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A SEARCH FOR WATER MASERS IN THE GRAVITATIONALLY LENSED QUASARS H1413+117 AND MG 0414+0534

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ABSTRACT

We searched for 22 GHz water maser emission from two gravitationally lensed quasars, H1413+117 (the Cloverleaf) at $z = 2.56$ and MG 0414+0534 at $z = 2.64$, using the Australia Telescope Compact Array. Detections of CO emission at millimeter wavelengths from these systems provide the redshifts of the molecular components with high precision and suggest substantial reservoirs of molecular gas. The observations were made with ~ 750 km s^{-1} of velocity coverage, enough to span the entire range of CO emission. No narrow water maser features were found in the observed bands in either source, though the sensitivities achieved were sufficient for detection if either (1) the water maser luminosity were substantially larger than found in nearby low-power active galactic nuclei (AGNs), which maser theory suggests is plausible, or (2) the water maser luminosity were typical of nearby detected AGNs but magnified by an extremely large factor, as might be the case near a lens caustic. The detection limits for a 1.5 km s^{-1} channel correspond to isotropic maser luminosities of a few $1000(m/10)^{-1}\ L_{\odot}$, where m is the lensing magnification factor, values that are comparable to the most luminous AGN water masers in the local universe for $m \approx 10$.

Key words: galaxies: nuclei — gravitational lensing — masers — quasars: individual (H1413+117, MG 0414+0534) — radio emission lines

1. INTRODUCTION

Observations of water masers in the 22 GHz 6_{16}–5_{23} transition toward active galactic nuclei (AGNs) show that the maser emission traces parsec-scale structures associated with the central engines, presumably massive black holes. The best example of the phenomenon is found in the nearby galaxy NGC 4258, where very long baseline interferometry shows that maser spots delineate a thin disk in Keplerian rotation (Miyoshi et al. 1995). Measurements of the accelerations and proper motions of the maser spots give a geometric distance measurement to NGC 4258 with a fractional uncertainty of just 4% (Herrnstein et al. 1997). The study of similar AGN maser systems at high redshift, well into the Hubble flow, could provide measures of cosmological parameters independent of the usual distance ladder (e.g., Koekemoer et al. 1995; Herrnstein 1999).

More than 500 nearby AGNs have been searched for water maser emission, with a success rate of a few percent (e.g., Greenhill et al. 1997). So far, no strong correlations have been found between the presence of maser emission and the global properties of the host galaxies, though the fact that water masers are not seen in type 1 Seyfert galaxies suggests that the masers are associated with material that obscures the AGN (Braatz, Wilson, & Henkel 1997).

A practical way to narrow the search in the distant universe is to focus on systems known to possess substantial reservoirs of molecular gas in close proximity to an AGN. Detections of emission from CO, an abundant and easily excited molecule, provide a short list of suitable targets. Moreover, these CO detections determine the redshift of the molecular material with high precision, an important consideration given the narrow fractional bandwidths generally available for observations at radio wavelengths. Another property that makes these high-redshift CO sources prime targets is the fact that, in most cases, the molecular medium appears strongly magnified by gravitational lensing. If water masers are present in these systems, then they will also be magnified, possibly by factors substantially larger than the CO emission because of the small sizes of the maser spots.

Although there are now solid detections of CO emission from at least seven cosmologically distant systems (e.g., Downes et al. 1998), the 22 GHz water maser lines in these systems are redshifted out of the tuning range of the receivers of most large radio telescopes, in particular the Very Large Array. However, at least three of the CO sources are accessible to the broader spectral coverage of the Australia Telescope Compact Array[2] (ATCA). Here we report the results of a search for water maser emission from two of these accessible high-redshift lensed quasars with CO emission, H1413+117 (the Cloverleaf) at $z = 2.56$ and MG 0414+0534 at $z = 2.64$. Multitransition CO and HCN studies of the Cloverleaf indicate a substantial mass of warm, dense molecular gas (Barvainis et al. 1997), apparently in rotation around the source of optical light (Kneib et al. 1998). The molecular medium of MG 04014+0534, a radio-loud quasar, is not as well studied as the Cloverleaf, but in this source as well, spatially resolved observations of the radio continuum and CO emission also attest to a close

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TABLE 1

OBSERVATIONAL PARAMETERS

Parameter	H1413+117	MG 0414+0534
Observation (1998).....	Jan 22/Aug 7–10	Feb 1
Pointing center:		
α (J2000.0).....	$14^h15^m46^s.23$	$04^h14^m37^s.71$
δ (J2000.0).....	11°30′00″.0	05°35′00″.0
Redshift	2.558	2.639
Flux calibrator	1934−638	1934−638
Phase calibrator.....	1415+133	0423−013
Spectral correlator	16 MHz, 512 channels	
Line frequency	6.2493 GHz	6.1102 GHz
Transition.....	H_2O 6_{16}–5_{23}	
Channel spacing	1.5 km s^{-1}	
Channel rms.....	2.7/1.4 mJy beam^{-1}	3.3 mJy beam^{-1}

association between the molecular gas and the AGN (Barvainis et al. 1998).

2. OBSERVATIONS

We observed the Cloverleaf with ATCA twice, first on 1998 January 22 and then again in four sessions from 1998 August 7 to 10 in order to make a more sensitive measurement and to check for the presence of time-variable features. Table 1 summarizes the observational parameters. The systemic redshift for the molecular gas in the Cloverleaf from observations of CO emission is $z = 2.558$ (Barvainis et al. 1997), which places the H_2O maser transition (rest-frequency 22.23508 GHz) at 6.2493 GHz. The east-west array provided a maximum baseline of 6 km and angular resolution $\sim 2''$ in the equatorial direction. The instrumental gains and phases were tracked with frequent observations of the nearby calibrator 1415+133. The correlator was configured to provide 512 channels spanning 16 MHz for each of the two orthogonal linear polarizations. This setup provides ~ 750 km s^{-1} of velocity coverage, which spans the entire range of CO emission. We used a similar setup to observe MG 0414+0534 on 1998 February 1. The systemic redshift for molecular gas in MG 0414+0534 from CO emission is $z = 2.639$ (Barvainis et al. 1998), and the H_2O maser transition is shifted to 6.1102 GHz. For this source, gains and phases were tracked with the calibrator 0423−013. The absolute flux scale was determined through observations of the standard strong calibrator 1934−638. Calibration and imaging were performed using standard routines in the MIRIAD software package (Sault, Teuben, & Wright 1995).

3. RESULTS

Radio continuum emission was detected from both the Cloverleaf and MG 0414+0534. In both cases the continuum emission is nearly unresolved. Figure 1 shows the spectra at the peak of the continuum emission obtained from the two observations of the Cloverleaf and the observation of MG 0414+0534. For the Cloverleaf, a fit to the visibilities averaged over the full bandwidth gives a 6.25 GHz continuum flux density 0.91 ± 0.10 mJy, consistent for the two epochs of observation and in agreement with previous observations made with the Very Large Array (e.g., McLeod et al. 1999). For MG 0414+0534, the measured flux density of 0.6 Jy at 6.11 GHz is also in line with previous observations near this frequency (Katz, Moore, & Hewitt 1997).

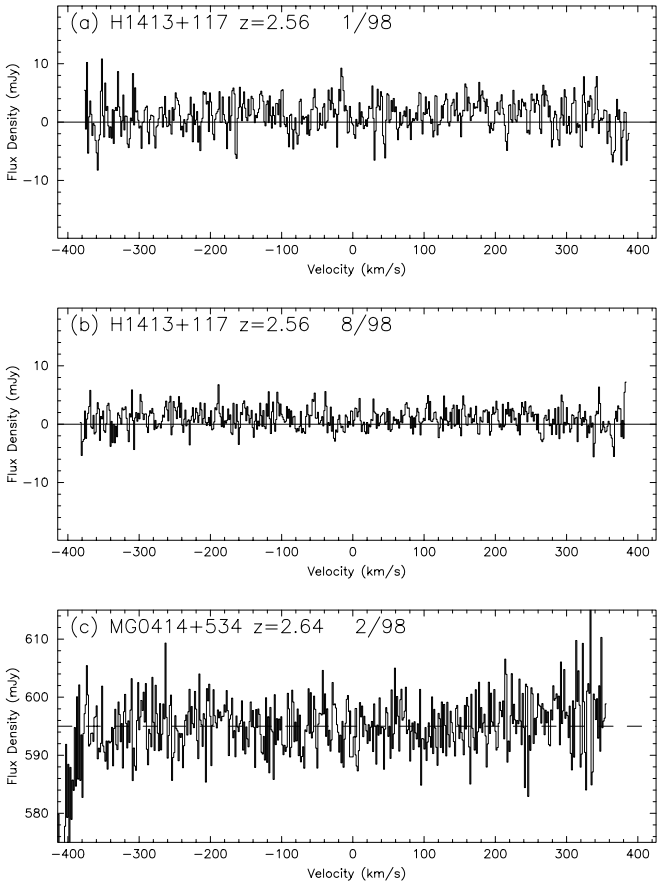

FIG. 1.—Spectra obtained for the H_2O maser line toward H1413+117 (the Cloverleaf) at two epochs and toward MG 0414+0534. The velocity offsets for the water maser transition are relative to $z = 2.558$ in (*a*) and (*b*), and to $z = 2.639$ in (*c*). A dashed line in (*c*) marks the continuum level for MG 0414+0534.

The spectra in Figure 1 show no significant features that might be associated with water maser emission. In particular, the suggestive feature in the first-epoch Cloverleaf spectrum near −15 km s^{-1} did not persist in the second-epoch measurement, which has a factor of 2 lower noise level. Of course, maser features may be present at velocities outside the range spanned by our 750 km s^{-1} observing band. In particular, a maser system similar to that found in NGC 5793 by Hagiwara et al. (1997), which is dominated by high-velocity features outside the range of CO emission with only weak (or absent) systemic features, would be missed. Such high-velocity features may come from the long tangential paths in a rapidly rotating circumnuclear disk.

To obtain a simple upper limit for narrow maser lines, we consider a rectangular line profile of one channel width. For cosmological parameters, we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout. With these assumptions, the 2 σ upper limit for the second-epoch Cloverleaf observation corresponds to an isotropic maser luminosity of $1100(m/10)^{-1}\ L_\odot$, where m is the lensing magnification factor; for MG 0414+0534, the limit is $2775(m/10)^{-1}\ L_\odot$. The magnification factor is estimated to be ~ 10 for the Cloverleaf and is likely to be similar or greater for MG 0414+0534 based on its radio lens configuration. The luminosity limits are higher for masers of greater velocity width, increased by a factor equal to the square root of the number of channels spanned by a hypothetical feature.

4. DISCUSSION

The limits we derive apply only to "systemic" maser features, within ~ 350 km s^{-1} of the CO emission line velocities. The relatively small velocity window is potentially a severe limitation, because maser emission may arise far from the velocity of CO emission, which samples a substantially larger region than the immediate AGN environment. Nonetheless, narrow water maser features in the observed velocity range with isotropic luminosities in excess of few 1000 $L_\odot$ would have been detected either if they have typical luminosities of a few times 10 $L_\odot$ and the magnifications were extremely large, as might be expected close to a lens caustic, or if the water masers were substantially more luminous than those found in nearby low-power AGNs. The top end of the water maser luminosity function is not known, but the most luminous water maser observed so far lies in the active galaxy TXFS 2226−184 at $z = 0.025$, with an isotropic luminosity of 6100 $L_\odot$ (Koekemoer et al. 1995). It appears plausible that substantially larger maser luminosities may arise in the X-ray–illuminated molecular media surrounding more distant and more powerful AGNs (Neufeld, Maloney, & Conger 1994).

The nondetections in the Cloverleaf and MG 0414+0534 are consistent with the low detection rate of water masers in the local universe. This may reflect a need for a special source geometry and orientation, a special combination of physical conditions in the nucleus, or both. Indeed, the Cloverleaf and MG 0414+0534 show broad optical emission lines, a fact that suggests relatively little material in front of the nucleus and perhaps unfavorable orientations for detecting maser emission. However, there are several reasons to be optimistic regarding future surveys for water emission from cosmologically distant sources.

1. *Accurate redshifts for circumnuclear molecular gas may be obtained from sensitive* CO *observations at millimeter wavelengths.*—Of the 12 nearby AGNs with water masers searched for CO, in only one has it not yet been detected (Raluy, Planesas, & Colina 1998). While the detection of CO emission from the host galaxy is not a sufficient condition for maser emission, because the maser phenomenon is localized to the AGN, a CO detection attests to the presence of molecular fuel and provides a target redshift for circumnuclear material.

2. *The molecular media are probably conducive to maser action.*—Detailed multitransition studies of the Cloverleaf (Barvainis et al. 1997), detecting CO up to the $J = 7$–6 line and the high dipole moment species HCN in the $J = 4$–3 line, demonstrate that the molecular gas is warm ($T \sim 100$ K) and dense ($n_{H_2} \sim 10^4$ cm^{-3}). These bulk properties suggest the presence of regions within the presumed clumpy medium that could give rise to water masers, which require temperatures of 200 to 1000 K and of densities 10^8 to 10^{10} cm^{-3}. In the model of Neufeld et al. (1994), the exposed faces of a circumnuclear molecular torus irradiated by X-rays from the central source create a warm transition zone from atomic to molecular gas where the water abundance is enhanced and maser luminosities of 10^2 $L_\odot$ pc^{-2} are possible. Observations of a larger sample of galaxies will clarify what additional conditions are necessary for detectable maser action.

3. *Gravitational lensing magnifications may be very large.*—It is probably no coincidence that most of the high-redshift CO sources observed to date show evidence of gravitational lensing; some magnification is probably required for detection with current instrumental sensitivities. The Cloverleaf, the best studied source, is lensed into four spots in the optical with separations of about 1″, and the latest subarcsecond CO images show four corresponding molecular emission regions (Yun et al. 1997; Alloin et al. 1997). According to the observations of Kneib et al. (1998), the lensed CO source shows a ~ 100 km s^{-1} velocity gradient, and detailed analysis of the lensed images suggests a disklike configuration about 100 pc in size surrounding a central mass of order 10^9 $M_\odot$. The gravitational lens magnifies the background source by a factor that depends sensitively on size and alignment. As previously noted, the magnification of the CO emission region is thought to be about a factor of 10. However, a physically smaller region of water maser emission could be magnified by a larger factor than the more extended CO emission, perhaps by an order of magnitude or more if the maser distribution includes any spots that happen to align favorably with the lens caustics. Such differential magnification likely explains many of the peculiar properties of the lensed CO source IRAS F10214+4724 (Broadhurst & Lehár 1995). In this situation, careful modeling is required to recover the underlying source geometry.

4. *Water masers around high-power AGNs may be extremely luminous.*—The gas that lies close to the AGN will be too hot and dense to support water masers. For a highly luminous AGN, water maser emission might then arise at substantially larger radii than for lower luminosity cases, and at the same time be sustainable over a substantially larger area. Herrnstein (1999) has argued that conditions suitable for water masers could be prevalent at distances from 1 to 10 pc from the AGN core, and if the maser emission is saturated, the apparent luminosities would be enormous because of the long gain path, perhaps 1000 times larger than the water masers associated with low-luminosity AGNs in the local universe (see eqs. [6] and [7] of Haschick et al. 1990). While no such ultraluminous water masers are known, systematic searches have not yet been made of the distant high-power AGNs that might harbor them.

5. CONCLUSIONS

We searched for 22 GHz water maser emission from the Cloverleaf and MG 0414+0534 quasars redshifted to near 6 GHz. These sources were selected because (1) the precise redshifts of the molecular components are known from CO observations, and the water maser transitions lie at accessible frequencies, (2) reservoirs of warm, dense molecular gas are known to be present in proximity to the AGNs in these sources, and (3) the molecular emission regions are strongly gravitationally lensed, thereby boosting sensitivity to weaker features. A possible disadvantage for these sources is the direct detections of broad optical emission lines that suggest unfavorable orientations. Although the sensitivity obtained was sufficient to detect water masers with isotropic luminosities comparable to the strongest ones known in the local universe, or any of the substantially more luminous ones that maser theory suggests are plausible, no significant maser features were found.

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