WATER MASERS ASSOCIATED WITH STAR FORMATION IN THE ANTENNAE GALAXIES

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Received 2010 March 15; accepted 2010 May 10; published 2010 May 20

ABSTRACT

We present Very Large Array (VLA) observations with 80 mas resolution (~9 pc) of the recently discovered Galactic-analog (GA)-H2O masers in the Antennae interacting galaxies (NGC 4038/NGC 4039; Arp244). Three regions of water maser emission are detected: two in the “interaction region” (IAR) and the third ~5.6 (≥600 pc) west of the NGC 4039 nucleus. The isotropic H2O maser luminosities range from 1.3 to 7.7 L⊙. All three maser regions are mostly obscured in the optical/near-infrared continuum, and are coincident with massive CO-identified molecular clouds. The H2O maser velocities are in excellent agreement with those of the molecular gas. We also present archival VLA 3.6 cm data with ~0′′.28 (~30 pc) and ~0′′.8 (~90 pc) resolution toward the maser locations. All three maser regions are coincident with compact 3.6 cm radio continuum emission, and two are dominated by thermal ionized gas, suggesting the presence of natal super star clusters containing the equivalent of a few thousand O stars. We also present detailed comparisons between the radio data and existing Hubble Space Telescope Advanced Camera for Surveys (optical) and NICMOS (near-IR) data and find that both maser regions in the IAR are also associated with Paα emission and neither source is detected shortward of 2 μm. These results highlight the potential of using GA-H2O masers to pinpoint sites of young super star cluster formation with exquisite angular resolution.

Key words: galaxies: interactions – galaxies: ISM – galaxies: starburst – galaxies: star clusters: general – masers – radio lines: galaxies

1. INTRODUCTION

Water masers are found in the vicinity of ~70% of infrared bright (100 μm > 1000 Jy and 60 μm > 100 Jy) ultracompact H II (UCHII) regions in our Galaxy (Churchwell et al. 1990; Kurtz & Hofner 2005), providing excellent signposts for active star formation. The term “kilomaser” was coined to describe extragalactic H2O masers with luminosities comparable to the brightest star formation H2O masers in our Galaxy (e.g., W49N; LH2O ∼ 1 L⊙). Kilomaser isotropic luminosities (LH2O < 10 L⊙) are much lower than the more widely studied “megamasers” found in the nuclear regions of active galactic nuclei (AGNs; i.e., NGC 4258) with luminosities up to 104 L⊙ (Barvainis & Antonucci 2005). Since “kilomasers” can in principle be either of nuclear (i.e., amplifying a background AGN) or star formation origin, we will use the term “Galactic-analog” (GA)-H2O maser to refer to non-nuclear masers with kilomaser luminosity. Nata super star clusters are thought to contain thousands of UCHII regions, therefore GA-H2O masers may help pinpoint sites of young extragalactic cluster formation, though there have been few searches with the required sensitivity. Until recently, GA-H2O masers had been unambiguously detected toward only six nearby galaxies: LMC, M82, IC 342, IC 10, M33, and NGC 2146 with isotropic luminosities in the range 0.005–4 L⊙ (Whiteoak & Gardner 1986; Henkel et al. 2005; Castangia et al. 2008, and references therein). The remaining few known H2O kilomasers are either associated with AGN activity or their origin is ambiguous.

We recently conducted a Greenbank Telescope5 (GBT) search for H2O masers toward four nearby starburst galaxies (3Mpc < D < 22 Mpc) known to harbor natal super star clusters and without known AGNs (or at worst low-luminosity AGNs) down to a sensitivity level sufficient to detect strong GA-H2O masers. Positive detections were found for all four galaxies (the Antennae galaxies, He2-10, NGC 4214, and NGC 5253; Darling et al. 2008) suggesting that GA-H2O maser emission may be common in starburst galaxies. The unusual success of this mini survey arises from its order-of-magnitude greater sensitivity compared to most previous single-dish surveys for either kilomasers or megamasers.

The strongest masers were detected toward the Antennae (D ~ 22 Mpc)6 interacting galaxies (NGC 4038/NGC 4039; Arp244). Indeed, this violent merger is an ideal laboratory to study how H2O maser emission behaves in regions of extreme star formation. In this Letter, we report sensitive high angular resolution Very Large Array (VLA) water maser observations of the Antennae galaxies, along with archival 3.6 and 6 cm continuum, CO, and optical/near-IR data in order to pinpoint the maser locations and determine the nature of the emission.

2. VLA OBSERVATIONS AND DATA REDUCTION

We observed the (616–523) ortho-water maser line at 22.23508 GHz toward the Antennae galaxies in the VLA A-configuration using fast switching and reference pointing. The full width at half-power (FWHP) at the Doppler shifted frequency of ~22.11 GHz is ~2′′, encompassing both nuclei (NGC 4038 and NGC 4039), as well as the interaction region (IAR; see Figure 1(a)); in comparison, the GBT primary beam was only 30′′. In order to cover the velocity extent of maser emission detected with the GBT with similar

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6 Antennae distance estimates range from 13.8 ± 1.7 Mpc (Saviane et al. 2008) to 22 ± 3 Mpc (Schweizer et al. 2008); we adopt 22 Mpc.
velocity resolution (3.7 km s\(^{-1}\)) required three correlator settings, each with two intermediate frequencies (IFs). We also retrieved A- and B-configuration 3.6 cm continuum data, as well as BnA-configuration 6 cm data from the VLA archive (the B-configuration data were included in the multi-configuration study of Neff & Ulvestad 2000). Further details of the VLA data are given in Table 1. Data calibration followed standard high-frequency procedures in AIPS, including using a model for the brightness distribution of the absolute flux calibrator 3C 286; absolute flux calibration is good to \(\sim 5\%\). The line-free channels from the \(\sim 22.11\) GHz data were used to estimate the 1.3 cm continuum emission in the UV-plane. The maser line data were subsequently imaged in CASA (to facilitate regridding of the six IFs), and primary beam correction was applied. The continuum data were imaged in AIPS, and the primary beam was corrected. The astrometric accuracy is better than \(\sim 0.05\); while the relative position uncertainty of the maser data is an order of magnitude better. All velocities are presented in the barycenter frame, optical definition.

3. RESULTS

3.1. \(\text{H}_2\text{O}\) Maser Emission

As shown on the three-color \textit{Spitzer} composite in Figure 1(a), three distinct regions of \(\text{H}_2\text{O}\) maser emission are resolved by the VLA: two are located in the 24 \(\mu\)m bright IAR between the

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**Figure 1.** (a) Three-color \textit{Spitzer} image of the Antennae galaxies with RGB mapped to 24, 8, and 3.6 \(\mu\)m. Green + symbols show the locations of the three \(\text{H}_2\text{O}\) maser regions detected by the VLA. In panels (b)–(d) the VLA \(\text{H}_2\text{O}\) maser spectra are shown by the solid histogram, and \(\sim 4^\prime\) resolution \(\text{CO}(1-0)\) spectra from Wilson et al. (2000) are superposed as dot-dashed lines.
we find isotropic H$_2$O maser luminosities ranging from 1.3 to $\lesssim 7.7$.

Differences in intensity between the VLA and GBT data can be attributed to the Gaussian taper and UV weighting adjustments indicated after the resolution; $\lesssim$ indicates a cut.

Archival 3.6 cm (8.46 GHz) Continuum Observations

| Parameter                                   | Value |
|---------------------------------------------|-------|
| Project (config.)                           | AB1304 (A) |
| Observing dates                             | 2008 Nov 10, 11, 15 |
| Bandwidth                                   | 6 $\times$ 6.25 MHz |
| Velocity bandwidth                          | 1360–1740 km s$^{-1}$ |
| Velocity resolution                         | 3.7 km s$^{-1}$ |
| Spec. line resolution                       | 108 mas $\times$ 61 mas (P.A. $= +1^{\circ}$) |
| Spec. line rms noise                         | 1 mJy beam$^{-1}$ |
| Cont. resolution                            | 350 mas $\times$ 220 mas (P.A. $= 10^{\circ}$); $\lesssim$1000 k$\lambda$ |
| Cont. rms noise                              | 0.14 mJy beam$^{-1}$ |

Archival 6 cm (4.85 GHz) Continuum Observations

| Parameter                                   | Value |
|---------------------------------------------|-------|
| Project (config.)                           | AN074 (BnA) |
| Observing date                              | 1997 Jan 31 |
| Bandwidth                                   | 2 $\times$ 50 MHz |
| Cont. resolution (A)                        | 1$\circ$03 $\times$ 0$\circ$.67 (P.A. $= -2^{\circ}4$) |
| Cont. rms noise                              | 0.022 mJy beam$^{-1}$ |

Notes. A Briggs weighting of robust $= 0$ was used unless otherwise specified. UV weighting adjustments are indicated after the resolution; $\lesssim$ indicates a Gaussian taper and $>$ indicates a cut.

$^a$ Natural weighting was used.

Table 1
VLA Observing Parameters

| Parameter                                | Value |
|------------------------------------------|-------|
| H$_2$O Maser and 1.3 cm (22.11 GHz) Continuum Observations |       |
| Project (config.)                        | AB1304 (A) |
| Observing dates                          | 2008 Nov 10, 11, 15 |
| Bandwidth                                | 6 $\times$ 6.25 MHz |
| Velocity bandwidth                       | 1360–1740 km s$^{-1}$ |
| Velocity resolution                      | 3.7 km s$^{-1}$ |
| Spec. line resolution                    | 108 mas $\times$ 61 mas (P.A. $= +1^{\circ}$) |
| Spec. line rms noise                      | 1 mJy beam$^{-1}$ |
| Cont. resolution                         | 350 mas $\times$ 220 mas (P.A. $= 10^{\circ}$); $\lesssim$1000 k$\lambda$ |
| Cont. rms noise                           | 0.14 mJy beam$^{-1}$ |

Table 2
VLA Water Maser Properties

| Region          | $\alpha$ (J2000) | $\delta$ (J2000) | $V_{\text{range}}$ (km s$^{-1}$) | $V_{\text{peak}}$ (km s$^{-1}$) | $S_{\text{peak}}$ (mJy) | $\int S dv$ (mJy km s$^{-1}$) | $L_{\text{H}_2\text{O}}$ (L$_{\odot}$) |
|-----------------|-----------------|-----------------|-------------------------------|-------------------------------|-----------------|-----------------------------|-------------------------------|
| H$_2$O-East     | 12:01:55.4590 (2) | $-18:52:45.653$ (5) | 1502–1528                      | 1520.4                        | 9.3 (0.9)       | 116 (12)                    | 1.3 (0.1)                     |
| H$_2$O-SE       | 12:01:54.9959 (4) | $-18:53:05.543$ (8) | 1439–1539                      | 1515.1                        | 7.2 (1.0)       | 370 (25)                    | 4.1 (0.4)                     |
| H$_2$O-West     | 12:01:53.1257 (1) | $-18:53:09.805$ (2) | 1639–1689                      | 1670.5                        | 44.3 (0.1)      | 690 (25)                    | 7.7 (0.5)                     |

Notes. Positions and peak flux densities measured from two-dimensional Gaussian fits. Isotropic line luminosities were computed from $L_{\text{H}_2\text{O}} = (2.3 \times 10^{-5} L_{\odot}) \times D^2 \times \int S dv$, where the distance $D$ was assumed to be 22 Mpc and $\int S dv$ is in mJy km s$^{-1}$ (Henkel et al. 2005).

3.2. Radio Continuum Emission

We have created matched resolution $\sim 0\arcsec 8$ ($\sim 90$ pc) 3.6 and 6 cm continuum images with a high signal-to-noise ratio ($S/N$), as well as higher resolution $\sim 0\arcsec 28$ ($\sim 30$ pc) 1.3 and 3.6 cm images, albeit with significantly less sensitivity. Care was used to match the UV-coverage of the continuum pairs at both resolutions. These images are the highest resolution radio images available to date toward the Antennae (see, for example, the $\sim 1\arcsec 1$ resolution 3.6 cm VLA data of Neff & Ulvestad 2000). A complete analysis of these data throughout the Antennae will be presented in a forthcoming paper, for now we concentrate on the maser locations. Radio continuum sources associated with H$_2$O-East and H$_2$O-West are detected in the $\sim 0\arcsec 8$ resolution 3.6 and 6 cm images (also see Neff & Ulvestad 2000, their sources 4-4 and 1-3, respectively). We have also resolved compact continuum emission toward H$_2$O-SE in the $\sim 0\arcsec 28$ 1.3 and 3.6 cm images (this source is not resolved from the bright Neff & Ulvestad 2000 source 2-1 at poorer resolutions). The radio source associated with H$_2$O-East is also detected in the higher resolution (poorer sensitivity) 1.3 and 3.6 cm continuum images, though H$_2$O-West is not. The 3.6 cm continuum contours are shown in Figures 2(a)–(d) (see Section 4.1).

The radio continuum sources are denoted CM-H$_2$O-East, CM-H$_2$O-SE, and CM-H$_2$O-West, and their observed flux densities and spectral indices ($S \propto \nu^\alpha$) are listed in Table 3. The spectral index for CM-H$_2$O-East is flat and in good agreement with Neff & Ulvestad (2000), their source 4-4, $\alpha = -0.16 \pm 0.19$. We also find a flat (or possibly inverted) spectrum for CM-H$_2$O-SE (detected here for the first time). In contrast, we find that CM-H$_2$O-West has a steep spectrum ($\alpha = -0.6^{+0.4}_{-0.2}$), while Neff & Ulvestad (2000) inferred an inverted spectrum (their source 1–3, $\alpha = +0.38 \pm 0.19$). This inconsistency can be explained by the fact that these authors use a fitted size for this source at 3.6 cm, but only a peak flux density at 6 cm due to a poor Gaussian fit, thus underestimating the 6 cm flux density. Since both CM-H$_2$O-East and CM-H$_2$O-SE have flat radio spectra, and are coincident with Pa$_\alpha$ emission (see Section 4.1), both are likely to be dominated by thermal H ii regions. In contrast, CM-H$_2$O-West has a steep spectrum and thus appears to be dominated by non-thermal emission; broader radio wavelength coverage is required to disentangle a thermal component for this maser region.

For the two thermal sources, CM-H$_2$O-East and CM-H$_2$O-SE, the production rate of ionizing photons (Q$_{\text{HII}}$) can be estimated using Equation (2) from Condon (1992) assuming thermal, optically thin emission (see Johnson et al. 2009). Although the 1.3 cm data would generally be preferred (to exclude two nuclei and one is located 5$\arcsec 6$ ($\gtrsim 600$ pc) to the west of the NGC 4039 nucleus. For ease of referencing, these three maser regions are denoted H$_2$O-East, H$_2$O-SE, and H$_2$O-West. We call these “maser regions” because at the current resolution $\sim 80$ mas ($\sim 9$ pc), the observed emission is most likely the sum of many individual maser spots. Spectra of the maser emission are shown in Figures 1(b)–(d) and the observed properties are given in Table 2. At the current angular resolution, no variation of maser position with velocity is detected. The range of maser velocities detected by the VLA is in excellent agreement with that of the GBT data, despite the 16$\times$ larger area covered in the VLA data. Differences in intensity between the VLA and GBT data can be explained by the maser offsets from the GBT pointing center (see Figure 1(a)). Using the observed line properties (Table 2) we find isotropic H$_2$O maser luminosities ranging from 1.3 to 7.7 L$_{\odot}$, which is on the high side, but not dissimilar to the other galaxies with known GA-H$_2$O emission (see Section 1). The H$_2$O luminosity sensitivity limit is $\sim 0.6 L_{\odot}$ (assuming $V_{\text{peak}} = 5$ mJy ($5\sigma$) and $\Delta V_{\text{WHM}} = 10$ km s$^{-1}$) brighter than the majority of Galactic water masers.
non-thermal contamination, and to have a higher likelihood of being optically thin), we have used the 3.6 cm data to determine $Q_{\text{Lyc}}$ due to its superior sensitivity (see Table 1). An O7.5V star produces an ionizing flux of $Q_{\text{Lyc}} = 10^{49}$ s$^{-1}$ (hereafter O*; Leitherer et al. 1999; Vacca et al. 1996), suggesting that the ionized gas associated with the two IAR maser regions is equivalent to $\sim 2000–5000$ O* stars. Note that these $Q_{\text{Lyc}}$ values could be underestimated if a significant fraction of the ionizing flux is absorbed by dust or able to escape from the H II region (see Johnson & Kobulnicky 2003; Reines et al. 2008; Johnson et al. 2009).

4. DISCUSSION

4.1. Multiwavelength Comparison of the Maser Environments

To further assess the nature of the sources associated with the maser emission, we have obtained existing Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) and NICMOS data, along with Owens Valley Radio Observatory (OVRO) CO(1–0), and Submillimeter Array (SMA) CO(3–2) molecular line data (Whitmore et al. 1999; Wilson et al. 2000; Petitpas et al. 2007). To use these data, we must first ensure the registration of the different data sets. The astrometry of the
VLA data is good to 0′.05, far superior to the other available data. Because of their shorter wavelengths, the OVRO and SMA CO positions are likely less accurate (~0′.2). The \( \text{H}_2\text{O} \)-East maser is coincident with a massive thermal \( \text{H}_2\text{O} \) optically bright star-forming regions but is located in an optically uninteresting region between higher S\( \text{S}\) spectra from Wilson et al. (2000, these data have significantly

\[ \Delta v_{\text{FWHM}} = 55 \text{ km s}^{-1}, \]

which is somewhat blueward of the \( \text{H}_2\text{O}-\text{East} \) maser and CO(1–0) peak velocity of 1520 km s\(^{-1}\) (see Figure 1(b)), suggesting the \( \text{Br} \gamma \) originates in outflowing ionized gas in front of the maser region. Gilbert & Graham (2007) find that the bright cluster to the southwest (their source “D,” and Neff & Ulvestad 2000, source CM-4-2) has a \( \text{Br} \gamma \) velocity offset by 100 km s\(^{-1}\) from \( \text{H}_2\text{O}-\text{East} \), suggesting that these clusters may be separated significantly along the line of sight in addition to the ~4′ (\( \gtrsim \)430 pc) plane-of-sky distance.

4.1.2. \( \text{H}_2\text{O}-\text{SE} \) Region

The \( \text{H}_2\text{O}-\text{SE} \) region is located only 0′.5 (~60 pc) to the northeast of the most massive (~5 \times 10^6 M_\odot) and brightest mid-IR to cm-\( \lambda \) star cluster (= WS80, B1, CM-2-1, WIRC157, Peak 1) in the whole of the Antennae galaxies (see, for example, Whitmore & Zhang 2002; Gilbert & Graham 2007; Neff & Ulvestad 2000; Brandl et al. 2005, 2009; we denote this cluster as WS80 for ease of referral). Though the optical \( \text{H}_2\text{O} \) data have more than sufficient resolution, \( \text{H}_2\text{O}-\text{SE} \) is not detected. The majority of longer wavelength data do not have sufficient resolution, so that only the integrated properties of \( \text{H}_2\text{O}-\text{SE} \) plus the WS80 cluster are available. Indeed, the \( \text{H}_2\text{O}-\text{SE} \) region has been resolved and detected in only one other study—that by Snijders et al. (2006) using the Very Large Telescope VISIR instrument at 12.81 \( \mu \text{m} \) (NEII + continuum, their source “1b”).

The \( \text{H}_2\text{O}-\text{SE} \) source contributes about 1/5 of the total flux of the combined \( \text{H}_2\text{O} \)-SE + WS80 regions at this wavelength, similar to what is seen in the 0′.28 resolution 3.6 cm data.

Wilson et al. (2000) find this region to be coincident with the confluence of two SGMCs, and as seen in Figure 1(c), both the maser and CO(1–0) show particularly broad emission. Gilbert & Graham (2007) find a \( \text{Br} \gamma \) velocity for WS80 (their source “B1”), of \( \text{v}_{\text{peak}} = 1476 \text{ km s}^{-1} \) with an FWHM = 70 km s\(^{-1}\). These values are in excellent agreement with the \( \text{H}_2\text{O}-\text{SE} \) maser kinematics (1515.1 km s\(^{-1}\) and 100 km s\(^{-1}\)), suggesting that \( \text{H}_2\text{O}-\text{SE} \) and WS80 are in close proximity kinematically as well as spatially.

Estimated ages for the WS80 cluster range between 1 and 3.5 Myr (Whitmore & Zhang 2002; Gilbert & Graham 2007; Snijders et al. 2007), though it is difficult to pinpoint cluster ages of \( \lesssim 3 \) Myr due to the lack of evolution in colors and ionizing fluxes. Whitmore & Zhang (2002) infer an extinction value of \( A_V = 7.6 \) for WS80, and Gilbert & Graham (2007) find \( A_F = 1.2 \), or roughly \( A_V = 10 \) for a simple screen model. Interestingly, in order to account for the lack of detection of \( \text{H}_2\text{O}-\text{SE} \) at shorter wavelengths, Snijders et al. (2006) suggest that \( A_V > 72 \) for \( \text{H}_2\text{O}-\text{SE} \). Given its very high extinction, \( \text{H}_2\text{O}-\text{SE} \) may be an extremely young super star cluster in the making, though it is difficult to distinguish between extreme youth (and thus small physical size and \( Q_{13\text{c}} \) compared to WS80) versus a simply less massive (and thus less able to clear its natal material) but more evolved cluster.

4.2. \( \text{H}_2\text{O}-\text{West} \) Region

The western maser resides in an optically thick dust lane coincident with a CO(3–2) molecular cloud, and is virtually invisible at every other available wavelength except for weak radio emission (see Figure 2(b)). Moreover, because the radio emission is dominated by non-thermal emission, it is impossible to discern the nature of any ionized thermal emission that might be associated with the maser region. It is possible that this source would be apparent at mid- to far-IR wavelengths, but unfortunately none of the available data have...
sufficient resolution to identify it. It is also notable that this maser has an exceptionally large luminosity (7.7 \( L_\odot \)) for a GA-H\(_2\)O maser. Hopefully, future high-resolution near- to mid-IR data may help shed light on this deeply embedded maser source.

5. CONCLUSIONS

We have imaged the GBT-discovered GA-H\(_2\)O masers in the Antennae galaxies with exquisite angular resolution (~80 mas), and find two maser regions in the IAR and a third 5′′6 (> 600 pc) west of the NGC 4039 nucleus. All three masers show excellent kinematic and spatial agreement with dense CO molecular gas. The IAR maser regions are located in areas of high optical/near-IR extinction, and are coincident with thermal ionized gas suggesting the presence of several thousand O\(^*\). Indeed, both of these maser regions seem to pinpoint extremely young sites of deeply embedded super star cluster formation. These results highlight the promise of using GA-H\(_2\)O masers to precisely locate the earliest phases of extragalactic cluster formation. The current isotropic luminosity sensitivity limit of 0.6 \( L_\odot \) is still brighter than most Galactic H\(_2\)O masers suggesting we may only be seeing the bright tip of the maser distribution. With its new broad bandwidth correlator, the Expanded Very Large Array will be an ideal instrument for future GA-H\(_2\)O maser studies (the 1.3 cm data presented here could be taken in 1/3 the time, while achieving 10× better continuum sensitivity).

This research used archival Spitzer and HST data, operated by the Jet Propulsion Laboratory and Space Telescope Science Institute, respectively, under NASA contracts. We thank B. Brandl, C. Wilson, D. Iono, and G. Petitpas for providing their published data in digital format. K.J. acknowledges support from NSF through CAREER award 0548103 and the David and Lucile Packard Foundation through a Packard Fellowship.

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