJ, 590, 162
Greenhill, L. J., Gwinn, C. R., Antonucci, R., & Barvainis, R. 1996, ApJ, 472, L21
Greenhill, L. J., Kondratko, P. T., Lovell, J. E. J., Kuiper, T. B. H., Moran, J. M., Jauncey, D. L., & Baines, G. P. 2003b, ApJ, 582, L11
Greenhill, L. J., Kondratko, P. T., Moran, J. M., & Tilak, A. 2009, ApJ, 707, 787
Greenhill, L. J., Tilak, A., & Madejski, G. 2008, ApJ, 686, L13
Grupe, D., & Mathur, S. 2004, ApJ, 606, L41
Hagiwara, Y. 2007, AJ, 133, 1176
Hagiwara, Y., & Edwards, P. G. 2015, ApJ, 815, 124
Hagiwara, Y., Diamond, P. J., & Miyoshi, M. 2002, A&A, 383, 65
Hagiwara, Y., Diamond, P. J., Miyoshi, M., Rovilos, E., & Baan, W. 2003, MNRAS, 344, L53
Hagiwara, Y., Diamond, P. J., Nakai, N., & Kawabe, R. 2001, ApJ, 560, 119
Herrnstein, J. R., et al. 1999, Nature, 400, 539
Ishihara, Y., Nakai, N., Iyomoto, N., Makishima, K., Diamond, P., & Hall, P. 2001, PASJ, 53, 215
Komossa, S., Voges, W., Xu, D., Mathur, S., Adorf, H.-M., Lemson, G., Duschl, W. J., & Grupe, D. 2006, AJ, 132, 531
Komossa, S., Xu, D., Zhou, H., Storchi-Bergmann, T., & Binette, L. 2008, ApJ, 680, 926
Kondratko, P. T., et al. 2006, ApJ, 638, 100
Kondratko, P. T., Greenhill, L. J., & Moran, J. M. 2005, ApJ, 618, 618
Kondratko, P. T., Greenhill, L. J., & Moran, J. M. 2008, ApJ, 678, 87
Kuo, C. Y., et al. 2011, ApJ, 727, 20
McHardy, I. M., Green, A. R., Done, C., Puchnarewicz, E. M., Mason, K. O., Branduardi-Raymont, G., & Jones, M. H. 1995, MNRAS, 273, 549
Madejski, G., Done, C., Życki, P. T., & Greenhill, L. 2006, ApJ, 636, 75
Mamyoda, K., Nakai, N., Yamauchi, A., Diamond, P., & Huré, J.-M. 2009, PASJ, 61, 1143
Masini, A., et al. 2016, A&A, 589, A59
Mathur, S., Kuraszkiewicz, J., & Czerny, B. 2001, New Astron., 6, 321
Mineshige, S., Kawaguchi, T., Takeuchi, M., & Hayashida, K. 2000, PASJ, 52, 499
Miyoshi, M. Moran J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
Molina, M., Bassani, L., Malizia, A., Stephen, J. B., Bird, A. J., Bazzano, A., & Ubertini, P. 2013, MNRAS, 433, 1687
Mullaney, J. R., & Ward, M. J. 2008, MNRAS, 385, 53
Mundell, C. G., Pedlar, A., Baum, S. A., O'Dea, C. P., Gallimore, J. F., & Brinks, E. 1995, MNRAS, 272, 355
Nagar, N. M., Oliva, E., Marconi, A., & Maiolino, R. 2002, A&A, 391, L21
Osterbrock, D. E., & Pogge, R. W. 1985, ApJ, 297, 166
Ott, J., et al. 2013, ApJ, 771, L41
Panessa, F., et al. 2011, MNRAS, 417, 2426
Peterson, B. M., et al. 2000, ApJ, 542, 161
Reid, M. J., Braatz, J. A., Condon, J. J., Greenhill, L. J., Henkel, C., & Lo, K. Y. 2009, ApJ, 695, 287
Risaliti, G., Nardini, E., Salvati, M., Elvis, M., Fabbiano, G., Maiolino, R., Pietrini, P., & Torricelli-Ciamponi, G. 2011, MNRAS, 410, 1027
Rush, B., Malkan, M. A., Fink, H. H., & Voges, W. 1996, ApJ, 471, 190
Surcis, G., Tarchi, A., Henkel, C., Ott, J., Lovell, J., & Castangia, P. 2009, A&A, 502, 529
Tarchi, A., Castangia, P., Columbano, A., Panessa, F., & Braatz, J. A. 2011, A&A, 532, A125
Turner, T. J., Miller, L., George, I. M., & Reeves, J. N. 2006, A&A, 445, 59
Ulvestad, J. S., Antonucci, R. R. J., & Goodrich, R. W. 1995, AJ, 109, 81
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
van den Bosch, R. C. E., Greene, J. E., Braatz, J. A., Constantin, A., & Kuo, C.-Y. 2016, ApJ, 819, 11
Véron-Cetty, M.-P., Véron, P., & Gonçalves, A. C. 2001, A&A, 372, 730
Wagner, J. 2013, A&A, 560, A12
Wang, T., & Lu, Y. 2001, A&A, 377, 52
Whalen, D. J., Laurent-Muehleisen, S. A., Moran, E. C., & Becker, R. H. 2006, AJ, 131, 1948
Woo, J.-H., Yoon, Y., Park, S., Park, D., & Kim, S. C. 2015, ApJ, 801, 38
Zhang, J. S., Henkel, C., Kadler, M., Greenhill, L. J., Nagar, N., Wilson, A. S., & Braatz, J. A. 2006, A&A, 450, 933
Zhu, G., Zaw, I., Blanton, M. R., & Greenhill, L. J. 2011, ApJ, 742, 73