Searches for H$_2$O Masers toward Narrow-Line Seyfert 1 galaxies

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Abstract

We present searches for 22 GHz H$_2$O masers toward 36 narrow-line Seyfert 1 galaxies (NLS1s), selected from known NLS1s with $v_{\text{sys}} < \sim 41000$ km s$^{-1}$. Out of the 36 NLS1s in our sample, 11 NLS1s 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 3 $\sigma$ 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 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$_2$O 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 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 — masers — radio lines: ISM — galaxies: Seyfert

1 Introduction

Luminous extragalactic H$_2$O 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$_2$O 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$_2$O 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 $\sim \pm 1000$ km s$^{-1}$ from galaxy’s systemic velocity, which indicates presence of a rotating disc around a super massive black hole in host galaxies (Miyoshi et al. 1995; Greenhill et al. 1996; Herrnstein et al. 1999; Hagiwara et al. 2001; Ishihara et al. 2001; Greenhill et al. 2003b; Kondratko et al. 2005; Kondratko et al. 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 & 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 Eddington limit could have smaller black hole masses (∼ 10⁶ M⊙) (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_BH – σ relation have been shown compared to broad-line AGNs 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 NLS1's central engine with some different approaches.

Hagiwara et al. (2003) first discovered a bright H₂O maser toward the narrow-line Seyfert 1 galaxy, NGC 4051. Stimulated by this discovery, single-dish observations searching for new extragalactic H₂O masers toward narrow-line Seyfert 1 galaxies were conducted, and these observations yielded the detections of new H₂O masers in three narrow-line Seyfert 1 galaxies of Mrk 766, IRAS 03450+0055, and IGR J16385-2057 (Tarchi et al. 2011). The detection of H₂O 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 H₂O masers in active galaxies (a.k.a. “megamasers”) have been found in type 2 Seyfert, LINER, narrow-line Seyfert 1, and other types of Seyfert nuclei. Some fraction of the megamasers are considered to be associated with ejecta from AGNs, such as jets or winds (e.g., Claussen et al. 1998; Greenhill et al. 2003b). 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; Doi et al. 2015a; Doi et al. 2015b). The results would imply that H₂O masers in NLS1s are a potential tracer of the circumnuclear regions of AGN by analogy with the masers in type 2 Seyferts with (sub)parsec-scale non-thermal jets. The H₂O 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 H₂O masers in type 2 Seyfert, LINERs, and radio galaxies (e.g., Miyoshi et al. 1995; Hagiwara et al. 2001; Greenhill et al. 2003b; Kuo et al. 2011; Ott et al. 2013). However, the origin of H₂O 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 H₂O 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 70m telescope at Tidbinbilla (DSS-43). The studies of many H₂O 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). The article also uses results from other searches for maser detection. Throughout this article, cosmological parameters of H₀ = 73 km s⁻¹ Mpc⁻¹, ΩM = 0.73, and ΩΛ = 0.27 are adopted.

2 Sample Selection

In our survey, relatively nearby 36 NLS1s (v_{sys} < 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 H₂O maser sources. Two NLS1s hosting known H₂O maser emission, NGC 4051 and NGC 5506 were selected to search for new high-velocity components: NGC5506 has been identified as an obscured narrow-line Seyfert 1 galaxy by near-IR spectroscopy (Nagar et al. 2002), but not 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 4 NLS1s were observed also at Nobeyama or Effelsberg, were observed in 2012 at Tidbinbilla (Table 1). In all, 36 NLS1s were observed in our program. Mrk 766 that implies an evidence for an accretion disc around the central black hole from X-ray observations (Turner et al. 2006) was included to our list without knowing the fact that the galaxy was observed in other surveys. Coordinates and systemic velocities of galaxies observed in our program, 1 σ sensitivities, and velocity resolutions at each telescope are listed in Table 2.

3 Observations

Single-dish searches for 22 GHz H₂O maser emission toward NLS1s were made during the periods of 25 May to 3 June, 2005, 3 to 6 February, 2006, 12 to 14 March, 2012, and 23 July to 23 October, 2012. These observations in the first and third periods were carried out using the Nobeyama 45 m telescope (NRO 45 m), in the second period were conducted using the Effelsberg 100 m telescope, and 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-
switchen mode. These observations are summarized in Table 1. Originally, all 26 sources were scheduled at both Nobeyama 45 m and Effelsberg 100 m telescopes, however some sources were observed once and some were twice due to technical problems of telescope back-end at Effelsberg or weather conditions. In addition, 10 new sources below +20 degree declinations 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 1h to 2h by observing 43 GHz SiO maser stars near galaxies, which resulted in the pointing accuracy of $\sim 5''$ to $\sim 10''$, 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 flux density accuracy of $\sim 10\%$ is estimated. In the Nobeyama 45m observations in 2005, 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 $\sim 2100$ km s$^{-1}$ for each polarization, nearly centred on the systemic velocity and having a frequency resolution of 39 kHz ($\sim 0.5$ 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 bandwidth was employed, each of them has 4096 spectral points, providing 61 kHz frequency resolution. The total velocity coverage and velocity resolution are $26000$ km s$^{-1}$ and $0.83$ km s$^{-1}$. In our analysis of the SAM45 data, two frequency channels were smoothed, which resulted in the velocity resolution of $\sim 1.6$ km s$^{-1}$. (Note that in Table 2 the sources listed with a 0.5 km s$^{-1}$ velocity resolution were observed using the AOS spectrometer, and those with the 1.6 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 $\sim 40''$ 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 in 78 kHz frequency resolution. In our observations, four IF bands for each circular polarization were being used, which resulted in the total velocity coverage of $\sim 2100$ km s$^{-1}$, nearly centred on the systemic velocity and velocity resolution of $\sim 1.1$ km s$^{-1}$. The pointing calibration was made by observing nearby strong continuum sources every 1h to 1.5 h, yielding a pointing accuracy of better than $\sim 5$ arcsec. 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). Accuracy of 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 $\sim 48''$. Pointing errors were measured and corrected by using nearby bright quasars before observations, resulting 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 $\sim 860$ km s$^{-1}$ and spectral resolution of 31.25 kHz or 0.42 km s$^{-1}$. The telescope sensitivity of 1.5 Jy K$^{-1}$ is adopted (Greenhill et al. 2003a), and 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$_2$O maser source was detected at $3\sigma$ detection level of $\sim 8$ mJy = $90$ mJy per a spectral channel, by excluding the NRO 45 m observation of IRAS 17020+4544 that shows a very high rms value. This implies that no strong H$_2$O 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 intensity variability of the maser. The maser in Mrk 766 should have been marginally detected in $2\sigma$ at Effelsberg, if its peak flux density was as bright as that observed at the NRAO Green Bank Telescope (GBT) in 2008 ($\sim 15$ mJy) (Tarchi et al. 2011). The H$_2$O maser spectra of NGC 4051 in Figure 1 show the flux variability between two epochs of the two known features at $V = 679$ and $738 - 741$ km s$^{-1}$, which were reported in earlier observations (Hagiwara et al. 2003; Hagiwara 2007). No new H$_2$O maser features were found in the observed bands toward the galaxy. The maser emission in the NLS1s was searched in the velocity range of $\sim \pm 400 - 800$ 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 and 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 H₂O maser in NLS1

Of the 36 sources observed in our observations, Mrk 766 is included. However, the maser in the galaxy was not detected both in 2005 and 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 σ < 3 mJy per a spectral channel of 0.33 km s⁻¹) than ours (1 σ ~ 3 – 48 mJy per a 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 H₂O maser in NLS1s is estimated to be ~ 6% (5/82). It is shown that the nominal detection rates of the past H₂O megamasers surveys of type 2 Seyferts and LINERs are ~ 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 \( v_{sys} < 20000 \) km s⁻¹ sample. The GBT “snapshot” survey of nearby galaxies \( v_{sys} < 5000 \) km s⁻¹ by Braatz et al. (2008) has the 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 H₂O maser surveys whose detection rates are, at most, several percent. Moreover, the recent systematic study that compiled the results of past megamasers surveys revealed that the detection rate will be improved from ~3% to ~16% with the bias of higher extinction and higher optical luminosity, that is, the luminosity of \([O_{III}] \lambda 5007\) (Zhu et al. 2011). Finally, we speculate that there is no evidence that incidence of H₂O 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 problem in our programme lies in insufficient sensitivities of our survey, which makes it difficult to have 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 H₂O megamasers

In earlier studies, correlation between the incidence of H₂O maser emission and high column density \( (N_{H}) \) in type 2 Seyferts and LINERs was demonstrated (Kondratko et al. 2006; Zhang et al. 2003; Greenhill et al. 2008; Castangia et al. 2013): Of 42 AGN megamasers whose column densities are available from published hard X-ray data, 95% have \( N_{H} \geq 10^{23} \) cm⁻², or, alternatively, 60% are Compton thick, with \( N_{H} \geq 10^{24} \) cm⁻² (Greenhill et al. 2008). Moreover, of 21 disc masers in which masers originate in subparsec- or parsec-like objects, 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 et al. (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 H₂O 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 whose column density measured by hard X-ray toward a nucleus is not available in the literature (Table 3). It is interesting to note that one of the best-studied disc masers, NGC 4258 \( (N_{H} = 0.6 - 1.3 \times 10^{23} \) cm⁻²) and a known disc maser NGC 4388 \( (N_{H} = 0.02 \) – \( 4.8 \times 10^{23} \) 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 H₂O masers in NLS1s

The small number of the detection of NLS1 masers demonstrates that masers are seen less enhanced because the masering discs are viewed less edge-on in line of sight, which is consistent with a picture of type 1 Seyfert nuclei in AGN unified model (Antonucci & Miller 1985; Urry & Padovani 1995). The masers in NLS1 are associated with AGN-activity like other AGN masers. However, their averaged apparent maser luminosity \( (10 \ L_{\odot} \lesssim L(H_{2}O) \lesssim 100 \ L_{\odot}) \) is one order of magnitude lower than that of high-luminosity masers with \( L(H_{2}O) \gtrsim 100 \ L_{\odot} \) (Hagiwara 2007). According to Zhang et al. (2006), comparison between kilomasers \( (L(H_{2}O) \lesssim 10 \ L_{\odot}) \)
and high-luminosity masers shows that high-luminosity masers have higher $N_{\text{H}}$. 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 luminosity as low ($10 \, L_{\odot} \lesssim L(\text{H}_2\text{O}) \lesssim 100 \, L_{\odot}$) as in other AGN masers. Fig. 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 $\sim 100 \, \text{km} \, \text{s}^{-1}$, which could be explained by lower disc inclination angle of NLS1s: the apparent line of sight velocities ($v_{\text{los}}$) are expressed as $v_{\text{los}} = v_{\text{rad}} \sin i$, where $i$ is a disc inclination angle, and $v_{\text{rad}}$ with $i \approx 30^\circ$–$40^\circ$ is calculated to be about 30–50\% smaller than those in 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

Fig. 1 demonstrates that the maser flux density in NGC 4051 is by a factor of $\sim 3$ weaker than that in earlier observations due to variability. The maser in the galaxy was first detected in 2002 by Hagiwara et al. (2003). They argued about the maser in the galaxy being 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 broadly distributed narrow line emission in the galaxy is consistent with a wind maser associated with nuclear galactic winds related to formation of narrow-line Seyfert 1 spectra (Greenhill et al. 2003b). 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 variability of the column density. Similarly, Mrk 766 shows $N_{\text{H}}$ 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 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$_2$O masers toward 36 narrow-line Seyfert 1 galaxies (NLS1s) using the Nobeyama 45 m, Effelsberg 100 m, and Tidbinbilla 70m 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 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 NLS1s 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 NLS1s 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.

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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 degree declinations included |

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

Fig. 1. Spectra of H$_2$O maser ($\Delta \nu = 2.1$ km s$^{-1}$) between 275 km s$^{-1}$ – 775 km s$^{-1}$ toward the centre of NGC 4051, obtained with the Effelsberg 100 m in 2002 and 2006. A vertical dotted line and arrows denote the systemic velocity of the galaxy (730 km s$^{-1}$). The vertical axis denotes flux density scaled in Jansky, and the horizontal axis LSR velocity.

Fig. 2. Published GBT spectra of H$_2$O masers in the 3 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 systemic velocity of the galaxies.
### Table 2. Summary of observations of narrow-line Seyfert 1 galaxies

| Source  | $\alpha_{2000}$ | $\delta_{2000}$ | $V^3$ | $\sigma_{45}$ | $\sigma_{100}$ | $\sigma_{70}$ | $\Delta \nu_{45}$ | $\Delta \nu_{100}$ | $\Delta \nu_{70}$ |
|---------|-----------------|-----------------|-------|--------------|--------------|--------------|----------------|----------------|----------------|
| MRK 335 | 00h06m19.5s     | +20d12m10s     | 7730  | 21           | 4.0          |              | 1.5            | 1.1            |                |
| I Zw 1  | 00h53m34.9s     | +12d41m36s     | 18330 | 9.8          | 6            | 1.5          | 1.6            |                |                |
| MRK 359 | 01h27m32.5s     | +19d10m44s     | 5212  | 17           |              |              | 1.5            |                |                |
| MRK 1044| 02h30m05.5s     | -08d59m53s     | 4932  | 15           | 9            | 1.5          | 1.6            |                |                |
| MRK 618 | 04h36m22.2s     | -10d22m34s     | 10658 | 4.3          |              |              | 1.6            |                |                |
| PKS 0558–504| 05h59m47.4s | -50d26m52s     | 41132 | 6.5          |              |              | 1.6            |                |                |
| J 07084153–4933066| 07h08m41.5s | -49d33m07s     | 12162 | 5.5          |              |              | 1.6            |                |                |
| MRK 382 | 07h55m25.3s     | +39d11m10s     | 10139 | 16           | 3.6          |              | 1.5            | 1.1            |                |
| MRK 0110| 09h25m12.8s     | +52d17m10s     | 10580 | 17           | 5.3          |              | 1.5            | 1.1            |                |
| MRK 705 | 09h26m03.3s     | +12d44m04s     | 8739  | 8.7          | 3.3          | 12           | 1.5            | 1.1            | 1.6            |
| MRK 0124| 09h48m42.6s     | +50d29m31s     | 16878 | 15           | 2.9          |              | 1.5            | 1.1            |                |
| MRK 1239| 09h52m19.0s     | -01d36m43s     | 5974  | 14           | 8.5          | 5.5          | 1.5            | 1.1            | 1.6            |
| KUG 1031+398| 10h34m38.6s | +39d38m28s     | 12724 | 16           | 3.8          |              | 1.5            | 1.1            |                |
| MRK 734 | 11h21m47.0s     | +11d44m18s     | 15050 | 3.1          |              |              | 1.1            |                |                |
| MRK 42  | 11h53m41.8s     | +46d12m43s     | 7385  | 17           |              |              | 1.5            |                |                |
| NGC 4051| 12h03m09.6s     | +44d31m53s     | 700   | 16           | 5.9          |              | 1.5            | 1.1            |                |
| MRK 766 | 12h18m26.5s     | +29d48m46s     | 3876  | 12           | 7.3          |              | 1.5            | 1.1            |                |
| WAS 61  | 12h42m10.6s     | +33d17m03s     | 13045 | 3.2          |              |              | 1.1            |                |                |
| J 12431152–0053442| 12h43m11.5s | -00d53m45s     | 24546 | 31           |              |              | 1.6            |                |                |
| NGC 4748| 12h52m12.4s     | -13d24m53s     | 4386  | 5.0          |              |              | 1.6            |                |                |
| MRK 783 | 13h02m58.9s     | +16d24m27s     | 20146 | 21           | 2.9          |              | 1.5            | 1.1            |                |
| IRAS 13224–3809| 13h25m19.4s | -38d24m53s     | 19726 | 22           |              |              | 1.6            |                |                |
| PG 1404+226| 14h06m21.8s | +22d24m46s     | 29380 | 17           |              |              | 1.5            |                |                |
| NGC 5506| 14h13m14.8s     | -03d12m27s     | 1853  | 5.6          |              |              | 1.1            |                |                |
| MRK 478 | 14h42m07.4s     | +35d26m23s     | 23700 | 3.4          |              |              | 1.1            |                |                |
| PG 1448+273| 14h51m08.8s | +27d09m27s     | 19487 | 18           | 6.5          |              | 1.5            | 1.1            |                |
| IRAS 15091-2107| 15h11m59.8s | -21d19m02s     | 13373 | 12           |              |              | 1.6            |                |                |
| 15480–051 | 15h48m56.8s | -04d59m34s     | 29917 | 2.9          |              |              | 1.1            |                |                |
| MRK 493 | 15h59m09.6s     | +35d01m48s     | 9392  | 12           |              |              | 1.5            |                |                |
| IRAS 17020+4544| 17h03m30.4s | +45d40m47s     | 18107 | 48           | 3.0          |              | 1.5            | 1.1            |                |
| MRK 507 | 17h48m38.4s     | +68d42m16s     | 16758 | 14           |              |              | 1.5            |                |                |
| 1927+654 | 19h27m19.5s     | +65d33m54s     | 5096  | 2.8          |              |              | 1.1            |                |                |
| 1H 1934–063 A | 19h37m33.0s | -06d13m05s     | 3074  | 27           |              |              | 1.6            |                |                |
| 2159+0113 | 21h59m24.0s | +01d13m05s     | 30041 | 5.0          |              |              | 1.6            |                |                |
| AKN 564 | 22h42m39.3s     | +29d43m31s     | 7400  | 9.8          | 4.7          |              | 1.5            | 1.1            |                |
| 2327–1023| 23h26m56.1s     | -10d21m43s     | 19557 | 4.6          |              |              | 1.6            |                |                |

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1. NLS1s hosting 22 GHz H$_2$O maser are indicated in bold type.
2. Right ascension ($\alpha_{2000}$) and declination ($\delta_{2000}$).
3. Source coordinates are taken from NED.

Note: $\sigma_{45}$, $\sigma_{100}$, and $\sigma_{70}$ are 1 $\sigma$ noise per velocity resolution.

$\Delta \nu_{45}$, $\Delta \nu_{100}$, and $\Delta \nu_{70}$ are velocity resolutions at Nobeyama, Effelsberg, and Tidbinbilla.
Table 3. Column density of the known NLS1 masers

| Source            | \(N_H^*\) (\(10^{22} \text{ cm}^{-2}\)) | References          |
|-------------------|----------------------------------------|---------------------|
| IRAS 03450+0055   | \(-^\dagger\)                          | Rush et al. (1996)  |
| NGC 4051          | 8 – 37                                 | Madejski et al. (2006) |
| Mrk 766           | 20 – 30\( ^\dagger >\)                | 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).

\( ^\dagger\) Galactic \(N_H\) (soft X-ray) from the ROSAT All-Sky Survey is \(5.89 \times 10^{20} \text{ cm}^{-2}\).

\( ^\dagger\) Lower limit value.
