A third H\textsc{i} 21-cm absorption system in the sight-line of MG J0414+0534: a redshift for Object X?

S. J. Curran,\textsuperscript{1}\textsuperscript{*} M. T. Whiting,\textsuperscript{2} A. Tanna,\textsuperscript{1} C. Bignell\textsuperscript{3} and J. K. Webb\textsuperscript{1}

\textsuperscript{1}School of Physics, University of New South Wales, Sydney NSW 2052, Australia
\textsuperscript{2}CSIRO Australia Telescope National Facility, PO Box 76, Epping NSW 1710, Australia
\textsuperscript{3}National Radio Astronomy Observatory, PO Box 2, Rt. 28/92 Green Bank, WV 24944-0002, USA

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ABSTRACT

We report the detection of the third H\textsc{i} 21-cm absorber in the sight-line towards the $z = 2.64$ quasar MG J0414+0534 (4C+05.19). In addition to the absorption at the host redshift and in the $z = 0.96$ gravitational lens, we find, through a decimetre-wave spectral scan towards this source, strong absorption at $z = 0.38$. We believe this may be associated with ‘Object X’, an additional feature apparent in the field of the lensing galaxy and lensed images, on the basis of its close proximity to the quasar images and the possible detection of the [O\textsc{iii}] doublet in a published optical spectrum. If real, the strength of the [O\textsc{iii}] emission would suggest the presence of an active galactic nucleus, or a gas-rich galaxy undergoing rapid star formation, either of which is consistent with the strong outflows apparent in the 21-cm spectrum. Although this is the strongest intervening 21-cm absorber found to date (a column density of $N_{\text{HI}} \gtrsim 10^{22}$ cm$^{-2}$, for a modest $T_{\text{v}}/f \gtrsim 300$ K), simultaneous observations failed to detect any of the 18-cm OH lines at the 21-cm redshift. This suggests that, as for the lensing galaxy, this is not the primary location of the intervening material responsible for the very red colour of MG J0414+0534.

Key words: galaxies: active – galaxies: high-redshift – galaxies: individual: MG J0414+0534 – galaxies: ISM – quasars: absorption lines – radio lines: galaxies.

1 INTRODUCTION

Radio-band observations of absorption systems along the sight-lines to distant quasars provide a powerful probe of the cool atomic and molecular gas at high redshift. This gas constitutes the reservoir of the raw material which forms stars, planets and all other non-diffuse structures in the early Universe. As well as giving an insight into how the contents of present-day galaxies came to be, redshifted H\textsc{i} 21-cm and OH 18-cm absorption lines have the potential to be very useful in determining whether the fundamental constants of nature have changed since these large look-back times (see Curran, Kanekar & Darling 2004 and references therein).

Unfortunately, such absorption is currently rare, with only 76 H\textsc{i} 21-cm absorbers known at $z \gtrsim 0.1$, 41 of which are due to intervening systems (summarized in Curran 2010),\textsuperscript{1} with 35 being associated with the quasar/quasar host providing the background illumination (summarized in Curran & Whiting 2010).\textsuperscript{2} The OH 18-cm absorption is rarer still, with only five systems known (Chengalur, de Bruyn & Narasimha 1999; Kanekar & Chengalur 2002; Kanekar et al. 2003, 2005), three of which are intervening and two being associated with the background source.

All of the OH and 80 per cent of the detected H\textsc{i} absorption occurs at $z \lesssim 1$. Much of this bias is due to the limited availability of interference-free bands at low frequencies, although there are additional effects contributing to lower detection rates at high redshift: for the intervening systems, the 21-cm detection rates (61 per cent at $z \lesssim 1$ cf. 33 per cent at $z \gtrsim 1$, Curran 2010) can be attributed to the geometry effects introduced by a flat expanding Universe, causing the coverage of the background flux to be systematically lower at higher redshift (Curran & Webb 2006; Curran et al. 2010). For associated systems, the rates (39 per cent at $z \lesssim 1$ cf. 17 per cent at $z \gtrsim 1$) are biased by the traditional optical selection of targets, where only the most ultraviolet (UV) luminous sources are known at high redshift, since the intense UV flux from the nearby active galactic nucleus (AGN) ionizes/excites the cool gas beyond detection (Curran et al. 2008). Although both of these effects are present in some cases at $z \lesssim 1$, they are always present for the high-redshift sources.

Optical selection effects further compound the detection of the OH absorption in that, despite much searching for objects in the millimetre band, where four of the five OH absorbers were originally

\textsuperscript{*}E-mail: sjc@phys.unsw.edu.au

\textsuperscript{1} With the addition of one new intervening absorber reported in Srianand et al. (2010).

\textsuperscript{2} With the addition of three new associated absorbers, two reported in Curran et al. (2011a) and one in Curran et al. (2011b).
discovered, millimetre-wave absorption is yet to be found in an optically selected target (see Curran et al. 2004). Curran et al. (2006) suggest that this is due to the optical brightness of these objects selecting against the dustier, and thus most molecular abundant absorbers. This is demonstrated through the optically selected damped Lyman $\alpha$ absorption systems (DLAs) having optical–near-infrared (optical–near-IR) colours of $V-K \lesssim 4$ and molecular fractions of $F \equiv 2N_{H_2}/2N_{HI} + N_K \approx 10^{-2}$–0.3, whereas the radio absorbers have $V-K \gtrsim 5$ and $F \approx 0.6$–1 (see fig. 3 of Curran, Whiting & Webb 2009).

This is a strong evidence that the background quasar light is reddened by the dust in the foreground absorber, which protects the molecular gas from the harsh UV environment. Thus, in order to increase the number of redshifted OH (and HI) absorbers known, we should target the reddest objects. However, due to their very faintness, optical spectra are not generally available and so we do not have a redshift to which to tune the telescope. We have therefore embarked on a programme of wide-band (200 and 800 MHz) spectral scans of very red ($V-K \gtrsim 6$) radio-loud objects with the Green Bank Telescope (GBT) in search for the dust and molecular gas responsible for the obscuration.

In this Letter, we report the detection of very strong 21-cm absorption at $z = 0.38$ towards the $z = 2.64$ quasar MG J0414+0534 (4C+05.19), where we have previously detected the 21-cm absorption in the $z = 0.96$ gravitational lens (Curran et al. 2007a). With an optical–near-IR colour of $V-K = 10.26$, this is the reddest of our targets and, although the 21-cm absorption has also been detected in the lens, in the host galaxy (Moore, Carilli & Menten 1999), the OH absorption remains undetected at either of these three redshifts.

### 2 Target Selection and Observations

As mentioned above, all of our targets were selected on the basis of their large optical–near-IR colours ($V-K \gtrsim 6$) and high radio fluxes ($\gtrsim 1$ Jy). Being a data base of bright and generally compact objects, with comprehensive optical photometry (Francis, Whiting & Webster 2000), these were taken from the Parkes Half-Jansky Flat-Spectrum Sample (Drinkwater et al. 1997), which, with the above conditions, gave five sources which could be scanned for both HI and OH by the GBT. However, given the very wide bandwidths required for the full spectral scans, much of the data are subject to severe radio frequency interference (RFI), with only limited parts of the band being useful (Tanna et al., in preparation). Nevertheless, we are able to obtain enough useful data on MG J0414+0534 to reveal a clear, strong detection of neutral hydrogen.

The 0.91–1.23 GHz range J0414+0534 observations were performed on 2007 January 23 using the PF2 receiver and the autocorrelation spectrometer over a 200-MHz-wide bandpass (with 16 384 lags), centred on 1.0 GHz in two orthogonal linear polarizations. This band was observed for a total of 2 h in 5-min position-switched scans and the removal of RFI-affected scans left 44 min of good data, with a mean system temperature of $T_{sys} = 24$ K and an rms noise level of $\approx 10$ mJy per 3.56 km s$^{-1}$ (at 1030 MHz) channel in the clear parts of the bandpass.

The data were calibrated, flagged and averaged using the gbtidl package and, as seen in each of the polarizations, an absorption feature was detected close to 1030 MHz (Fig. 1). Due to the structure of the line and the strength of the main component (a velocity-integrated optical depth of $\int \tau dv = 11$ km s$^{-1}$), we believe that the feature is due to 21-cm absorption at a redshift of $z \approx 0.38$.

### 3 Results and Discussion

#### 3.1 The H I 21-cm Absorption

In each polarization (Fig. 1), it is clear that the absorption is comprised of several components and in Fig. 2 we show the Gaussian fits to the profile and summarize these in Table 1.

A single Gaussian fit to the main component gives $1030.0450 \pm 0.0057$, that is, $z = 0.378974 \pm 0.000008$ for the redshift of the absorber. This, in addition to the separate Gaussian fits to the blueshifted and redshifted features (see below), gives a velocity-integrated optical depth of $\int \tau dv = 17 \pm 3$ km s$^{-1}$. This is the

![Figure 1](https://academic.oup.com/mnrasl/article-abstract/413/1/L86/1747633/1)

**Figure 1.** The absorption profile at 1030 MHz towards J0414+0534 in each of the two orthogonal linear polarizations. The data are shown at the observed 12.207 kHz channel spacing, which gives 3.56 km s$^{-1}$ at 1030 MHz. The flux density is found to be 2.21 Jy at 1.03 GHz, cf. 2.12 Jy at 1.4 GHz (Katz et al. 1997).

![Figure 2](https://academic.oup.com/mnrasl/article-abstract/413/1/L86/1747633/2)

**Figure 2.** Gaussian fits to the absorption profile, where we fit three Gaussians to the central feature and one to each of the outlying features (summarized in Table 1). The flux scale is relative to 2.21 Jy and the velocity offset is relative to the central observing frequency of 1.000 GHz. As Fig. 1, the velocity resolution is 3.56 km s$^{-1}$.

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strongest intervening 21-cm absorber found to date (see table 1 of Curran et al. 2007b and fig. 12 of Curran et al. 2010), the next being at £ z = 0.52 towards B0235+164 with $f r d v = 14 km s^{-1}$ (Roberts et al. 1976). The line strength gives a neutral hydrogen column density of $N_{H1} = (2.9 ± 0.5) × 10^{19}$ (Roberts et al. 1976). The largest is $N_{H1} = 2.6 × 10^{20}$ cm$^{-2}$, which is in the top 2 per cent of the Sloan Digital Sky Survey Data Release 5 DLAs (Prochaska & Wolfe 2009). The largest is $N_{H1} = 8 × 10^{21}$ cm$^{-2}$, a value which is exceeded by the absorber for $T_s/f_r ≥ 300 K$.

In addition to the main component, there is a strong redshifted and a weaker blueshifted component offset at $≈+151$ and $≈−143 km s^{-1}$, respectively. These features have absorption line strengths which are $≈40$ and $≈20$ per cent of the main profile ($f r d v = 10 ± 1 km s^{-1}$), the redshifted feature being as strong as any of those in the main profile (Table 1). We interpret these as being due to outflows from the nucleus of the galaxy, which contain a significant portion of the absorbing gas. This is reminiscent of the Circinus galaxy, a nearby Seyfert in which the outflowing molecular gas mass is comparable with that in the disc (Curran et al. 1999).

If the disc of the galaxy intervenes most of the background flux, as may be evident from the large optical depth, the relatively narrow full width at half-maximum of the main profile (FWHM = 86 ± 6 km s$^{-1}$) may suggest a low to intermediate inclination for the galactic disc. Thus, this may have an axis direction similar to that of the outflow, which we believe is directed close to the line of sight, since it must intercept much of the flux from J0414+0534. However, this is not a necessity, as the galactic disc (in which the absorption occurs) need not be coplanar with the circumnuclear torus, invoked by unified schemes of AGNs, which collimates the outflow (Curran & Whiting 2010 and references therein).

### 3.2 The OH 18-cm absorption

Since the purpose of our spectral scans is to find the intervening molecular gas responsible for the reddening of the background quasar, the frequencies covering the four 18-cm $^2P_{3/2}$ OH lines were observed simultaneously in separate intermediate frequencies. Given the redshift of the 21-cm absorption, we expect the OH transitions to occur at 1169.15 (1612), 1207.71 (1665), 1209.13 (1667) and 1247.69 MHz (1720 MHz). Examining the data which contain these frequencies (Fig. 3), we see that there may indeed be two features coincident with the 1665 ($F = 1−1$) and 1667 MHz ($F = 2−2$) transitions (OH1667 panel), although, even after the removal of the worst RFI, the bandpass is somewhat bumpy. From a Gaussian fit to the higher frequency feature, we obtain a centroid of 1212.314 ± 0.009 MHz, which is where the $F = 2−2$ transition would occur at a redshift of $z = 0.37535 ± 0.0001$ implying that the $F = 1−1$ transition should be redshifted to 1210.89 ± 0.01 MHz. However, this is observed at 1209.80 ± 0.03, which in conjunction with the fact that $z = 0.37535$ is out of range of any of the HI features (Table 1) leads us to conclude that these are artefacts of an unstable bandpass.

Since the 1665-MHz band is the cleanest over the 21-cm redshift, we use this transition to obtain an optical depth limit. Curran et al. (2007a) found a correlation between the HI and OH profile widths for the five known redshifted OH absorbers and so we resample the rms noise level of 1.8 mJy per 10 km s$^{-1}$ to the FWHM of the main 21-cm absorption profile. This gives a $3σ$ limit of $f r_{1665MHz} dv ≤ 0.074 km s^{-1}$ per 86 km s$^{-1}$ or $N_{OH} ≤ 3.3 × 10^{17}$ ($T_s/f_r$), where $T_s$ is the excitation temperature of the gas. Normalizing this by the line strength of the main 21-cm profile gives $N_{OH}/N_{H1} ≤ 1.8 × 10^{-6}$ ($f_{1612}/f_{1667}$($T_s/f_r$), which is five times more sensitive than our previous limit in the $z = 0.96$ gravitational lens (Fig. 4).

If the molecular abundance is correlated with the red colour of the background quasar (Curran et al. 2011a), then it is apparent that none of the two known intervening 21-cm absorbing systems towards J0414+0534 is the cause of the reddening. Furthermore, from OH observations at the host galaxy redshift (Curran et al., in preparation), we have obtained a limit of $f r_{1612MHz} dv ≤ 0.16 km s^{-1}$ per 5 km s$^{-1}$ from the $F = 1−2$ transition. Rescaling this to the FWHM of $≈320 km s^{-1}$ for the 21-cm profile (Moore et al. 1999) gives $N_{OH} ≤ 3 × 10^{14}$ ($T_s/f_r$) or a normalized line strength of $N_{OH}/N_{H1} ≤ 2 × 10^{-4}$ ($f_{1612}/f_{1667}$($T_s/f_r$), which may not rule out strong OH absorption in the host galaxy (Fig. 4). Note that the low HCN abundance ($N_{HCN} ≤ 1.2 × 10^{13}$ cm$^{-2}$, for $T_s = 10 K$) found by Moore et al. (1999) may not rule out a large molecular abundance either, based on the fact that Kanekar et al. (2005) detect strong OH, but no HCO$^+$, absorption towards PKS 0132−097, which Curran et al. (2007a) suggest is due to differences in the coverage of the millimetre and decimetre-wave emission. Given that three H1 absorption systems are now known towards this source, it is feasible that the red colour of the background quasar arises from an accumulation of systems, rather than a single dusty intervening galaxy.

\[ ^4\text{The diameter of the background emission is 5 arcsec at 1.4 GHz (Katz, Moore & Hewitt 1997), which is 26 kpc at } z = 0.38 (H_0 = 71 km s^{-1} Mpc^{-1}, 
\[ ^5\text{The redshifted frequencies of the other three transitions were completely dominated by RFI.} \]
3.3 The origin of the absorption

Having discovered the absorption, the question of its origin arises. There have been a number of optical/near-IR studies of J0414+0534 (Schechter & Moore 1993; Angonin-Willaime et al. 1994; Falco, Lehár & Shapiro 1997) and these show, in addition to the four quasar images (A1, A2, B and C) and the lensing galaxy, a feature often referred to as ‘Object X’ (Fig. 5).

It is located about 1 arcsec west of component ‘B’, giving impact parameters between 5–15 kpc (for \(z = 0.38\)) and 8–25 kpc (for \(z = 0.96\)) to the four quasar images. The HST photometry (Falco et al. 1997) gives \(R > 26.268 \pm 0.063\) and \(I = 24.769 \pm 0.063\), thus having a different colour to the quasar images, while probably being slightly redder than the lensing galaxy.

We note that the spectrum of Tonry & Kochanek (1999) shows tantalizing evidence of peaks approximately where the [O iii] \(\lambda\lambda 4959, 5007\) Å doublet would be located for the \(\text{H} I\) absorption redshift of \(z = 0.3789\) (observed wavelengths of 6837 and 6903 Å). The slit position, as indicated in their fig. 1, would indeed lie directly across Object X and large [O iii] emission-line fluxes would be expected from an AGN or gas-rich galaxy undergoing rapid star formation, either of which is consistent with the observation of rapid outflows of \(\text{H} I\) in each direction.
4 SUMMARY

As part of an ongoing project, scanning the entire redshift space towards highly reddened radio sources, in search for the object responsible for the obscuration of the optical light, we have detected a second intervening 21-cm absorber at \( z = 0.38 \) towards the quasar \( \text{J0414}+0534 \). The other intervening absorber arises at \( z = 0.96 \), the gravitational lens (Curran et al. 2007a) and, combining with the absorption found at the host redshift (Moore et al. 1999), gives a total of three \( \text{H}_1 \) absorbers detected so far along this sight-line.

Although we cannot determine the \( T_s/f \) degeneracy for any of the three 21-cm absorbers, thus deriving the column densities, the 21-cm line strength in this new absorber is so far the strongest detected along this sight-line, being four times stronger than in the host galaxy \( N_{\text{HI}} = (7.5 \pm 1.3) \times 10^{18} \text{ cm}^{-2} \) and 19 times stronger than in the lens \( N_{\text{HI}} = 1.6 \times 10^{18} \text{ cm}^{-2} \), in fact, the strongest intervening 21-cm absorber found to date.

Despite the \( \text{H}_1 \) absorption strength and the very red colour of this source \( (V - K = 10.26) \), \( \text{OH} \) remains undetected to very strong limits \( N_{\text{OH}}/N_{\text{HI}} \leq 1.8 \times 10^{-6} (f_{\text{HI}}/f_{\text{OH}})(T_s/f_s) \), inferring that this new absorber is not the primary cause of the red colour. \( \text{OH} \) is also undetected in the lens and the host galaxy, although the latter is to relatively weak limits not allowing us to rule out that the host is where much of the reddening occurs.

We suggest that the absorption may be associated with the feature known as Object X in the optical field of \( \text{J0414}+0534 \); this could be spatially coincident with the spectrum of Tonry & Kochanek (1999), of which the 6837 and 6903 Å features are consistent with the expected wavelengths for the \([\text{O}III]\) doublet at the redshift of the 21-cm absorption feature. Not being a companion of the lensing galaxy \( \text{J0414}+0534 \) suggests that future surveys with the Square Kilometre Array may uncover a large population of faint, dusty, high-redshift galaxies.

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REFERENCES

Angonin-Willaine M.-C., Vanderriest C., Hammer F., Magain P., 1994, A&A, 281, 388
Brown R. L., Mitchell K. J., 1983, ApJ, 264, 87
Brown R. L., Roberts M. S., 1973, ApJ, 184, L7
Chengalur J. N., de Bruyn A. G., Narasimha D., 1999, A&A, 343, L79
Curran S. J., 2010, MNRAS, 402, 2657
Curran S. J., Webb J. K., 2006, MNRAS, 371, 356
Curran S. J., Whiting M. T., 2010, ApJ, 712, 303
Curran S. J., Rydbeck G., Johansson L. E. B., Booth R. S., 1999, A&A, 344, 767
Curran S. J., Kanekar N., Darling J. K., 2004, Science with the Square Kilometer Array, New Astronomy Reviews 48. Elsevier, Amsterdam
Curran S. J. et al., 2004, MNRAS, 352, 563
Curran S. J. et al., 2005, MNRAS, 356, 1509
Curran S. J. et al., 2006, MNRAS, 371, 431
Curran S. J. et al., 2007a, MNRAS, 382, L11
Curran S. J. et al., 2007b, MNRAS, 381, L6
Curran S. J. et al., 2008, MNRAS, 391, 765
Curran S. J., Whiting M. T., Webb J. K., 2009, Proc. Sci., 89, ch. 11
Curran S. J. et al., 2010, MNRAS, 402, 35
Curran S. J. et al., 2011a, MNRAS, in press (doi:10.1111/j.1365-2966.2011.18209.x) (arXiv:1012.1972)
Curran S. J., Whiting M. T., Webb J. K., Athreya A., 2011b, MNRAS, submitted (arXiv:1103.2595)
Darling J. et al., 2004, ApJ, 613, L101
Drinkwater M. J. et al., 1997, MNRAS, 284, 85
Falco E. E., Lehár J., Shapiro I. I., 1997, AJ, 113, 540
Francis P. J., Whiting M. T., Webster R. L., 2000, PASA, 17, 56
Gregg M. D. et al., 2002, ApJ, 564, 133
Kanekar N., Briggs F. H., 2003, A&A, 412, L29
Kanekar N., Chengalur J. N., 2002, A&A, 381, L73
Kanekar N., Chengalur J. N., de Bruyn A. G., Narasimha D., 2003, MNRAS, 345, L7
Kanekar N. et al., 2005, Phys. Rev. Lett., 95, 261301
Katz C. A., Moore C. B., Hewitt J. N., 1997, ApJ, 475, 512
Kochanek C. S., Dalal N., 2004, ApJ, 610, 69
Kochanek C. S. et al., 1999, in Holt S., Smith E., eds, AIP Conf. Ser. Vol. 470, Results from the CASTLES Survey of Gravitational Lenses. Am. Inst. Phys., New York, p. 163
Moore C. B., Carilli C. L., Menten K. M., 1999, ApJ, 510, L87
Prochaska J. X., Wolfe A. M., 2009, ApJ, 696, 1543
Roberts M. S. et al., 1976, AJ, 81, 293
Schechter P. L., Moore C. B., 1993, AJ, 105, 1
Srianand R. et al., 2010, MNRAS, 405, 1888
Tonry J. L., Kochanek C. S., 1999, AJ, 117, 2034
Trotter C. S., Winn J. N., Hewitt J. N., 2000, ApJ, 535, 671

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