Extremely Luminous Water Vapor Emission from a Type 2 Quasar at Redshift $z = 0.66$

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ABSTRACT

A search for water masers in 47 Sloan Digital Sky Survey Type 2 quasars using the Green Bank Telescope has yielded a detection at a redshift of $z = 0.660$. This maser is more than an order of magnitude higher in redshift than any previously known and, with a total isotropic luminosity of $23,000 \, L_\odot$, also the most powerful. The presence and detectability of water masers in quasars at $z \sim 0.3 - 0.8$ may provide a better understanding of quasar molecular tori and disks, as well as fundamental quasar and galaxy properties such as black hole masses. Water masers at cosmologically interesting distances may also eventually provide, via direct distance determinations, a new cosmological observable for testing the reality and properties of dark energy, currently inferred primarily through Type 1a supernova measurements.

*Subject headings:*

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$^1$Any opinions, findings, conclusions, and recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.
1. Introduction

Water vapor emission in the form of powerful masers has been detected in $\sim 10\%$ of Type 2 Active Galactic Nuclei (AGNs) observed in the local universe (Braatz et al. 2004). Some of these masers have spectral characteristics suggesting that they arise in a dusty molecular disk or torus viewed edge-on, where conditions are favorable for their formation. Such masers have provided unique diagnostics of some of the basic characteristics of AGNs, including information on the central black hole masses. Furthermore, in one case, the Seyfert 2 / LINER galaxy NGC4258, water masers have been used to determine a direct geometrical distance (Herrnstein et al. 1999) to the galaxy independent of the assumptions of the standard extragalactic distance ladder (Madore et al. 1999).

Most previous searches for water masers in AGNs have been confined to relatively nearby objects such as Seyfert galaxies, LINERs, and radio galaxies at $z < 0.1$ (Braatz et al. 2004; Tarchi et al. 2003). The vast majority of water masers have been found in Type 2 AGNs and LINERS. These are systems where the disk or torus thought to surround the nucleus in most AGNs is seen edge on, obscuring the nucleus optically but allowing masers beamed in the midplane of the torus to be observed at Earth. Until recently, the only Type 2 objects known at higher redshifts ($z > 0.1$) were radio galaxies and a few Ultraluminous Infrared Galaxies; searches for maser emission in high-$z$ radio galaxies to date have been unsuccessful (Barvainis, Henkel, & Antonucci, unpublished).

The recent compilation of a large new sample of luminous Type 2 quasars at redshifts between 0.30 and 0.83 by Zakamska et al. (2003) using the Sloan digital Sky Survey (SDSS) has provided a unique new opportunity to search for water maser emission in the distant universe. This redshift range corresponds closely to that of most of the Type 1a supernovae used to measure luminosity distance as a function of redshift, thereby testing cosmological models. A result of fundamental importance to modern physics is the determination, based on the supernova studies, that the content of the universe may be dominated by dark energy, a poorly understood quantity that may be related to Einstein’s Cosmological Constant. However, the possibility remains that the Type 1a supernova measurements may be subject to systematic errors (Riess et al. 2004), and an independent angular size distance measurement on cosmological scales to check the supernova results would be highly desirable.

Here we report the discovery of a water maser at redshift $z = 0.660$ in the Type 2 Quasar SDSS J080430.99+360718.1 (hereafter J0804+3607) using the Green Bank Telescope (GBT). This is the most distant water maser known by over an order of magnitude, and, with an apparent (isotropic) luminosity of $2.3 \times 10^4 \, L_\odot$, by far the most powerful. In addition to its implications for the study of black hole masses and other properties of quasars, this detection shows that powerful masers exist at redshifts high enough to potentially test the existence
of dark energy as derived from studies of Type 1a supernovae.

2. Observations

The observations were carried out on January 6 and January 9 2005 using the Green Bank Telescope of the National Radio Astronomy Observatory. The line was detected in both sessions (see Figure 1 for the final sum of both nights). No line was detected in the spectrum of another quasar at similar redshift, so the line cannot be attributed to interference or a receiver “birdie”. A total of 47 SDSS Type 2 quasars were observed, with J0804+3607 yielding the only detection. The sample is from Zakamska et al. (2003).

Each quasar was observed for 28 minutes of integration time in the initial survey. We obtained an additional 164 minutes (after discarding one bad 4-minute scan) of follow-up time on J0804+3607, for a total integration time of 192 minutes. The observing mode utilized two feeds separated by 5.5 arcminutes on the sky, each with dual polarization. The source was placed alternately in each beam, with a position switching interval of 2 minutes. Antenna pointing checks were made roughly every 2 hours, and typical pointing errors were less than 1/10 of a beamwidth. The antenna beamwidth is 1 arcminute at 13.4 GHz, the frequency of the detected line. We estimate the calibration uncertainty to be $\sim 20\%$.

The spectrum shown in Figure 1 has been hanning smoothed once to provide a channel width of 0.1 Mhz, or a velocity channel width of 2.2 km s$^{-1}$. The RMS noise on the baseline is 0.48 mJy. The central frequency of the main spike is 13.391 GHz, yielding a redshift of 0.660. The original spectrum was 200 MHz wide, and evidenced no other line features outside the region shown in the figure.

We discount a false identification with a local source of the J=7/2, F=4-4 13.44 GHz OH maser (e.g., Baudry & Diamond 1998) for the following reasons: a) such masers are rare; b) they are associated with regions of star-formation and as such will normally be found only towards the galactic plane; c) the probability of the detection of a slightly red-shifted 13.44 GHz OH maser within the beam of the GBT in a random direction is very low; and d) assuming the line to be water the redshift is extremely close, within 0.002, to that of the quasar ($z = 0.658$ based on narrow optical emission lines).

3. Discussion

Although the maser characteristics of J0804+3607 may or may not lend themselves to a direct distance determination as in the case of the nearby NGC4258, our discovery of a
maser in the range $0.5 < z < 1$ opens up the possibility of finding objects like NGC4258 that could be used to measure cosmological distances and test dark energy. The maser spectrum of J0804+3607 (Figure 1) consists of a narrow spike with a full width at half maximum (FWHM) of about 10 km s$^{-1}$ and a full width at zero intensity of about 40 km s$^{-1}$, together with a possible weak underlying broader component or wing extending to lower frequencies with FWHM $\sim 100$ km s$^{-1}$.

NGC4258 has a complex system of variable features spanning about 100 km s$^{-1}$ at the systemic velocity, with satellite lines centered at $\pm 900$ km s$^{-1}$ having maximum flux densities of 15 – 40% (time variable) of the main peak. In J0804+3607 there is no significant evidence for satellite features separated from the main emission. Any such lines would have been detectable at 40% of the main peak but not at 15%, given the signal-to-noise ratio obtained.

The redshift of the maser line in J0804+3607 is $z = 0.660$, slightly higher than the optical redshift of $z = 0.658$ based on O[III] emission. The line is thus redshifted by 360 km s$^{-1}$ relative to the O[III] velocity; there is no way to tell whether the detected maser component is a “systemic” or “satellite” (i.e., high-velocity) feature in a disk geometry. The maser is more than an order of magnitude higher in redshift than any previously known water maser – 3C403 was the highest at $z = 0.059$ (Tarchi et al. 2003). The total luminosity of the maser emission is 23,100 $L_\odot$, assuming $H_0 = 71$ km s$^{-1}$Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$. This includes both the narrow spike and the weak broader component. The next highest known maser luminosity is 6,800 $L_\odot$ for TXS 2226-184 (Koekemoer et al. 1995) (calculated using the same cosmological parameters).

The use of extragalactic H$_2$O masers as physical probes of the inner regions of AGNs saw a spectacular payoff in NGC4258 (Myoshi et al. 1995; Greenhill et al. 1995), where VLBI followup of the initial single-dish discovery revealed precise Keplerian rotation about a massive ($10^7 M_\odot$) compact object. Very importantly for AGN studies, the black hole mass was determined directly for the first time. Similarly, the masers in NGC1068 are in nearly Keplerian rotation and an upper limit to the black hole mass derived from the masers led to the fundamental conclusion that the continuum luminosity of the AGN is of order the Eddington luminosity (Greenhill et al. 1996).

Simple and accurate dynamical arguments for NGC4258 produced a distance of $7.2 \pm 0.3$ Mpc (Herrnstein et al. 1999). Although very useful for calibrating the distance ladder, this is too nearby to be indicative of the Hubble constant. A direct measurement of $H_0$ would be possible if a maser system like NGC4258 were found at a distance that places it well into the Hubble flow, and some candidates for this already exist (Braatz et al. 2004). One goal of the present study is to take this further and see what can be found at redshifts large enough that the apparent universal acceleration/cosmological constant/dark energy could be
explored. If maser distances can be determined at high redshifts \((z > 0.4)\), deviations from the Hubble law could be detected similar to those claimed by the supernova cosmology teams (Perlmutter et al. 1999; Garnavich et al. 1998; Riess et al. 2004). The assertions by these teams of universal acceleration based on Type Ia supernovae, and concomitant evidence for dark energy, clearly need observational confirmation and elaboration. The technique outlined here could, with some luck, provide such a check. Even a measurement of the angular size distance to a single object to \(\sim 10\%\) precision could help to distinguish between different cosmologies. For example, the ratio of the angular size distance versus redshift curves at \(z = 0.66\) for the Concordance Cosmology \((\Omega_M = 0.27, \text{ and } \Omega_\Lambda = 0.73)\) and a matter-dominated flat cosmology \((\Omega_M = 1)\) is 1437 Mpc/1139 Mpc = 1.26.

So far we have observed 47 objects, but there are at least 270 other SDSS Type 2 quasars known that are accessible via the frequency coverage of large telescopes like the GBT and the 100-m Effelsberg antenna. We are pursuing a much larger survey in search of appropriate maser systems for direct cosmological distance determinations.

The \(\text{H}_2\text{O}\) megamaser theory of Neufeld, Maloney, & Conger (1994) predicts that roughly 100 \(L_\odot\) of maser emission is produced for each square parsec of area illuminated by the primary AGN x-ray emission. If the maser emission is anisotropic, e.g. beamed in the plane of the torus, the \textit{apparent} luminosity could be much larger. Studies of the infrared luminosity from dust in quasars (e.g., Haas et al. 2000) suggest that the area of warm, dusty, illuminated molecular clouds increases in rough proportion to optical/UV/x-ray luminosity: the sublimation radius of the dust, which sets the innermost possible radius for the torus, scales as \(L_{\text{opt/UV}}^{1/2}\), where \(L_{\text{opt/UV}}\) is the optical/UV continuum luminosity (Barvainis 1987), and thus the \textit{area} of the torus illuminated scales simply as \(L_{\text{opt/UV}}\). Extremely powerful masers might thus be expected from high-luminosity quasars. Our discovery supports this scenario. Later theory papers made the geometry assumed by Neufeld, Maloney, & Conger (1994) more realistic, and considered various energy sources for the maser. These models, which do not change the basic energetics, are reviewed in Maloney (2002).

If we assume that the masers in J0804+3607 are analogous to those in NGC4258, we can compute their approximate distance from the central optical/UV/x-ray source of the quasar. Making a rough estimate of the continuum luminosity based on the \(\text{O}[\text{III}]\) \(\lambda5007\) line flux using typical Type 1 quasar ratios (Zakamska et al. 2003; Elvis et al. 1994), we find a bolometric luminosity of \(L_{\text{bol}} \sim 2 \times 10^{45}\) erg s\(^{-1}\) for J0804+3607. For NGC4258, \(L_{\text{bol}} \sim 10^{42}\) erg s\(^{-1}\) (Kartje, Königl, & Elitzur 1999). The radiative flux impinging on the masing region, which controls the physical conditions in the gas (especially the x-ray flux), scales as \(L_{\text{bol}}/r^2\). With this and the relative bolometric luminosities the radius of the maser region would be 45 times larger in J0804+3607 than in NGC4258. Given that the masers in NGC4258 arise
over a range $0.14 < r < 0.28$ pc (Herrnstein et al. 2005), the range in J0804+3607 would be $6.3 < r < 12.6$ pc. For the adopted cosmology this translates to an angular diameter of the masing region of $2 - 4$ milliarcsec, which is easily resolvable using VLBI.

In summary, this result indicates that water masers are detectable at high redshift, potentially providing information on black hole masses and physical conditions in the masing regions (molecular torus / warped disk) of quasars. High redshift masers might also eventually provide angular size distances as a function of redshift, a new cosmological observable.

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Fig. 1.— Spectrum of water maser emission at $z = 0.660$ from the Type 2 quasar SDSS J080430.99+360718.1. The full bandwidth of 200 MHz is not shown here to better emphasize the line. The effective spectral resolution and channel width, after hanning smoothing, is 0.1 MHz, or 2.2 km s$^{-1}$. 