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A gravitationally lensed water maser in the early Universe

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Water masers[1−4] are found in dense molecular clouds closely associated with supermassive black holes in the centres of active galaxies. Based upon the understanding of the local water maser luminosity function[5], it was expected that masers at intermediate and high redshifts would be extremely rare, but galaxies at redshifts $z > 2$ might be quite different from those found locally, not least because of more frequent mergers and interaction events. Using gravitational lensing as a tool to enable us to search higher redshifts than would otherwise be possible, we have embarked on a survey of lensed galaxies, looking for masers. Here we report the discovery of a water maser at redshift 2.64 in the dust- and gas-rich gravitationally lensed type 1 quasar MG J0414+0534[6−13], which, with an isotropic luminosity of 10 000 $L_\odot$, is twice as luminous as the most powerful local water maser[14], and half that of the most distant maser previously known[15]. Using the locally-determined luminosity function[5], the probability of finding a maser this luminous associated with any single active galaxy is 10^{-6}. The fact that we saw such a maser in the first galaxy we observed must mean that the volume densities and luminosities of masers are higher at that epoch.

Observations of the H_2O $6_{16} - 5_{23}$ transition (rest frequency 22.23508 GHz) from MG J0414+0534 (see Supplementary Information) were made with the 100 m Effelsberg radio telescope at the redshifted frequency of 6.1 GHz during July and September 2007. The radio spectrum (Fig. 1, upper panel) shows an emission feature detected with a signal-to-noise ratio of seven, which we identify as a water maser. The emission arises from the amplification of background photons by stimulated emission of water molecules that have been pumped up to a long-lived excited state by collisional excitation[4] (see Supplementary Information). The line emission cannot be associated with the lensing galaxy at redshift 0.958 or with a nearby "local" object because there are no known strong lines at the corresponding rest frequencies (11.975 GHz and 6.116 GHz, respectively).

To confirm the detection of water maser emission and to match it spatially with the lensed quasar, interferometric observations with the Expanded Very Large Array (EVLA) were made during September and October 2007. A clear emission line was detected with a signal-to-noise ratio of six (Fig. 1, bottom panel), when integrated over the position of the two strongest images (A1+A2) of the lensed quasar (Fig. 2). The maser line is also detected in the separate spectra of A1 and A2, although to a lower signal-to-noise ratio. The EVLA data were not sensitive enough to detect the water maser emission from the two weaker lensed images (B and C). The radial velocities measured with Effelsberg and the EVLA are identical to within the uncertainties (see Supplementary Table 1). The water maser line is also coincident in velocity with the blue-shifted peak of CO emission and with the strongest H I absorption trough previously reported from MG J0414+0534[12,13] (Fig. 1). There is no evidence of water maser emission at the velocities of the other known CO emission and H I absorption components. Our detection is consistent with a previously reported non-detection that did not reach sufficient sensitivity[16].

Hitherto, the highest redshift at which water had been observed was 0.66[15]. The H_2O maser in MG J0414+0534 is at a redshift of 2.639, which is a factor of six more distant (using luminosity distances). The measured maser transition requires gas temperatures in excess of 300 K and particle densities $n(H_2) \gtrsim 10^7$ cm^{-3} (see Supplementary Information). The most dense gas previously observed at high redshift was HCO^+ in the Cloverleaf gravitational lens system[17], tracing a density of 10^5 cm^{-3} in star-forming molecular clouds. The apparent unlensed luminosity, assuming that the maser originates from the same region as the continuum core emission and hence has approximately the same magnification (~ 35[9]; see Supplementary Information), is of order $10\,000\,L_\odot$. This luminosity is still extraordinarily high, the most luminous water maser known being in a type 2 quasar at redshift 0.66 with a luminosity of $23\,000\,L_\odot$[15]. In the event that the water maser is not coincident with the radio continuum, but lies closer (farther) to the lens caustic, the magnification could be higher (lower). We note, however, that all luminous (relatively nearby) water masers studied so far in detail are either associated with the circumnuclear accretion disk or a relativistic jet in its immediate vicinity.

Even without lensing, the water maser in MG J0414+0534 is among those with the highest known apparent luminosities[14,15]. Nevertheless, this discovery was possible only due to the additional amplification provided by the foreground galaxy; it acts as a cosmic telescope reducing the integration time required for the detection by a factor of order 1000. The probability of a single pointed observation like ours detecting a high redshift water maser with a luminosity greater than $10\,000\ L_\odot$ is only 10^{-6} (see Supplementary Information). This detection probability was deter-

mined by extrapolating the local water maser luminosity function[5] to higher luminosities without a cut-off, and assuming that the luminosity function at high redshift was the same as that locally. Thus, our detection of a water maser in MG J0414+0534 at redshift 2.64 rules out with a high confidence no evolution in the water maser luminosity function, and requires that the space density of luminous water masers was much larger at high redshift than in the local Universe. However, systematic searches for this population of unmagnified water masers at high-redshift will probably require a significant improvement in instrument sensitivity. The proposed Square Kilometer Array (SKA), expected to be operational within a decade, will provide such a dramatic improvement[1].

These apparent lensed and unlensed luminosities have been calculated based on the standard assumption of isotropic emission of radiation, for comparisons with the luminosity estimates of other masers. However, masers are likely to emit anisotropically[18]. Beaming is expected since differences in the gain path due to irregularities in the cloud shape and velocity coherence cause exponential changes in maser output brightness. Beaming may also occur in some cases due to the alignment of masing clouds occurring only in restricted directions or due to competitive pumping in saturated masers, in which the stimulated emission in one directional mode dominates over other directional modes. The resulting beamwidths are uncertain, but arguments have been made for values from 7 degrees[19] down to as low as milliarcseconds[20]. This expectation is testable for the first time using the gravitationally lensed water maser since the light seen through each of the lensed images was emitted in slightly different directions from the background quasar. The angle subtended between image regions A1 and A2, as seen from the quasar, is 0.5 arcseconds, and between images A1 and B is 2.3 arcseconds. The maser line is seen in the spectra of both lensed images A1 and A2 from the EVLA observations and so the maser beaming angle is greater than 0.5 arcseconds, ruling out milli-arcsecond beaming angles for this system. Furthermore, the intrinsic luminosity of the water maser must be greater than $5 \times 10^{-9}\ L_{\odot}$.

Of the $\sim$100 galaxies known to host 22.2 GHz water masers[21], most are in type 2 Seyfert or LINER (Low-Ionization Nuclear Emission-Line Region) galaxies at redshifts <0.06[2–4,22]. The notable exception is a type 2 quasar at redshift 0.66[15]. This is consistent with unification models[23] in which the type 2 optical spectrum is due to an edge-on orientation of the circumnuclear disk, causing the active nucleus to be hidden behind a large column of dust and gas (see Supplmentary Information). This geometry provides a long maser gain path-length for amplification and so the prevalence of masers in type 2 active galactic nuclei fits naturally with unification models. MG J0414+0534 is an intriguing object as it is one of the few type 1 active galactic nuclei and the only known type 1 quasar to show water maser activity.

At low redshifts, at least one third of known water masers are associated with the orbiting molecular clouds of circumnuclear accretion disks[21]. These water masers are typically found within 0.1 to 1.0 parsec of the supermassive black hole and tend to have multiple blue-shifted, redshifted, and systemic velocity components, where individual components have narrow line widths of <5 km s^{-1} [19,24,25]. In three cases, luminous water masers have also been found to be associated with the nuclear parts of relativistic jets that are ejected from some central engines[26–28]. These masers have relatively broad line widths, up to 100 km s^{-1}, and have velocities that tend to be offset from the systemic velocity of the host galaxy. Whether the water maser in MG J0414+0534 is associated with the circumnuclear accretion disk or is induced by a relativistic jet interacting with a gas cloud is not conclusive from our data alone. However, given that only a single emission line has been detected, and that it is broad and offset from the systemic velocity by -300 km s^{-1}, the jet-maser scenario seems most likely. The type 1 optical spectrum and beamed radio continuum emission of the quasar provide further support, since unification models of type 1 objects have the nucleus being viewed from above the plane of the disk. Masers originating from the circumnuclear accretion disk, however, are preferentially beamed in the plane of the disk. Therefore, disk masers are unlikely to be seen in active galactic nuclei of type 1, while masers associated with nuclear jets may well be detectable.

Future high-resolution imaging of the water maser line with very long baseline interferometry (VLBI) will provide the exact location of the emission relative to the core-jet radio structure already observed in MG J0414+0534[9,29]. Resolving such maser component distributions with VLBI would usually be challenging at cosmological redshifts since the angular resolution of global VLBI arrays operating at 6.1 GHz is $\sim$2 milliarcseconds, which corresponds to a spatial resolution of $\sim$15 parsec at redshift 2.639. However, for MG J0414+0534, the apparent angular extent of the radio structure is increased due to the foreground gravitational lens by a factor of $\sim$15 for the two strongest lensed images, A1 and A2[9] (see Supplementary Information). Hence, the spatial resolution of a VLBI image will be ~ 1 parsec. Furthermore, it will be possible to distinguish water masers separated by ~ 0.5 parsec in the background source if each masing component is detected with a signal-to-noise ratio of at least ten, thus matching or even resolving the $\gtrsim$0.5 parsec outer diameter of known maser disks in the Circinus galaxy and NGC 1068[28,30]. Thus, VLBI imaging of gravitationally magnified water masers has the powerful potential to trace the sub-parsec scale structure surrounding accretion disks at cosmological distances.

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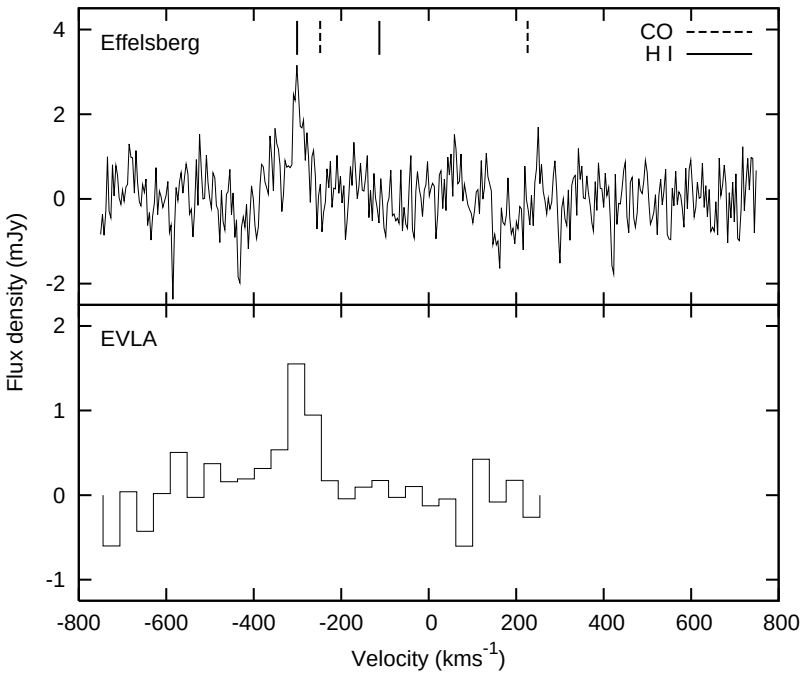
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Velocity (kms-1)

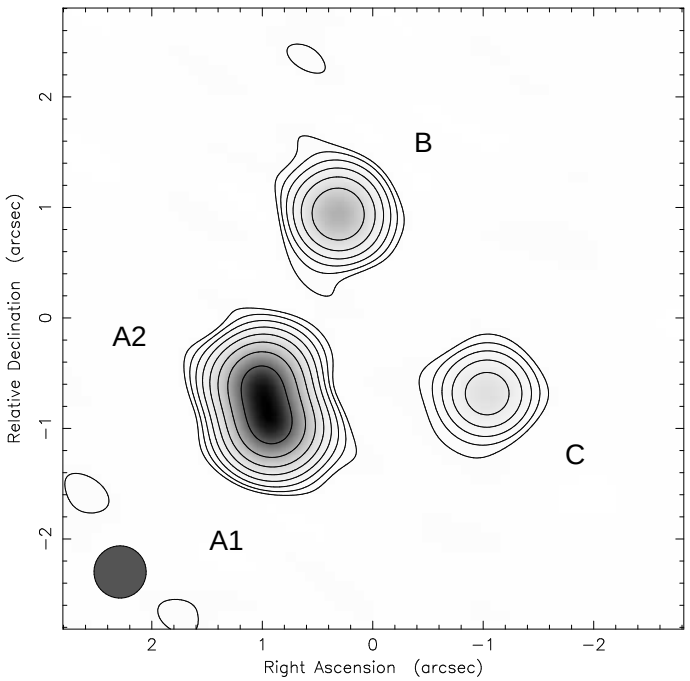
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Figure 1 The 6.1 GHz H_2O spectra of the lensed quasar MG J0414+0534. The velocity scale is relative to redshift 2.639 using the optical velocity definition in the heliocentric frame. The solid lines mark the H I absorption components ($-301\,\mathrm{km\,s^{-1}} \pm 13\,\mathrm{km\,s^{-1}}$ and $-113\,\mathrm{km\,s^{-1}} \pm 13\ \mathrm{km\,s^{-1}}$) and the dashed lines indicate the peaks of CO emission ($-238\,\mathrm{km\,s^{-1}} \pm 70\,\mathrm{km\,s^{-1}}$ and $+226\,\mathrm{km\,s^{-1}} \pm 70\ \mathrm{km\,s^{-1}}$). Top panel: The combined spectrum taken with the Effelsberg 100 m radio telescope on 16 July and 14 September 2007. The total on-source integration time was 14 h. The spectra were formed with a 1024 channel autocorrelator, which provided a channel width of 3.83 $\mathrm{km\,s^{-1}}$. The rms noise level of the spectrum is 0.6 mJy channel^{-1}. Bottom panel: The spectrum of lensed images A1 and A2 of MG J0414+0534 taken with the EVLA using nine of the upgraded 25 m antennas during 24, 28, and 30 September and 1 and 7 October 2007. The usable observing time was 12 hours on-source. The spectrum has 32 channels with a spectral resolution of 38.4 $\mathrm{km\,s^{-1}}$ channel^{-1}. The rms noise level is 0.3 mJy channel^{-1}.

Figure 2 The 6.1 GHz EVLA radio continuum image of MG J0414+0534. The water maser emission line shown in Figure 1 was obtained by integrating over lensed images A1 and A2. The data were taken with the EVLA in BnA configuration during September and October 2007. The observations (25 MHz bandwidth, 32 spectral channels) were amplitude calibrated relative to 3C 48, for which we adopted a flux density of 4.35 Jy, and were bandpass corrected by observing the calibrator PKS J0423–0120 approximately every 30 minutes. Natural weighting was used to increase the sensitivity to the weak line emission during imaging. The spectral line data were averaged over the inner 24 spectral channels to form a continuum dataset, which was self-calibrated and then deconvolved using CLEAN. The resulting antenna phase solutions were applied to the spectral line data resulting in a line dataset which was phase referenced to the continuum. For simplicity, and because the source is unresolved in the E-W direction, the continuum image was restored using a circular Gaussian beam with a full width at half-maximum (FWHM) of 0.47 arcsec. Note that the synthesised beam of the EVLA has a FWHM of 0.93 arcsec $\times$ 0.47 arcsec at a position angle of 79 degrees east of north. The total radio continuum flux density of the four lensed images is 0.56 Jy $\pm$ 0.06 Jy, which is in good agreement with previous measurements[16]. The image contours are (-3, 3, 6, 12, 24, 48, 96, 192, 384) $\times$ 0.43 mJy beam^{-1}. The rms noise is 0.43 mJy beam^{-1}.