THE DISCOVERY OF WATER MASER EMISSION FROM EIGHT NEARBY GALAXIES

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ABSTRACT

Using the Green Bank Telescope, we conducted a “snapshot” survey for water maser emission toward the nuclei of 611 galaxies and detected eight new sources. The sample consisted of nearby \( (v < 5000 \, \text{km s}^{-1}) \) and luminous \( (M_B < -19.5) \) galaxies, some with known nuclear activity but most not previously known to host AGNs. Our detections include both megamasers associated with AGNs and relatively low luminosity masers probably associated with star formation. The detection in UGC 3789 is particularly intriguing because the spectrum shows both systemic and high-velocity lines indicative of emission from an AGN accretion disk seen edge-on. Based on 6 months of monitoring, we detected accelerations among the systemic features ranging from 2 to 8 \( \text{km s}^{-1} \, \text{yr}^{-1} \), the larger values belonging to the most redshifted systemic components. High-velocity maser lines in UGC 3789 show no detectable drift over the same period. Although UGC 3789 was not known to be an AGN prior to this survey, the presence of a disk maser is strong evidence for nuclear activity, and an optical spectrum obtained later has confirmed it. With follow-up observations, it may be possible to measure a geometric distance to UGC 3789.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — ISM: molecules — masers — radio lines: galaxies

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1. INTRODUCTION

Water maser emission at 22 GHz is commonly detected toward Galactic H II regions, pinpointing the locations of massive star formation. The median isotropic line luminosity in these sources is \( 10^{-2} \, L_{\odot} \) (Genzel & Downes 1977), although in exceptional cases such as W49 the luminosity can reach \( \sim 1 \, L_{\odot} \). Analogs to the W49 maser have been observed in H II regions of several nearby galaxies as well, where the combined radiation from multiple sites of star formation can lead to somewhat larger luminosities. The most distant \( (14.5 \, \text{Mpc}) \) and luminous \( (L_{\text{H}_2O} \sim 8 \, L_{\odot}) \) example of this type was detected toward the starburst galaxy NGC 2146 (Tarchi et al. 2002). In recent years, masers in extragalactic star-forming regions have become an important tool for measuring proper motions of the host galaxies, as in IC 10 and M33 (Brunthaler et al. 2005, 2007).

Extragalactic water masers are also detected toward some active galactic nuclei (AGNs), usually Seyfert 2 or LINER galaxies (Braatz et al. 1997). These sources have been called “megamasers” because the isotropic line luminosities exceed the median value of Galactic masers by \( \sim 6 \) orders of magnitude. Both galactic and extragalactic masers, however, are not believed to emit isotropically, so the true line luminosity is smaller in each case by an unknown beaming factor. Masers in AGN accretion disks, specifically, are thought to be beamed in the plane of the disk.

High-resolution imaging shows that megamasers are located within parsecs of the galactic nucleus, where they are associated either with jet-cloud interactions, nuclear outflows, or parsec-scale accretion disks. Unlike star formation masers, which only have Doppler components detected within \( \sim 200 \, \text{km s}^{-1} \) of the galaxy’s systemic recession velocity, masers in AGN accretion disks have shown velocity offsets up to \( \sim 1300 \, \text{km s}^{-1} \) (Kondratko et al. 2006a) owing to rotation about the central black hole. In the case of NGC 4258, masers trace the accretion disk 0.11–0.28 pc from the black hole (Argon et al. 2007) and have been used to measure the most precise geometric distance to a galaxy, \( 7.2 \pm 0.2 \) (random statistical) \( \pm 0.5 \) (systematic) Mpc (Herrnstein et al. 1999). The topic of extragalactic masers has recently been reviewed by Lo (2005).

NGC 4258 is currently the only galaxy with a robust maser distance, but large surveys are seeking additional examples of disk masers appropriate for such a measurement. Most surveys target Seyfert 2 and LINER galaxies (e.g., Greenhill et al. 2003; Braatz et al. 2004; Kondratko et al. 2006a, 2006b). With sensitive observations using large aperture telescopes, overall detection rates are \( \lesssim 5\% \), and several disk masers have been identified. The masers detected by these surveys tend to be faint (peak fluxes of a few tens of mJy) and challenging to study in detail. Candidates for new surveys are limited by the number of AGNs identified in optical surveys.

While disk masers are clearly associated with active galaxies, the luminosity of the host AGN is modest in several of the most interesting cases. For example, the bolometric luminosity of NGC 4258, which has been classified either as a LINER or a weakly active Seyfert 1.9, is only \( 10^{42} \) erg s\(^{-1} \) (e.g., Chary et al. 2000). Furthermore, Ho et al. (1997) found that 43\% of a magnitude-limited sample of nearby galaxies host AGNs, mostly with low luminosity, demonstrating that many apparently normal galaxies in fact host low-luminosity AGNs. We were thus motivated to conduct a new survey for H2O maser emission in nearby galaxies not necessarily known to host AGNs. Our intention was to identify bright maser systems (\( \gtrsim 250 \) mJy) conducive to detailed Very Long Baseline Interferometry (VLBI) imaging and spectral line monitoring. With the GBT we can identify such masers using short integrations, making it possible to observe a large sample and balance the relatively low detection rate expected.

2. OBSERVATIONS

We conducted observations between 2005 September 27 and 2007 April 14 using the Green Bank Telescope (GBT) of the
National Radio Astronomy Observatory. The project was observed in 31 individual sessions, often assigned to fill short gaps in the telescope schedule. We configured the spectrometer with two 200 MHz spectral windows, each with 8192 channels, giving a channel spacing of 24 kHz corresponding to 0.33 km s\(^{-1}\) at 22 GHz. The spectral windows were overlapped slightly such that the total bandwidth coverage was 380 MHz (5100 km s\(^{-1}\)). The systemic recession velocity of each galaxy was typically centered in one spectral window, and the second window was offset to the red. For a few galaxies, the spectral windows were tuned with the systemic recession velocity in the overlap region, giving symmetric velocity coverage. We observed in dual circular polarization using a total power nodding mode in which the galaxy was placed alternately in one of two beams of the 18 m telescope receiver. A nodding cycle of 2.5 minutes per beam provided 5 minutes of integration per source. When time permitted, we obtained longer integrations to investigate possible detections. We reduced and analyzed the data using GBIDL. In order to enhance weak signals, we smoothed the blank sky reference spectra using a 16 channel boxcar function prior to calibration. We corrected the spectra for atmospheric attenuation using opacities derived from weather data, and we applied an elevation-dependent gain curve. The flux density scale uncertainty is about 15%, limited by noise tube calibration and pointing errors. To remove residual baseline shapes from each 200 MHz spectrum, we subtracted a polynomial (typically third-order) fit to the line-free channels of the calibrated spectrum. Typical rms noise levels for the 5 minute observations were 6 mJy per 0.33 km s\(^{-1}\) channel, after Hanning smoothing.

Our candidate galaxies were selected from the Third Reference Catalog of Bright Galaxies (de Vaucouleurs et al. 1991) using coarse criteria intended primarily to eliminate galaxies without well-defined nuclei and those unlikely to host a hidden AGN. The sample has (1) systemic recession velocity \( v < 5000 \text{ km s}^{-1} \), which corresponds to the distance at which the GBT could detect the NGC 4258 maser in 5 minutes; (2) Hubble stage \(-3 < T < +5\) to choose lenticulars and early-type spirals; (3) absolute magnitude \( M_B < -19.5\) to eliminate dwarf galaxies and boost the likelihood of a prominent nuclear black hole; and (4) declinations north of \(-30^\circ\), accessible to the GBT. We also eliminated galaxies previously searched with the GBT. These criteria identified 1074 candidate galaxies, not all of which were observed in the allotted time. We plan to observe the remaining galaxies in ongoing surveys. Galaxies were finally chosen for observation based on nearest neighbors, to minimize telescope slew time.

3. RESULTS

We searched for 22 GHz H\(_2\)O maser emission toward the nuclei of 611 galaxies and detected masers in eight. Table 1 lists properties of the detected masers, and Table 2 lists the undetected galaxies from the survey, along with relevant observing parameters. Each new maser was detected in more than one observing session except the one in NGC 1106, which was not identified until the data were reexamined at the conclusion of the scheduled observing. The best spectrum for each of the newly detected maser systems is shown in Figure 1. Velocities quoted in this paper are heliocentric and use the optical definition of Doppler shift.

Comments on the new masers and their host galaxies follow. For several of the galaxies, we discuss the maser profile in the context of an accretion disk maser. In this model, “systemic” emission refers to masers on the near side of the edge-on disk, along the line of sight to the black hole. “High-velocity” emission refers to masers located on the midline of the disk, rotating directly toward or away from the observer.

3.1. NGC 23

The maser detected in NGC 23 exhibits a broad profile relatively free of isolated, narrow features and centered near the systemic velocity (Fig. 1). The spectrum shows no evidence of high-velocity lines. The isotropic luminosity of the source is 180 \( L_\odot \), suggesting the maser is associated with an AGN. The profile resembles those from masers associated with nuclear jets, such as NGC 1052 (Claussen et al. 1998) and Mrk 348 (Peck et al. 2003). However, NGC 23 is not known to have an AGN. With \( L_\text{IR} = 11.05 L_\odot \) (Sanders et al. 2003), NGC 23 is a luminous infrared galaxy (LIRG). The intense star formation associated with LIRGs might be expected to produce a large number of star formation masers whose cumulative emission could reach the observed isotropic luminosity in NGC 23. However, Zhang et al. (2006) point out that the ultraluminous infrared galaxy (ULIRG) Arp 220 would have been detected easily in recent surveys if the maser emission were correlated with IR luminosity, yet Arp 220 has not been detected in H\(_2\)O. Two ULIRGs have been detected in the water maser line: UGC 5101 (Zhang et al. 2006) and NGC 6240 (Hagiwara et al. 2002; Nakai et al. 2002; Braatz et al. 2003). In both cases the masers appear to be associated with an AGN and not star formation (Hagiwara et al. 2003; Zhang et al. 2006). High-resolution imaging could resolve the issue of whether the maser in NGC 23 is associated with star formation or an AGN.
NGC 1106 is an emission-line galaxy, called a Seyfert 2 by Bonatto et al. (1996). The maser detected in this galaxy contains a single, narrow (1.0 km s$^{-1}$ FWHM) component at 3814 km s$^{-1}$, offset by 523 km s$^{-1}$ from the 4337 km s$^{-1}$ systemic recession velocity. The large velocity offset hints that the maser may be a high-velocity line in an accretion disk. The peak flux density is 74 mJy. Because the maser was not identified until all observations had been completed, we did not obtain a confirmation spectrum for this source. However, the maser line appears in both polarizations and in both beams of our observation. An observation of NGC 1106 by Kondratko et al. (2006b) with 13 mJy rms sensitivity failed to detect the line, but it would have appeared only at about 4$\sigma$ given their channel spacing of 1.3 km s$^{-1}$. We also note that variability is common in narrow high-velocity lines.

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3.3. UGC 3193

The maser observed toward the barred spiral galaxy UGC 3193 spans ~350 km s$^{-1}$ and is localized in four distinct velocity windows. The profile shows remarkable symmetry about the galaxy’s recession velocity, even in the details of the inner two complexes. However, no lines are detected at the systemic velocity itself. The profile thus hints that the maser originates in a slowly rotating, edge-on disk, with only high-velocity features detected. A spiral density pattern in an accretion disk or discrete rings could produce a pattern as observed. The absence of emission directly at the systemic velocity may indicate that the disk inclination or a warp prevents beaming of masers on the near side of the disk into our line of sight. Alternatively, a lack of background continuum emission that would otherwise provide seed emission for systemic features could account for the absence of detectable maser emission near the systemic velocity.

3.4. UGC 3789

The maser detected in UGC 3789 shows a profile characteristic of emission from an edge-on nuclear accretion disk. Maser lines are detected in three distinct velocity ranges (Fig. 1), roughly symmetric about the galaxy’s recession velocity of 3325 $\pm$ 24 km s$^{-1}$. Systemic lines are centered near 3275 km s$^{-1}$, offset slightly from the reported recession velocity. High-velocity lines span ~1500 km s$^{-1}$, suggesting the maser disk traces rotation speeds up to ~750 km s$^{-1}$.

On associating the maser in UGC 3789 with disk emission, we initiated a program to observe the source at roughly 3 week intervals in order to track the velocities of systemic maser components and measure the centripetal acceleration of the maser gas in orbit around the central black hole. The initial results of this monitoring program are shown in Figures 2 and 3. With the 6 months of data presented here we have measured accelerations for nine individual lines among the systemic features. The accelerations, listed in the Figure 2 caption, range from 1.8 to 8.1 km s$^{-1}$ yr$^{-1}$, with the smallest accelerations measured near ~3245 km s$^{-1}$ on the blue edge of the systemic features and the largest near ~3310 km s$^{-1}$ on the red edge. The mean of the nine accelerations identified in Figure 2 is 4.0 $\pm$ 0.8 km s$^{-1}$ yr$^{-1}$. The wide range of measured accelerations likely indicates that the systemic masers are not confined to a radially thin ring but rather are spread over a range of radial distance from the dynamical center of the galaxy. The acceleration of systemic masers in NGC 4258 also varies for different components, although with a smaller range (e.g., Humphreys et al. 2008). Among the high-velocity features, measured accelerations are all less than 0.3 km s$^{-1}$ yr$^{-1}$. Additional monitoring observations of UGC 3789 and a more detailed analysis of the accelerations will follow in a later paper.

A robust measurement of the mass of a black hole can be made by measuring the rotation curve of a maser disk from a VLBI map. Without VLBI we can still make an estimate. If we suppose that the systemic masers with the largest measured acceleration occur at the same orbital radius as gas producing the largest rotation velocities among the high-maser components and that the accretion disk is edge-on, we can approximate $M_{\text{BH}}$, the mass of the black hole, by $M_{\text{BH}} = r v^2 G = v^4/a G$. Here $r$ is the radius of the orbiting gas, $v$ is its rotation velocity, $a$ is the centripetal acceleration, and $G$ is the gravitational constant. Then $v \sim 750$ km s$^{-1}$ and $a \sim 8.1$ km s$^{-1}$ yr$^{-1}$ gives $M_{\text{BH}} \approx 9 \times 10^4 M_{\odot}$ for UGC 3789.

The systemic maser features in UGC 3789 are themselves split at ~3275 km s$^{-1}$ by a dip in the emission (Fig. 3). At times, the systemic emission in NGC 4258 has shown a similar dip (e.g., Greenhill et al. 1995), although later data showed no evidence for it in that galaxy (Bragg et al. 2000). Watson & Wallin (1994) and Maoz & McKee (1998) developed models that invoke an absorbing layer of noninverted H$_2$O in the maser disk to account for a dip in the emission.

Megamaser emission is a beacon of nuclear activity. While UGC 3789 had not been identified as an AGN prior to our survey,
an optical spectrum of the nucleus of the galaxy (L. Macri 2006, private communication) reveals line flux ratios, such as \([\text{O} \text{ iii}] 5007/\text{H}\beta\) and \([\text{O} \text{ i}] 6300/\text{H}\beta\), and line widths of \(\text{H}\alpha\) and \(\text{H}\beta\) indicative of a Seyfert 2 nucleus.

With additional observations, it might be possible to measure the distance to UGC 3789 using the maser method applied to NGC 4258 (Herrnstein et al. 1999). We are continuing GBT monitoring and collecting sensitive VLBI observations for this purpose, and the results of these studies will be presented in later papers.

3.5. NGC 2989

The weak maser emission detected in NGC 2989 spans 30 km s\(^{-1}\) and is centered near the systemic recession velocity of the galaxy. No high-velocity lines are detected. Although the isotropic luminosity (40 \(L_\odot\)) is large compared to masers in star formation regions, this galaxy has a nuclear H \(\alpha\) region (Veron-Cetty & Veron, 2003), and the line profile is otherwise consistent with maser emission associated with star formation. If confirmed as a star formation maser, this galaxy, at a nominal distance of 58 Mpc (assuming \(H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}\)) would be the most distant known source of such emission. However, we cannot rule out the possibility that the maser is associated with an AGN.

3.6. NGC 3359

The maser emission from NGC 3359 has several weak, narrow features spanning \(~10 \text{ km s}^{-1}\) with a total isotropic luminosity of 0.7 \(L_\odot\), comparable to the luminosity of the strongest masers from H \(\alpha\) regions in the Milky Way. No high-velocity lines are evident in the maser spectrum. NGC 3359 is an H \(\alpha\) galaxy, and the maser is consistent with star formation.

3.7. NGC 4527

In addition to containing a LINER (Ho et al. 1997), the galaxy NGC 4527 is bright in the far-infrared (S\(_{100 \mu m} = 64 \text{ Jy};\) Fullmer & Lonsdale 1989). Such far-infrared emission is commonly associated with dust heated by young, massive stars. The galaxy has been searched for H\(_2\)O maser emission previously by Kondratko et al. (2006b) and Henkel et al. (2005) but went undetected. The rms sensitivities in their observations were 12 mJy per 1.3 km s\(^{-1}\) channel and 15 mJy per 1.1 km s\(^{-1}\) channel, respectively. The modest isotropic luminosity (4 \(L_\odot\)) is consistent with maser emission from a star formation region, but the velocity offset from the systemic recession velocity (170 km s\(^{-1}\)) leaves open the possibility that the maser is associated with the LINER. We note that NGC 4527 was host to the peculiar Type Ia supernova 1991T.

3.8. NGC 7479

With a type 1.9 Seyfert nucleus (Ho et al. 1997), NGC 7479 has been targeted in previous surveys for H\(_2\)O masers in AGNs, including those by Kondratko et al. (2006b) and Bratetz et al. (1996), in which the rms sensitivities were 19 mJy per 1.3 km s\(^{-1}\) channel and 54 mJy per 0.66 km s\(^{-1}\) channel, respectively. We detected the 140 mJy line at 2532 km s\(^{-1}\) in the initial 5 minute integration, and the deeper spectrum shown in Figure 1 then revealed a number of distinct, weaker components redward of the systemic velocity. If the lines originate in an edge-on nuclear disk, the implied rotation speeds range up to 280 km s\(^{-1}\).

4. DISCUSSION

Megamasers in accretion disks can play an important role in cosmology. As a complement to observations of the cosmic
microwave background, a precise (≤3%) determination of the Hubble constant would provide a strong constraint on several key cosmological parameters, including the equation of state of dark energy (Hu 2005; Spergel et al. 2007). Measuring distances to water maser galaxies can contribute to improving the Hubble constant in two ways. First, maser distances to nearby galaxies (D ≤ 30 Mpc) such as NGC 4258 can be used to refine the absolute calibration of Cepheid variables and replace or supplement the Large Magellanic Cloud as the primary anchor in the extragalactic distance scale (Macri et al. 2006). Second, maser distances to galaxies in the Hubble flow can be used to measure H0 directly. Because maser distances are not based on standard candles and individual uncertainties should be uncorrelated, it may be possible to reduce the total error in H0 by measuring many such distances (e.g., Greenhill 2004). So far, however, a maser distance has only been possible for NGC 4258 (Herrnstein et al. 1999), and it is too close to measure H0 directly.

Measuring maser distances to galaxies requires a robust model of the rotation structure and geometry of the accretion disk from VLBI imaging and either proper motions of maser features on the near side of the disk, or centripetal accelerations measured by spectral line monitoring. While proper motions (∼30 μas yr⁻¹ in NGC 4258 at 7.2 Mpc; Herrnstein et al. 1999) might be challenging for galaxies in the Hubble flow, measuring accelerations is possible, as demonstrated here for UGC 3789. We note, however, that in UGC 3789 additional monitoring will be necessary to properly model the radial structure implied by the variation in accelerations among different maser components.

Prospects for mapping and modeling the disk in UGC 3789 based on VLBI observations can only be assessed when that imaging is available. However, it is clear from the large number of bright (∼20 mJy) maser features within each of the three spectral complexes that the rotation curve can be well sampled. Moreover, the mean acceleration (∼4.0 km s⁻¹ yr⁻¹) and mean rotation...
velocity (~600 km s^{-1}) suggest a disk radius of ~0.09 pc. At a nominal distance to UGC 3789 of 46 Mpc, this corresponds to ~0.4 mas. Such a maser disk can be resolved by VLBI at 22 GHz.

5. SUMMARY

In this survey for extragalactic water masers we employed a “snapshot” strategy designed to detect bright emission from nearby galaxies that may host hidden nuclear activity. Although the detection rate was low (1.3%), we observed a large number of galaxies and detected eight new masers. While it is not possible to assess the nature of these systems until they are imaged with interferometers, several appear particularly interesting. If confirmed as a star formation maser, the source in NGC 2989 would be the most distant and luminous example of that class. The maser in NGC 23 has a profile that resembles those of jet masers, but it is a LIRG and not known to host an AGN. In UGC 3193 the maser profile is remarkably symmetric but shows no emission directly at the systemic velocity of the galaxy. The most intriguing detection is in UGC 3789, which was not previously known to be an AGN. Its spectral profile is characteristic of maser emission from an accretion disk, and we have made a preliminary measurement of accelerations for several of its systemic features. With future VLBI studies and disk modeling, it may be possible to measure a geometric distance to this galaxy based on observations of its maser disk.

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