LOW-LUMINOSITY EXTRAGALACTIC WATER MASERS TOWARD M82, M51, AND NGC 4051

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ABSTRACT

Subarcsecond observations using the Very Large Array (VLA) are presented for low-luminosity H2O maser emission in M82, M51, and NGC 4051. New maser features have been detected within the M82 starburst complex. They are largely associated with star-forming activity such as optically identified starburst-driven winds, H ii regions, or the early phase of star formation in the galaxy. The H2O maser in M51 consists of blueshifted and redshifted features relative to the systemic velocity of the galaxy. The redshifted features are measured to the northwest of the nuclear radio source, while the location of the blueshifted counterpart is displaced by ~2" from the radio source. A small velocity gradient closely aligned with the radio jet is detected from the redshifted features. The redshifted maser most likely amplifies the background radio continuum jet, while the blueshifted counterpart marks off-nuclear star formation in the galaxy. All of the detected maser features in the narrow-line Seyfert 1 galaxy NGC 4051 remain unresolved by new VLA observations. Due to the low luminosity of the maser, the maser excitation is not directly related to the active galactic nucleus.

Key words: galaxies: active — galaxies: individual (M82, M51, NGC 4051) — galaxies: ISM — galaxies: starburst — radio lines: galaxies

1. INTRODUCTION

Since the discovery of the first 22 GHz extragalactic H2O maser toward M33 by Churchwell et al. (1977), significant progress in studies of extragalactic H2O masers has been made, with the first detection of a nuclear H2O maser toward an active galactic nucleus (AGN) in NGC 4945 (Dos Santos & Lépine 1979). A number of single-dish surveys searching for new H2O masers in active galaxies have been conducted since, in which more than 1000 galaxies were observed. These surveys were stimulated by the VLBI imaging of H2O maser components in a subparsec-scale, thin, warped, edge-on disk displaying Keplerian rotation around the nucleus of the Seyfert 2 galaxy NGC 4258 (e.g., Herrnstein et al. 1998). These surveys have increased the total number of extragalactic H2O masers to ~60 at present (Henkel et al. 2005; Kondratko et al. 2006).

It is generally recognized that extragalactic H2O masers can be grouped according to their isotropic luminosity (Liso; e.g., Greenhill et al. 1993). High-luminosity (Liso > 10 L•) H2O masers are associated with active nuclei. Low-luminosity (Liso < 10 L•) H2O masers are mostly associated with star-forming activity; however, some of them may also contain or be in low radio luminosity AGNs. The luminosities of Galactic H2O masers that are commonly observed in the envelopes of evolved stars and star-forming regions range, typically, from 0.001 to 1 L•, and no H2O maser with a luminosity well above 1 L• has ever been found in our Galaxy. Accordingly, H2O masers observed in nearby star-forming or starburst galaxies such as M33, M82, NGC 253, and NGC 6946 with Liso values of 0.01–1 L• (e.g., Churchwell et al. 1977; Claussen et al. 1984; Ho et al. 1987; Baudry & Brouillet 1996) are most likely to originate in star-forming activity in the host galaxy. On the other hand, there has been debate over the nature of a population of H2O masers with luminosities of 1 L• ≤ Liso ≤ 10 L•, most of which are considered to arise in prominent sites of star formation or starburst activity in galaxies. However, some of their host galaxies show AGN activity; low-luminosity water masers have been detected toward LINER or type 1 Seyfert nuclei in recent sensitive single-dish surveys (Henkel et al. 2002; Hagiwara et al. 2003; Braatz et al. 2004). They could simply be low-luminosity analogs of the high-luminosity masers in narrow-line AGNs such as LINERs and type 2 Seyfferts, and lower maser luminosities might be explained by a close face-on view of obscuring structure around the nucleus, such as a disk or torus in the line of sight, or a misalignment between the disk and a nuclear continuum in the line of sight (Hagiwara et al. 2003). It is important to explore the subpopulation of extragalactic masers with 1 L• ≤ Liso ≤ 10 L• at high angular resolution, as they could advance the study of extragalactic star formation or probe the nuclei in low radio luminosity AGNs.

M82 (D = 3.63 Mpc; Freedman et al. 1994) is a well-known nearby starburst galaxy with a long observing history at various wavelengths. The galaxy hosts a number of exotic radio sources within its starburst complex, including main- and satellite-line OH masers and absorption, which trace cold molecular material in the galaxy (e.g., Seaquist et al. 1997; McDonald et al. 2002). Several low-luminosity H2O maser features were detected at 1.4" resolution in earlier Very Large Array (VLA) observations (Baudry & Brouillet 1996); however, the resolution was not sufficient to pin down or resolve the maser to investigate its association with radio continuum sources such as the nucleus, jet, compact H ii regions, or supernova remnants (SNRs).

The Whirlpool galaxy, M51 (D = 9.6 Mpc; Sandage & Tammann 1975), has provided an ideal laboratory for studying molecular materials in a galactic star-forming environment. These materials are more abundant in the spiral arms than in the central region. The nuclear region is very complex, showing molecular emission that is asymmetric in both position and velocity with respect to the nucleus: the dominant redshifted emission peak is 1" to the west of the radio/optical nucleus (e.g., Scoville & Young 1983; Scoville et al. 1998). Ho et al. (1987) first reported the discovery of low-luminosity H2O maser emission toward the galaxy. A snapshot observation pinpointed the location of the known redshifted maser features (Hagiwara et al. 2001) northwest of the continuum peak of the galaxy, while the blueshifted feature(s) have not previously been measured. Due to the insufficient velocity coverage of the earlier observation, the overall
### Table 1
Summary of VLA Observations

| Object       | Date     | R.A.       | Decl.       | Cal. Source | R.A. | Decl. | Velocity Range | $\Delta V^*$ | $t^b$ | Beam (HPBW) | P.A. | $\sigma_{\text{rms}}$ |
|--------------|----------|------------|-------------|-------------|------|-------|----------------|-------------|-------|-------------|------|------------------------|
| M82          | 2002 Apr 13 | 09 51 42.200 | 69 54 59.30 | 0955+654    | 09 54 57.847 | 65 48 15.53 | 50–130         | 1.3         | 9     | 93 x 80     | 45   | 1.1                  |
| M51          | 2003 Jul 4 | 13 29 52.708 | 47 11 42.79 | 1419+542    | 14 19 46.597 | 54 23 14.78 | 365–525        | 5.3         | 8     | 82 x 77     | 6    | 1.1                  |
| NGC 4051     | 2003 Jul 4 | 12 03 09.606 | 44 31 52.52 | 1153+493    | 11 53 24.466 | 49 31 08.83 | 640–725        | 1.3         | 9     | 77 x 72     | 81   | 1.3                  |

**Notes.**—Equinox for M82 is B1950.0; equinox for M51 and NGC 4051 is J2000.0. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Velocity resolution.

$^b$ Total observing time.
distribution of the maser emission has not yet been explored in detail.

NGC 4051 (\(D = 9.7\) Mpc; Adams 1977) is known to be a narrow-line Seyfert 1 galaxy (NLS1) showing a “broad” emission line in H\(\beta\) (FWHM < 2000 km s\(^{-1}\)), narrower than that typically observed (FWHM = 2000–10,000 km s\(^{-1}\)) toward broad-line Seyfert 1 galaxies (Osterbrock & Pogge 1985). NLS1s are characterized by their housing of low-mass black holes radiating near their Eddington limits (e.g., Williams et al. 2004). NGC 4051 exhibits very strong X-ray intensity variability on many different timescales (e.g., Lawrence et al. 1987), which is interpreted as a result of its nuclear activity and extended starburst components dominated by soft X-ray emission (Singh 1999). Hagiwara et al. (2003) detected an H\(_2\)O maser in NGC 4051 and identified it toward the center of the galaxy with a complex nuclear radio structure (e.g., Ulvestad & Wilson 1984). The maser luminosity is estimated to be \(\approx 2\) \(L_\odot\). The maser features span \(\approx 300\) km s\(^{-1}\) and straddle the systemic velocity of \(V_{\text{LSR}} = 730 \pm 3\) km s\(^{-1}\) (Hagiwara et al. 2003) nearly symmetrically. These Doppler-shifted maser features appear to indicate the presence of a rotating disk; however, there has been no compelling evidence found to support the presence of a disk (Hagiwara et al. 2003). The origin of low-luminosity H\(_2\)O masers in NLS1s, including NGC 4051, remains unexplored.

In this paper I report subarcsecond imaging of H\(_2\)O masers toward these three nearby galaxies, in order to update the earlier observations with higher resolution and sensitivity and to further explore the nature of low-luminosity masers. All of them are so weak (flux density < 100 mJy) that they cannot be studied in VLBI observations. Thus, subarcsecond imaging is currently the best method to resolve the masers. In \(\S\) 5 the statistical infrared and radio properties of the H\(_2\)O masers are discussed. Throughout this paper \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) is adopted.

2. OBSERVATIONS

Spectral line observations at 22 GHz using the NRAO\(^1\) VLA were carried out for measurement of H\(_2\)O maser emission (\(6_{16} - 5_{15}\) transition) toward three nearby galaxies, M82, M51, and NGC 4051, from 2002 to 2003. All the observations were performed on these galaxies when the array was in the A configuration. All the observations were made by employing two intermediate-frequency (IF) bands of width 12.5 or 6.25 MHz with a single polarization, divided into 32 or 64 spectral channels, yielding velocity resolutions of 1.32 or 2.63 km s\(^{-1}\) channel\(^{-1}\). Each IF band was centered on a velocity selected to cover all the maser emission, with respect to the local standard of rest (LSR).

Because the low-luminosity maser emission is difficult to detect within an atmospheric coherence time at 22 GHz, phase-referencing observations were employed, using a nearby calibrator source (Table 1) several degrees away from each galaxy. The observations were thus performed by switching to the phase-referencing source, typically every 2 minutes for 30 s. Amplitude and bandpass calibration were performed using observations of 3C 286, and the flux density scale was estimated to be accurate to within 10\%. The data were calibrated and mapped in the standard way using the NRAO Astronomical Image Processing

\(^1\) The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
A summary of the observations, including IF velocity ranges, synthesized beam dimensions, and rms noise for each observing run, is provided in Table 1. After the phase and amplitude calibrations, the image cube was continuum-subtracted using channels with no significant line emission in order to obtain only the line emission. Thus, the maser emission in M82 was separated out from the continuum emission. The continuum image of M82 was produced, collecting only line-free channels within a single 6.25 MHz IF band. In the \((u, v)\) data of M51 and NGC 4051, no continuum emission was detected to a 3 \(\sigma\) rms noise level of 0.6 mJy beam\(^{-1}\) for M51 and 0.48 mJy beam\(^{-1}\) for NGC 4051.

In this paper the B1950.0 coordinate system is adopted for the observations and figures of M82, since this system was used in many earlier works on M82 in the literature.

**3. RESULTS**

**3.1. M82**

Figure 1 shows the locations of the detected H\(_2\)O masers and other known sources in M82. A single-dish spectrum and individual VLA spectra of the H\(_2\)O masers are displayed in Figures 2 and 3. All five VLA spectra had detections above the \(\sim 5 \sigma\) level. However, one might suggest that the detected features at N2 and N3 need to be confirmed. All of these maser features remained unresolved at the angular resolution of \(\sim 93\) mas, corresponding to 1.7 pc at the adopted distance, in the robust weighted maps.

The entire galaxy was searched, and no other water maser emission was found in the velocity range of \(V_{\text{LSR}} = 50–150\) km s\(^{-1}\). The known redshifted emission (e.g., Claussen et al. 1984) in the galaxy was not seen in this observation. In addition to the four masers S1–S4 (using the designation by Baudry & Brouillet 1996), detected with the VLA in the C configuration at 1.4\(\text{''}\) resolution (Baudry & Brouillet 1996), three maser sources are newly detected in our observing run (Fig. 3). They are hereafter labeled N1, N2, and N3. None of the positions of the H\(_2\)O masers

![Figure 2](image2)

**Fig. 2.**—Single-dish spectrum of the H\(_2\)O maser toward the center of M82. The velocity resolution is 1.1 km s\(^{-1}\). The total integration time is \(\sim 60\) minutes, observed with the Max-Planck-Institut für Radioastronomie 100 m telescope at Effelsberg on 2002 March 7. The amplitude is scaled in janskys.

![Figure 3](image3)

**Fig. 3.**—VLA H\(_2\)O maser spectra toward five locations in M82 within \(V_{\text{LSR}} = 70–150\) km s\(^{-1}\). The masers toward S1 and S2 were originally detected at 1\(\text{''}\) resolution of the VLA (Baudry & Brouillet 1996). Their positions are constrained at 0.1\(\text{''}\) resolution in this paper. The masers at N1, N2, and N3 are new detections.
coincide with those of the OH masers, luminous X-ray sources, and infrared peaks that have been measured to date.

Table 2 shows the positions, peak flux intensities, velocities, and velocity widths of the detected masers at the highest angular resolution of 0.93″. These new maser positions are constrained better than those at 1.4″ resolution measured with the VLA in the map configuration by Baudry & Brouillet (1996). The shapes of the detected maser spectra that were reported in Baudry & Brouillet (1996) were relatively unchanged since their observation in 1993. The positions of S1 and S2 are consistent to within 0.08″ between the two observations, and the difference is most likely due to different interferometer beam sizes. No maser emission at or near the location of S3 and S4 was detected at a 3σ level of 3.3 mJy beam−1 in this observation, probably due to intensity variation of the maser. Table 2 lists the positions of the maser features at S2, in which the emission profile is peaked at several velocities, spanning ≈30 km s−1, but all lying in an ∼0.01″ region centered on R.A. (B1950.0) = 09h51m42.1799s, decl. (B1950.0) = 69°54′59.620″.

Table 3 lists the nearest discrete continuum source and radio recombination line (RRL) for each H2O maser. In order to compare the positions between the masers and discrete continuum sources in the literature (McDonald et al. 2002 and references therein), the published positions of two known sources at 15 GHz were adjusted to those on our 22 GHz continuum map, which led to a sensible shift of <0.05″ for 41.95+57.5 and 43.30+59.2. Therefore, one can estimate that positions between the two observations can be compared at an accuracy of <0.05″. The maser positions in Table 3 show an offset of 0.2″−0.3″ (corresponding to 0.36−0.54 pc) from the nearest continuum peaks. Such a large separation makes it difficult to conclude that the detected maser is associated with an H ii region or SNR. Thus, the masers are not essentially associated with any continuum source at this resolution. Alternatively, (compact) H ii regions were not detected due to the sensitivity limit of these observations.

### Table 2

| Component | αB1950.0 (09h51m00s) | δB1950.0 (69°54′00″) | Peak Flux (mJy) | Velocity (LSR) (km s−1) | Feature Width (Channel) | LH2O (L⊙) |
|-----------|-----------------------|-------------------|----------------|-------------------------|------------------------|-------------|
| S1b       | 42.6476 ± 0.0006      | 58.180 ± 0.003    | 13             | 126                     | 2                      | 0.008       |
| S2        | 42.1808 ± 0.0002      | 59.263 ± 0.001    | 63             | 108                     | 3                      | 0.062       |
| N1        | 42.1825 ± 0.0014      | 59.252 ± 0.004    | 15             | 98                      | 1                      | 0.006       |
| N2        | 42.3951 ± 0.0012      | 58.195 ± 0.007    | 8              | 84                      | 1                      | 0.003       |
| N3        | 40.9436 ± 0.0007      | 58.756 ± 0.004    | 16             | 146                     | 1                      | 0.006       |
| N4        | 41.2053 ± 0.0014      | 59.602 ± 0.007    | 5              | 98                      | 1                      | 0.002       |

a Each channel is 1.3 km s−1 wide.
b Adopting labels in Baudry & Brouillet (1996).

d 3.3 mJy beam due to different interferometer beam sizes. No maser emission at and velocity widths of the detected masers at the highest angular resolution of 0.93″. These new maser positions are constrained better than those at 1.4″ resolution measured with the VLA in the C configuration by Baudry & Brouillet (1996). The shapes of the detected maser spectra that were reported in Baudry & Brouillet (1996) were relatively unchanged since their observation in 1993. The positions of S1 and S2 are consistent to within 0.08″ between the two observations, and the difference is most likely due to different interferometer beam sizes. No maser emission at or near the location of S3 and S4 was detected at a 3σ level of 3.3 mJy beam−1 in this observation, probably due to intensity variation of the maser. Table 2 lists the positions of the maser features at S2, in which the emission profile is peaked at several velocities, spanning ≈30 km s−1, but all lying in an ∼0.01″ region centered on R.A. (B1950.0) = 09h51m42.1799s, decl. (B1950.0) = 69°54′59.620″.

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### Table 3

| H2O MASER | POSITION ID | αB1950.0 (09h51m00s) | δB1950.0 (69°54′00″) | θap (arcsec) | ORIGIN | αB1950.0 (09h51m00s) | δB1950.0 (69°54′00″) |
|-----------|-------------|---------------------|-------------------|--------------|--------|---------------------|-------------------|
| S1        | 42.64+58.1  | 42.694              | 58.24             | 0.31         | H ii   | 42.61               | 58.0              |
| S2        | 42.18+59.2  | 42.210              | 59.04             | 0.22         | H ii   | 42.19               | 58.8              |
| N1        | 42.39+58.2  | 42.481              | 58.36             | 0.49         | H ii   | ...                 | ...               |
| N2        | 40.94+58.7  | 40.938              | 58.87             | 0.17         | H ii   | 40.97               | 58.5              |
| N3        | 41.20+59.6  | 41.302              | 59.64             | 0.51         | SNR    | ...                 | ...               |

a McDonald et al. (2002).
b Rodriguez et al. (2004).
c Angular distance between each maser spot and the nearest continuum source.
peak of the galaxy (Hagiwara et al. 2001), suggesting that the maser does arise from the radio jet rather than in a low-luminosity nucleus of the galaxy.

Figure 5 also displays the first moment map produced from the spectral-line data cube containing only 10 velocity channels of redshifted features in Figure 4. A weak velocity gradient, roughly from south to north, is seen along the axis P.A. = 155°. The value of the gradient is approximately 10 km s\(^{-1}\)/0.1°, or 2 km s\(^{-1}\)/pc. The gradient is very weak but real, at least from 554 to 563 km s\(^{-1}\), although the two extrema at the edges \(V_{\text{LSR}} = 564\) and 553 km s\(^{-1}\) are less certain. However, the zeroth-moment map is well sampled with a good signal-to-noise ratio toward the center portions of the source. As the VLA beam is 82 × 77 mas\(^2\) at P.A. = 6°, there is no possibility that the gradient along P.A. = 155° is arising from effects of the beam shape or orientation. Accordingly, I conclude that the observed velocity gradient and its axis are real.

Fig. 4.— H\(_2\)O maser spectra of M51, observed with VLA-A on 2003 July 4. The left panel covers the blueshifted velocity range, and the right panel covers the redshifted range. The velocity resolution is 5.3 km s\(^{-1}\). The spectra were obtained from two IF channels, each with 12.5 MHz bandwidth.

Fig. 5.— Left: Large-scale 8.4 GHz nuclear continuum of M51 imaged by the VLA (Bradley et al. 2004), superposed with two approximate positions of the H\(_2\)O maser. The redshifted cluster is marked in red in the vicinity of the continuum peak, and the blueshifted feature(s) marked in blue is offset from both the peak and the other maser cluster. Right: First velocity moment map of the redshifted maser from the uniform-weight map. A small velocity gradient over the maser is identified. Contours are spaced at 1–2 km s\(^{-1}\) and labeled with the absolute LSR velocity scale.
3.3. NGC 4051

VLA spectra of the H$_2$O maser toward the center of NGC 4051 (Fig. 6) cover most of the known features in the range $V_{\text{LSR}} = 640$–780 km s$^{-1}$. The location of the systemic feature peaking at $V_{\text{LSR}} = 730$ km s$^{-1}$ is measured at R.A. (J2000.0) = $12^h3^m3^s.7$ and decl. (J2000.0) = $+44^\circ$31.5268, and all other features are confined to within about 0.01 (or 0.5 pc) from the systemic feature, resulting in the masers being unresolved at this resolution. The beam-deconvolved size of each maser feature is smaller than 40 mas, that is, about 2 pc. The result is consistent with the earlier VLA-A snapshot by Hagiwara et al. (2003). Although this new observation has improved $(u, v)$ coverage over the previous single VLA snapshot, no new useful information is obtained.

4. DISCUSSION

4.1. M82

4.1.1. H$_2$O Masers and Luminous X-Ray Sources

The positions of the luminous hard X-ray sources in M82 were measured within an accuracy of 0.7" by Chandra (Kaaret et al. 2001; Matsumoto et al. 2001); however, none coincide with those of the H$_2$O masers detected in this observation. In addition, there was no high-brightness radio source detected at 22 GHz toward any of these luminous X-ray sources, suggesting that these X-ray sources are not likely to be low-luminosity AGNs. Since the masers do not overlap any high-brightness radio sources like an AGN or jet, they are off-nuclear masers that are not directly amplifying the background continuum, as in the case of nuclear H$_2$O masers. This is consistent with the fact that the maser luminosity in the galaxy is 1–5 orders of magnitude lower than those of the nuclear H$_2$O masers.

4.1.2. H$_2$O Masers and Other Sources

None of the H$_2$O masers detected in this observation are associated with infrared peaks at 2.2 μm, which were considered to be low-luminosity AGN candidates or the dynamical center of the galaxy (Dietz et al. 1986), suggesting that the masers in M82 are not nuclear masers. The separations between each H$_2$O maser peak and the center of the nearest continuum source, given in Table 3, indicate that there are no H$_2$O masers at the locations of the H ii regions or radio SNRs. According to the 5 GHz MERLIN and 15 GHz VLA-PT observations of continuum sources in the galaxy by McDonald et al. (2002), the angular size of each H ii region appearing in Table 3 is ~0.1–0.2" (2–4 pc) in radius. It is understood that the sizes of Galactic compact H ii regions excited by central stars are typically 0.05–0.5 pc and Galactic H ii regions are less than ~5 pc in radius (e.g., Garay & Lizano 1999). Given the observed separations between the masers and the centers of compact H ii regions that range from 0.17" to 0.51", corresponding to 3–10 pc, it is less plausible that the masers in the galaxy are directly associated with H ii regions or ionizing central

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**TABLE 4**

| Component         | $\alpha_{\text{J2000.0}}$ (13h30m00s) | $\delta_{\text{J2000.0}}$ (47°11'00") | Peak Flux (mJy) | Velocity (LSR) (km s$^{-1}$) | Feature Width (Channel)$^a$ | $L_{H_2O}$ ($L_\odot$) |
|-------------------|--------------------------------------|----------------------------------------|-----------------|-----------------------------|-----------------------------|---------------------|
| Blueshifted component | 52.5486 ± 0.0016                 | 43.337 ± 0.012                        | 8.2             | 445                         | 2                           | 0.1                 |
| Redshifted components | 52.7089 ± 0.0001                 | 42.790 ± 0.001                        | 41.8            | 539                         | 1                           | 0.47                |
|                  | 52.7087 ± 0.0001                 | 42.789 ± 0.001                        | 52.6            | 565                         | 1                           | 0.58                |
|                  | 52.7091 ± 0.0001                 | 42.788 ± 0.002                        | 23.4            | 576                         | 1                           | 0.26                |

$^a$ Each channel is 5.3 km s$^{-1}$ wide.

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Fig. 6.—H$_2$O maser spectra from the nucleus of NGC 4051 with a velocity resolution of 1.3 km s$^{-1}$ using the VLA. The spectra consist of two independent IF channels that cover the velocity range of $V_{\text{LSR}} = 640$–780 km s$^{-1}$, straddling the systemic velocity of $V_{\text{LSR}} = 730$ km s$^{-1}$. 
stars in the galaxy. In contrast, VLBI observations revealed that the H$_2$O maser in the nearby star-forming galaxy M33 is associated with the H II region IC 133 (Greenhill et al. 1993). It is thus plausible that some other H$_2$O features in M82 might be found in H II regions. The deconvolved angular sizes of RRL emission (H290) in the galaxy displayed in Table 3 range from 1.4" to 1.7" (25–30 pc), just greater than the VLA synthesized beam of 0.9" (Rodriguez et al. 2004) that includes the masers at S1, S2, and N2. The H$_2$O maser would not have originated from the RRL-emitting ionized gas, but the RRL marks the prominent star-forming regions in the galaxy, where maser excitation actively occurs. The velocity deviation of the ionized gas (100–130 km s$^{-1}$) and molecular gas (110–145 km s$^{-1}$) from the galaxy’s rigid rotation velocity has been observed and accounts for the expansion of starburst-driven winds in the galaxy (e.g., Matsushita et al. 2005), but the kinematics connecting the masering clouds with the ionizing medium is not obviously seen from this observation.

4.1.3. What are the Masers in the Galaxy?

The interpretation of the nature of the H$_2$O masers in M82 is not straightforward, since none have distinct continuum counterparts as effective pummeling agents. Weiss et al. (1999) imaged an expanding shell-like structure (superbubble) traced by CO and CO isotopes in the galaxy, with a diameter of $\approx$30 pc and expansion velocity of $\approx$45 km s$^{-1}$. According to their analysis, the velocity of the approaching side of the expanding shell is $V_{\text{LSR}} = 95$ km s$^{-1}$, and the receding velocity is $V_{\text{LSR}} = 190$ km s$^{-1}$. Thus, the former has an H$_2$O maser counterpart at $V_{\text{LSR}} = 86$ and 94 km s$^{-1}$, but the latter is not covered in this observation. If the maser at S2 is associated with the shell, it could be excited at the shock front of the starburst-driven winds. It is interesting to note that thermal 100 GHz continuum emission has been imaged inside the CO superbubble, and the distribution of the H$_2$O masers roughly underlines the continuum emission originating from starburst activity (Matsushita et al. 2005). About 10 OH main-line masers are observed that are associated with blueshifted parts of expanding wind-driven shells (Weiss et al. 1999), and the velocities and locations of these OH and H$_2$O masers are largely consistent (Pedlar 2005; Matsushita et al. 2005). These OH masers trace the 1667 MHz OH absorption along the major axis of the galaxy, and the OH dynamics understood as solid-body rotation agrees well with the CO emission (Shen & Lo 1995) and H I absorption (Wills et al. 2000). However, there are distinct deviations from this at 350 and $\sim$70 km s$^{-1}$ (Pedlar et al. 2004), although neither is observed in our observations. Therefore, the detected blueshifted H$_2$O masers are concentrated on the same molecular disk that is traced by OH absorption and CO emission; however, the association of the H$_2$O masers with the expanding shells or molecular outflows is not obvious from our data.

Similarly, in the starburst galaxy NGC 253, the locations of low-luminosity H$_2$O masers ($\sim$1 $L_\odot$) are measured toward the nuclear region with the VLA at $\sim$1" resolution (Henkel et al. 2004). The association of the strongest blueshifted maser features with the RRL, an expanding supernova, or starburst-driven winds is proposed, like the case in M82; however, there is no compelling evidence for that from their observations.

The extent of the CO($J = 2 \rightarrow 1$) molecular clouds and outflows is not inconsistent with that of the H$_2$O maser (Weiss et al. 2001). Molecular outflows in our Galaxy are observed in H$_2$O emission, typically on scales of 1–10 AU, which is at least 100 times smaller than the masers measured on the parsec scale with the VLA. Accordingly, even if the masers probed part of the outflow, they would not be resolved on these scales by analogy with the cases of young stellar objects (YSOs) in our Galaxy. It is believed that H$_2$O masers indicate sites of star formation and appear at a certain stage of the evolutionary history of protostars. It is also understood that CH$_3$OH, OH, and H$_2$O masers are observed at different evolutionary stages of star formation, and H$_2$O emerges at the earliest stage of massive star formation during the rapid accretion phase (Churchwell 2002). Masers in a galaxy that does not accompany compact H II regions and OH masers may be the signposts of the early stage of star formation and are most likely to be associated with molecular outflows or accretion disks around extragalactic YSOs that have not been studied to date (e.g., Torrelles et al. 1998).

4.2. M81

4.2.1. Blueshifted Features

The precise location of the known weak and variable blueshifted features lying from $V_{\text{LSR}} = 435$ to 445 km s$^{-1}$ in this galaxy (Hagiwara et al. 2001) has been an open question. One of them has been pinpointed in this observation for the first time. Taking the fact that the maser luminosity of the blueshifted emission is approximately 0.17 $L_\odot$, from the VLA spectrum and is not associated with any known radio continuum sources in the galaxy, one can infer that AGN activity is not the major source giving rise to the maser. The blueshifted emission is displaced 1"o, or 82 pc, from the redshifted counterpart near the nucleus; thus, no hint of physical connection exists between these velocity clusters. From what do the features arise? The peak velocity of $V_{\text{LSR}} = 445$ km s$^{-1}$ is in the velocity range of the central HCN emission (Kohno et al. 1996). The features lie in the central dense region of the HCN emission, where the mean velocity field of the HCN emission is $V_{\text{LSR}} \approx 480$ km s$^{-1}$, that is, 35 km s$^{-1}$ shifted from the maser (Kohno et al. 1996). Thus, it is impossible to find common mechanisms connecting the two different velocity gradients traced by the maser and the HCN. All that one can speculate is that the maser traces the most dense part ($\approx$10$^3$ cm$^{-3}$) of the circumnuclear molecular gas within 10 pc of the nucleus. As a result of this observation, the bipolar jet model proposed in Hagiwara et al. (2001), in which the blueshifted features are associated with the approaching side of the jet, is no longer eligible.

4.2.2. Central Kinematics

One of the most exciting results from this observation is that part of the velocity structure of the dense molecular gas within a few parsecs of the nucleus is resolved at subarcsecond resolution. The detected velocity gradient is about 2 km s$^{-1}$ pc$^{-1}$, and the direction of the gradient (P.A. $\approx$ 155$^\circ$) is similar to that of the radio jet but not to the rotational axis of the inner torus with a radius of 70 pc (P.A. $\approx$ 160$^\circ$–165$^\circ$) postulated from the distribution of the HCN($J = 1 \rightarrow 0$) emission observed at 4" resolution (Kohno et al. 1996). Most of the redshifted maser features in Figure 4 are neither in the velocity range of CO($J = 1 \rightarrow 0$) ($V_{\text{LSR}} = 387–547$ km s$^{-1}$) nor in that of HCN($J = 1 \rightarrow 0$) ($V_{\text{LSR}} = 377–546$ km s$^{-1}$). The velocity ranges of the masers do not agree with those of the HCN emission and the HCN torus model proposed in Kohno et al. (1996); however, the axis of the HCN torus is not inconsistent with the direction of the maser velocity field.

Given the fact that the blueshifted features are separated by $\sim$80 pc from the rest of the features and do not coincide with the nucleus, the whole maser system is unlikely to trace a subarcsecond Keplerian disk observed with the nuclear H$_2$O maser, if it exists. However, it is possible that only the redshifted features trace a part of a rotating disk, and the blueshifted features on the disk are invisible. Assuming that the observed maser is on a disk at a radius $r$ from the nucleus and with a rotating velocity of $V_{\text{rot}}$,
the observed velocity gradient \( (dV/dl) \) along P.A. = 155° can be expressed as \( dV/dl \approx d(V_{\text{rot}} \sin \theta)/dl(\theta) = V_{\text{rot}}/r \), where \( i \) is the projected distance, \( i \) is the disk inclination, and the approximation of \( \sin \theta \approx \theta \) is made. Adopting the disk inclination of 80° from the edge-on circumnuclear-nuclear disk with a radius of 70 pc (Kohno et al. 1996), together with the observed parameters of \( dV/dl = 2 \text{ km s}^{-1} \text{ pc}^{-1} \) and \( V_{\text{red}} - V_{\text{sys}} = V_{\text{rot}} \approx 100 \text{ km s}^{-1}, r \) is estimated to be 50 pc. The result suggests that the observed maser probes a disk on a scale of 10 pc but not a thin disk with \( r < 0.1 \) pc, such as the one in NGC 4258 (e.g., Herrnstein et al. 1998).

Does the maser disk lie in an inner part of the circumnuclear HCN disk? Taking this value for the radius of a molecular disk, the mass confined within the disk is \( 1.2 \times 10^{8} M_{\odot} \), that is, 1 or 2 mg larger than the molecular hydrogen and dynamical mass within \( r < 70 \) pc, based on the estimation from the HCN intensities (Kohno et al. 1996). Accordingly, we cannot account for the detected velocity field with a subparsec-scale masering disk or a large scale molecular disk.

It is interesting to note that the velocity gradient of 0.65 km s\(^{-1}\) pc\(^{-1}\) along the radio jet axis was detected in CO(\( J = 3 \rightarrow 2 \)) at 4" resolution (~160 pc) using the Submillimeter Array by Matsushita et al. (2004), although the sampled area in their image is more than 100 times larger than that in this VLA observation. The CO velocity gradient in their position-velocity map covers that of the maser at \( V_{\text{SR}} = 555 - 565 \) km s\(^{-1}\). However, the observed CO gradient is more dominant in the direction perpendicular to the jet, and such a small velocity gradient in the thermally excited molecular gas is likely due to the internal turbulence, as also mentioned in Matsushita et al. (2004). Thus, there is no compelling evidence that the maser and CO(\( J = 3 \rightarrow 2 \)) trace the same kinematics, but both of them could be distributed in the same molecular cloud. In the VLBI observation of the 1667 MHz OH maser toward the type 1 Seyfert nucleus in Mrk 231, a weak velocity gradient of 1.4 km s\(^{-1}\) pc\(^{-1}\) across the torus structure with a radius of 65 pc is reported in OH emission (Klöckner et al. 2003), which does not agree with any thermal molecular gas structure. In this sense, the OH maser in Mrk 231 is similar to the H\(_{2}\)O maser in M51. The axis of the OH torus in Mrk 231 is not aligned with the major axis of the nuclear continuum source; rather, it is perpendicular to the nuclear continuum axis. This is different from the case of M51, in which the velocity field of the maser is almost aligned with the jet axis, which might rule out the presence of a masering disk in the galaxy. Note that there are still some other blueshifted features whose positions have not yet been pinned down, some of which could be on a masering torus within 1 pc from the center, along with redshifted counterparts. If the maser in M51 is resolved down to scales of 0.1 pc using VLBI, the velocity structures of the maser will be interpreted differently. The most plausible explanation for the maser and its velocity gradient based on these observations is that the maser arises in a dense molecular environment in the foreground of a radio jet, amplifying the background radio continuum jet (Claussen et al. 1998), or, alternatively, is from a shocked dense region near the boundary of the jet (Hagiwara et al. 2001). The weak radio intensity of the jet would account for the low luminosity of the maser.

4.3. NGC 4051

The luminosity of the H\(_{2}\)O maser in NGC 4051 is \(< 1 L_{\odot} \), very low for nuclear masers. It might appear that such a low-luminosity maser is not related to direct AGN activity. However, Hagiwara et al. (2003) proposed that the low luminosity of the maser and narrower total velocity span of the Doppler-shifted features \((\sim 100 \text{ km s}^{-1})\) might be due to low-gain maser amplification, resulting from a small inclination of a disklike structure surrounding the AGN. Hagiwara et al. (2003) hypothesized that the maser originated from a less edge-on disklike configuration surrounding a nucleus, which would cause relatively short gain paths in the line of sight. This could account for the low luminosity of the maser. Madejski et al. (2006), however, argue that the maser in NGC 4051 is unlikely to be connected with direct AGN activity, in that the X-ray-absorbing medium is significantly ionized in NGC 4051, and such an ionized absorbing medium is unlikely to be physically close to the masering medium. They suggest that the origin of the maser in NGC 4051 is in nuclear winds, because the broadly spread (~280 km s\(^{-1}\)) narrow-line spectrum is similar to that of the Circinus galaxy. Circinus hosts highly Doppler-shifted maser features with a total velocity range of \(< 160 \text{ km s}^{-1}\) that are introduced as nuclear wind components, together with features tracing an edge-on disk with a sub-Keplerian rotation (Greenhill et al. 2003). However, a physical mechanism driving the nuclear winds in the galaxy has not yet been proposed.

One can speculate that the medium giving rise to the maser is geometrically separated from the X-ray absorber. The inner edge of the absorber could be illuminated by direct X-ray radiation and hence ionized, which would also cause a high time variability of the X-ray-measured column density \( N_{\text{H}} \), while the masering medium could exist in the outer edge of a thin disk that is much less ionized because of a large radial distance from the X-ray heating source. The known periodic intensity variability at hard X-ray bands might occur in the inner edge of the disk (e.g., Herrnstein et al. 1998), while the time interval of the intensity variability of the maser is very different. In the case of NGC 4388, the radius of the absorbing medium is estimated from the variability of \( N_{\text{H}} \) to be a few hundred Schwarzschild radii \( (R_{\text{Sch}}/\text{Elvis et al. 2004}) \), that is, 100 times smaller than the (sub)parsec-scale obscuring medium observed in the H\(_{2}\)O maser. H\(_{2}\)O masers in NGC 4258 are distributed in a region between 40,000\( R_{\text{Sch}} \) and 80,000\( R_{\text{Sch}} \) from the nucleus (e.g., Herrnstein et al. 1998). Therefore, it is less plausible that the masering medium and X-ray-ionizing structure occur in a single physical structure. Thus, we still cannot rule out the presence of a maser disk in NGC 4051. In any case, the hypothesis proposed by Hagiwara et al. (2003) should be tested at milliarcsecond angular resolutions by resolving the maser distribution on scales of 0.1 pc or less.

5. FAR-INFRARED VERSUS RADIO INTENSITY CORRELATION DIAGRAM

There is a known strong linear correlation between the far-infrared (FIR) flux density and the radio flux density at 1.4 GHz from nuclear starburst galaxies (Helou et al. 1985; Condon et al. 1991), which implies that FIR radiation and nonthermal radio emission at 1.4 GHz are closely connected with star-forming activity. In Figure 7 there are three different comparisons: the ratios of the FIR flux to the 1.4 GHz radio flux from high-luminosity H\(_{2}\)O masers, as well as from low-luminosity H\(_{2}\)O masers and prototypical OH megamasers (OHMMs) from ultraluminous FIR galaxies. The low-luminosity masers and OHMM samples follow well the known FIR-radio correlation. The mean constant ratios of these three samples are also displayed in Figure 7, from which one can see that the ratio for the low-luminosity masers is steeper than those of the other two. The reason for this deviation is that the FIR fluxes are relatively more dominant for the low-luminosity masers, which supports the idea that the low-luminosity masers are powered by star-forming activity rather than AGN activity. We cannot discriminate the synchrotron emission at 1.4 GHz from either SNR or AGN ejecta, but the FIR
LOW-LUMINOSITY WATER MASERS IN ACTIVE GALAXIES

6. SUMMARY

Low-luminosity extragalactic H$_2$O masers have been identified in different physical environments related to star formation, such as H II regions, YSOs, or possibly SNRs. Given the fact that the luminosity of the strongest Galactic H$_2$O maser, W49N, is \( \sim 1 L_\odot \), the origin of these low-luminosity masers can be explained by star-forming activity in their host galaxies. Many of the host galaxies of these masers contain star-forming regions or exhibit starburst activity but do not contain an AGN. These H$_2$O masers may reveal new stellar phenomena relevant to extragalactic star-forming activity.

The kinematics of H$_2$O masers in M82 is broadly consistent with OH or CO solid-body rotation along the galaxy’s major axis, but locally the masers are not associated with any other molecular emission. Including the three new detections, the masers are not directly associated with any continuum sources, such as compact H II regions or radio SNRs, suggesting that the masers arise from the earliest stage of star-forming activity in the galaxy. For the masers in M51, the detected blueshifted features are significantly offset from the nuclear radio continuum, while the redshifted counterparts are in the nuclear radio source. Seemingly, the maser in the galaxy amplifies the radio jet continuum, which needs to be confirmed at higher resolution. The most remarkable result is that a small velocity gradient roughly along the jet has been detected from redshifted emission at 0.1" resolution. However, the interpretation of the velocity gradient is not straightforward. The nature of the maser in NGC 4051 is controversial and also needs to be studied at higher resolutions. A study of the distribution of the rare H$_2$O masers toward a NLS1 showing a low accretion rate and hence a smaller black hole mass is of great interest. According to a statistical study, it is found that the mean FIR-to-radio flux ratio of low-luminosity H$_2$O masers is higher than that of their high-luminosity counterparts, suggesting that the maser excitation of low-luminosity water masers such as the one in M82 is related primarily to star-forming activity, rather than AGN activity.

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