A FORTHRIGHT H I 21 cm ABSORPTION SYSTEM IN THE SIGHT LINE OF MG J0414+0534: A RECORD FOR INTERVENING ABSORBERS

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ABSTRACT
We report the detection of a strong H I 21 cm absorption system at z = 0.5344, as well as a candidate system at z = 0.3389, in the sight line toward the z = 2.64 quasar MG J0414+0534. This, in addition to the absorption at the host redshift and the other two intervening absorbers, takes the total to four (possibly five). The previous maximum number of 21 cm absorbers detected along a single sight line is two and so we suspect that this number of gas-rich absorbers is in some way related to the very red color of the background source. Despite this, no molecular gas (through OH absorption) has yet been detected at any of the 21 cm redshifts, although, from the population of 21 cm absorbers as a whole, there is evidence for a weak correlation between the atomic line strength and the optical–near-infrared color. In either case, the fact that so many gas-rich galaxies (likely to be damped Lyα absorption systems) have been found along a single sight line toward a highly obscured source may have far-reaching implications for the population of faint galaxies not detected in optical surveys, a possibility which could be addressed through future wide-field absorption line surveys with the Square Kilometer Array.

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

Online-only material: color figures

1. INTRODUCTION

Absorption of the 21 cm electron spin-flip transition of neutral hydrogen (H I) is a powerful probe of the reservoir of star-forming material in the early universe. At high redshift, 21 cm absorption can provide important insight into star formation rates and galaxy evolution at a time when chemical abundances were markedly different from the present day. Furthermore, in combination with other absorbing species, H I 21 cm can provide measurements of the fundamental constants at large look-back times (Curran et al. 2004 and references therein). In five cases, OH 18 cm absorption has been found coincident with the H I (Chengalur et al. 1999; Kanekar & Chengalur 2002; Kanekar et al. 2003, 2005) and the hydroxyl radical is of particular interest for measurement of the constants since it allows highly sensitive measurements from a single absorbing species (Darling 2003).

However, the detection of either transition at z > 0.1 is a rare occurrence. For H I 21 cm, 80 systems have been detected7 and, despite much searching (Curran et al. 2011b and references therein), the detection of OH 18 cm is rarer yet, with only the aforementioned five detections to date.8 Curran et al. (2006, 2011a) have shown that the molecular fraction in the known molecular absorbers is correlated with the optical–near-infrared color, thus indicating that their colors are due to the presence of dust required to shield the molecular gas from the ambient UV field. Therefore, selecting objects for which an optical redshift is available selects against those with a high molecular fraction, making the detection of molecular absorbers difficult.

Hence, in an attempt to increase the number of redshifted detections of both species, we have performed full spectral scans with the Green Bank Telescope (GBT) toward five highly reddened (optical–near-infrared colors of V − K > 6) radio-loud objects (A. Tanna et al., in preparation). For the reddest (V − K = 10.26) of the targets, the z = 2.64 quasar MG J0414+0534 (4C +05.19), three 21 cm absorption systems have already been detected (see Table 1). In this Letter we report the detection of a further absorber at a redshift of z = 0.534, as well as a candidate system at z = 0.339.

2. THE DETECTION OF ONE (AND POSSIBLY TWO) NEW ABSORPTION FEATURE(S)

We have now completed the analysis of the data along the entire redshift space toward MG J0414+0534 (see Curran et al. 2011c for details), in which we find a further two possible absorption profiles, near 926 MHz and 1061 MHz. The absorption feature close to 926 MHz was the least subject to radio frequency interference (RFI), which appears as narrow absorption profiles, near 926 MHz and amplitude fluctuations. These can be seen in Figure 1 (top panel), which essentially constitutes a low-resolution time-lapse series of the entire 146.3 s exposure scans.

In the final averaged spectrum (Figure 1, bottom panel), a persistent absorption feature was apparent, which maintains consistency throughout the observations, with GBT RFI monitoring indicating that this part of the band is predominantly clear of interference. There remains, however, a two channel wide spike redshifted by ≈40 km s−1 from the peak of the profile. The RFI nature of this is confirmed in spectral animations of

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6 For all of these the FWHM of the OH profile is similar to that of the H I (Curran et al. 2007a).
7 Half of which occur in systems intervening the sight lines to more distant radio sources, with the other half associated with a source’s host galaxy (see Curran 2010; Curran & Whiting 2010 and references therein).
8 Three of which are intervening and two are associated absorbers.
Table 1

| Redshift  | Location       | $N_{\text{HI}}$ (cm$^{-2}$) | $N_{\text{OH}}$ (cm$^{-2}$) | $N_{\text{OH}} / N_{\text{HI}}$ | Reference         |
|-----------|----------------|-----------------------------|-----------------------------|-------------------------------|------------------|
|           |                | $7.5 \times 10^{19} \cdot (T_{\text{spin}} / f_{\text{HI}})$ | $\leq 3 \times 10^{14} \cdot (T_{\text{ex}} / f_{\text{OH}})^{a}$ | $\leq 2 \times 10^{-4}$ | Moore et al. (1999) |
| 0.95974   | Lensing galaxy | $1.6 \times 10^{18} \cdot (T_{\text{spin}} / f_{\text{HI}})$ | $\leq 4.9 \times 10^{12} \cdot (T_{\text{ex}} / f_{\text{OH}})$ | $\leq 9 \times 10^{-6}$ | Curran et al. (2007a) |
| 0.53435   | Object X       | $\geq 2.8 \times 10^{19} \cdot T_{\text{spin}}$ | $\leq 1.3 \times 10^{14} \cdot (T_{\text{ex}} / f_{\text{OH}})$ | $\leq 5 \times 10^{-6}$ | This Letter        |
| 0.37895   | —              | $2.9 \times 10^{19} \cdot (T_{\text{spin}} / f_{\text{HI}})$ | $\leq 3.3 \times 10^{13} \cdot (T_{\text{ex}} / f_{\text{OH}})$ | $\leq 2 \times 10^{-6}$ | Curran et al. (2011c) |
| 0.33878   | —              | $\geq 6.7 \times 10^{19} \cdot T_{\text{spin}}$ | $\leq 5.0 \times 10^{14} \cdot (T_{\text{ex}} / f_{\text{OH}})$ | $\leq 8 \times 10^{-6}$ | This Letter$^b$   |

Notes. The first column lists the redshift, followed by the feature with which the absorption is associated. $N_{\text{HI}}$ and $N_{\text{OH}}$ give the H$\text{I}$ 21 cm and OH 18 cm line strengths, respectively, followed by the normalized OH line strength, in terms of $(f_{\text{HI}} / f_{\text{OH}}) \cdot (T_{\text{ex}} / T_{\text{spin}})$. The last column gives the reference for the discovery of the absorption and the line strengths. $^a$OH limit from Curran et al. (2011c). $^b$If genuine 21 cm absorption (Section 2).

Figure 1. The absorption feature near 926 MHz toward J0414+0534. Top: as seen in individual 146.3 s exposure scans of each linear polarization. Bottom: detail showing the averaged spectrum. In this and Figure 2, the spectrum is shown at the observed spectral resolution of 3.4 km s$^{-1}$ and a first order polynomial removed from the bandpass, with the best fit Voigt profile overlaid. The lower panel shows the standard deviation of each channel from the mean across all individual scans.

(A color version of this figure is available in the online journal.)

Figure 2. As per Figure 1, but for the feature near 1061 MHz.

(A color version of this figure is available in the online journal.)

Close to 1061 MHz, the dominant RFI was apparent as “packets,” one of which impinges on one side of a possible absorption feature. RFI monitoring indicates that these packets (spaced $\sim 1$ MHz apart) are due to aircraft radar and much of the data are heavily affected. Again, through the animation of contiguous 5 s integrations, the packets behave in a similar fashion to the RFI spikes close to 925 MHz, displaying time-dependent fluctuations. Flagging the data most strongly affected leaves approximately one-third of the scans, allowing us to retain some data at all frequencies, particularly on the blueshifted side of the line. While the RFI packets are still apparent in the final averaged spectrum (Figure 2, bottom panel), it is clear that the absorption feature at 1061 MHz maintains a stable, deep profile shape over the course of the observations (even beneath the RFI). Furthermore, the packets vary regularly in time, flipping between positive, negative, and zero fluxes, whereas the

$^9$ For the other possible candidate, OH 18 cm, we expect two features separated by $1.9572/(z + 1)$ MHz.
absorption profile is consistent and has an identical appearance in two different intermediate frequencies (0.9–1.1 GHz and 1.05–1.25 GHz). The stability of the putative line is confirmed in the standard deviation spectrum, which identifies time varying features, where the peak is not coincident with the most variable channels (Figure 2, bottom panel). However, given that the nearby RFI is not restricted to one or two channels, this feature requires confirmation from an independent observation.

3. RESULTS AND DISCUSSION

3.1. Absorption by Neutral Hydrogen

The mean frequency of the first feature (Figure 1) is 925.73±0.09 MHz, which for H1 21 cm gives, from the flagged data, a flux-averaged mean redshift of z = 0.534±0.00002, cf. the peak redshift of zpeak = 0.53437±0.00002, obtained from the deepest channel in the peak of the profile. There is a decrease in the bandpass response below 950 MHz, giving a continuum flux of 0 = 1.82±0.05 Jy, cf. the 2.3 Jy seen over the rest of the band, which yields an observed peak optical depth of τobs = ΔS/S = 0.30±0.04. Unlike the vast majority of redshifted 21 cm absorption, this peak depth that the optically thin approximation cannot be applied (where ΔS 0.3 S, i.e., τ ∝ −ln (1 − τobs/fHI) ∝ τobs/fHI. Since, by definition, the covering factor fHI ≤ 1, the peak optical depth is then τpeak ≥ 0.36±0.06 and the velocity integrated optical depth ∫τdv ≥ 16±3 km s−1. This gives a column density of NHI ≥ 2.8×1019 cm−2, where Tspin [K] is the mean harmonic spin temperature of the gas.

The mean frequency of the second feature (Figure 2) is 1060.97±0.04 MHz, which for H1 21 cm gives a redshift of z = 0.338777±0.000006, cf. the peak redshift of zpeak = 0.33882±0.00002. The peak depth of the line is ΔS = 1.059 Jy and the continuum flux is S = 2.331±0.015 Jy, giving a peak τobs = 0.45±0.01. Again, the optically thin approximation is not applicable and so τpeak ≥ 0.61±0.02, giving ∫τdv ≥ 37±1 km s−1 and NHI ≥ 6.7×1019 cm−2. If genuine, this would be the second deepest redshifted 21 cm feature yet found, although given our concerns about its authenticity (Section 2) this requires confirmation.

We note that there are apparent similarities in the shapes of the two absorption profiles as a function of velocity, although, in addition to different depths, the widths exhibit a slight difference, with the 926 MHz profile having an FWHM ≈ 44 km s−1, cf. FWHM ≈ 61 km s−1 at 1061 MHz. Since the profile shapes are not consistent in frequency space, we believe it unlikely that these are due to an instrumental artifact, which lends some weight to the reality of the 1061 MHz feature. The shape of each line has much broader wings than those produced by a single Gaussian profile and are best fit by a single Voigt profile, which we interpret as the effect of pressure broadening convolved with the velocity dispersion of the gas.

Lastly, in Table 1 we list the derived column densities together with the other 21 cm absorbers thus far found toward J0414+0534. Even the weakest (that arising in the lensing galaxy) is likely to qualify as a damped Lyα absorption system (DLA), requiring only (Tspin/fHI) ≥ 125 K to reach the defining NHI ≥ 2×1020 cm−2. That is, all of the absorbers so far found along the sight line toward J0414+0534 are likely to be associated with gas-rich galaxies.

3.2. Optical Counterparts

Confirmation of 21 cm detections can be done through optical imaging and spectroscopy, either by finding absorption lines in the quasar spectrum at matching redshifts or by identifying the absorbing galaxy. Detecting common optical absorption lines, such as Mg II, from these systems is made difficult by the extremely red color of the quasar’s optical spectrum: for z = 0.5343 and z = 0.3388 the Mg II doublet would appear at 429 nm and 375 nm, respectively, where the quasar flux is very low (Hewitt et al. 1992; Lawrence et al. 1995). Furthermore, Moore et al. (1999) detect strong 21 cm absorption in the host galaxy and any associated Lyα absorption (centered on 442.6 nm at z = 2.64) would likely conceal the nearby z = 0.5343 Mg II line.

There is evidence from the spectrum of Hewitt et al. (1992) of the λ3589, 5897 Na I doublet at z = 0.3388. This identification is made difficult by both the low resolution of the published spectrum and the presence of the nearby Ca II H+K line from the lensing galaxy at z = 0.958. It is, however, suggestive of a galaxy at the redshift of the 1061 MHz putative detection. The same Na I line at z = 0.534 coincides with strong sky-line subtraction residuals in the Hewitt et al. spectrum.

Identifying the corresponding absorbing galaxy is also difficult. No published spectroscopy exists of neighboring field galaxies, although Tonry & Kochanek (1999) presented long-slit spectroscopy of the lensing galaxy, taken with the slit placed across “Object X,” the closest field galaxy. Curran et al. (2011c) identified two peaks in the low-resolution spectrum at the wavelengths expected for [O III] at z = 0.3789. It is likely, then, that this object does not correspond to either of the detections presented here. Hubble Space Telescope images indicate numerous nearby galaxies, but none have redshift measurements or estimates. Detailed, deep multi-object, and/or integral-field spectroscopy of this field would be required to fully resolve the identification of the specific absorbing galaxies.

3.3. The Incidence of Multiple Intervening Absorbers Along a Single Sight Line

The detection of at least one new absorber now gives at least three intervening systems along the sight line to J0414+0534 (Table 1). All of these systems are likely to be DLAs (Section 3.1), indicating a similar sight line to the z = 3.02 quasar CTQ 247, toward which Lopez et al. (2001) report the detection of four DLAs. However, at z = 2.55, 2.59, and 2.62, three of these arise in a single broad feature and the fourth, at z = 1.91, is inferred from the metal lines. With a rest-frame equivalent width of Wλ21216 = 6.0 Å for the Lyα line, this is more likely to be a Lyman-limit system than a DLA.

In order to quantify how rare an occurrence the presence of at least three DLAs along a single sight line is, we use the Prochter et al. (2006) sample of strong (Wλ2796 > 1 Å) Mg II absorbers. These are obtained from Sloan Digital Sky Survey (SDSS) DR3 observations of 45,023 QSO sight lines, which span 0.35 < zMg II < 2.3, a similar redshift range to the 21 cm observations toward J0414+0534 at z = 2.64. However, the GBT scan below 700 MHz is completely dominated by RFI and so is not sensitive to any absorption between the lensing galaxy and J0414+0534 (A. Tanna et al., in preparation), restricting the redshifts scanned to z ≲ 1. The total number of sight lines

10 The deepest being τpeak ≥ 0.71 at z = 0.524 toward AO 0235+164 (Roberts et al. 1976).

11 There are two galaxies, u2fl1#038 and u2fl1#044, at relatively large separations (1.3–1.5 arcmin), although these are extremely red objects and so are likely to be at z > 1 (Yan & Thompson 2003).
Figure 3. The OH data at frequencies close to the redshift of the H\textsubscript{i} absorption, $z_{\text{H}i} \pm 0.005$. The left panels show the expected frequencies of OH absorption for the $z = 0.534$ absorption feature and the right panels for the putative $z = 0.339$ feature. All but the last panel are part of a 200 MHz wide scan and so shown at the observed spectral resolution of 3–4 km s$^{-1}$. For 1720 MHz at $z = 0.339$, the spectrum is from an 800 MHz wide scan and shown at the observed resolution of 21 km s$^{-1}$.

probed for a given redshift value is in excess of 15,000 for much of this range (see Figure 2 of Prochter et al. 2006), peaking at 22,000–23,000 for $0.6 < z < 0.9$. Of these, there are 2564 unique sight lines that exhibit $W_{\lambda_{2796}} > 1$ Å absorption at $z \leq 1$. Only 78 of these contain two distinct\textsuperscript{12} absorbers, with a further 4 sight lines containing three absorbers.

Restricting this to DLA-strength absorbers ($W_{\lambda_{2796}} \gtrsim 3$ Å, assuming the $W_{\lambda_{2796}} - N_{\text{HI}}$ relation of Ménard & Chelouche 2009; see also Curran et al. 2007c), there are 81 sight lines that contain a DLA, but none with more than one. Zero sight lines with at least two DLA-strength absorbers out of $\gtrsim 15,000$ sight lines means that, with at least three distinct DLAs at $z < 1$, the sight line toward J0414+0534 is unprecedented. Our use of SDSS QSOs (Prochter et al. 2006) selects against reddened sight lines (see Figure 1 of Curran et al. 2011a) where dust extinction is low, and so extinction may be significant in the sight line of J0414+0534, given the very red color and the high incidence of cold, neutral absorbing gas.

\textsuperscript{12} Separated by at least 10,000 km s$^{-1}$ (or $\Delta z \gtrsim 0.03$).

3.4. Reddening of the Quasar Light

3.4.1. Reddening by Dust Associated with Molecular Gas

From H\textsubscript{i} 21 cm at $z = 0.5344$, we expect the 1665 and 1667 MHz OH main lines at 1085.3985 and 1086.67 MHz and the 1612 and 1720 MHz satellite lines at 1050.75 and 1121.33 MHz, respectively. Likewise, if real, for H\textsubscript{i} 21 cm at $z = 0.3388$, we expect the OH 18 cm lines at 1243.94 and 1245.40 MHz (main) and 1204.22 and 1285.11 MHz (satellite). There is, however, no evidence of OH absorption in either case (Figure 3).

In Table 1 we list the best OH column density limits for these systems, together with those of the previous searches. Based on the optical–near-infrared color of $V - K = 10.26$, we expect molecular fractions of close to unity (Curran et al. 2011a) where dust extinction is low, and so extinction may be significant in the sight line of J0414+0534, given the very red color and the high incidence of cold, neutral absorbing gas.
of 21 cm absorbers detected over the useful fraction of the band, in conjunction with the apparent obscuration of the source, may have far-reaching implications for the number of gas-rich galaxies missed by optical surveys.

4. SUMMARY

We have now completed the analysis of a full-band decimeter wave spectral scan toward the very red (\(V - K = 10.26\)) quasar MG J0414+0534. From the 46% of the band not completely ruined by RFI, we have found three (possibly four) strong intervening absorbers, in addition to the previously detected absorption in the host galaxy at \(z = 2.64\) (Moore et al. 1999). At a total of four (or five), this represents a new record in the number of 21 cm absorbers found along a single sight line, the previous being a total of two systems toward PKS 1830–211 (Lovell et al. 1996; Chengalur et al. 1999), which has \(V - K = 6.25\) (see Curran et al. 2006).

The new detections occur at redshifts of \(z = 0.3388\) and \(z = 0.5344\), each being very strong absorbers with column densities of \(N_{\text{HI}} \geq 6.7 \times 10^{19} \cdot T_{\text{spin}}/f_{\text{HI}}\) and \(\geq 2.8 \times 10^{19} \cdot T_{\text{spin}}\) cm\(^{-2}\), respectively. This qualifies both as DLAs for a paltry \(T_{\text{spin}} \sim 10\) K (an order of magnitude lower than the lowest yet found; Curran et al. 2007b). However, given the RFI in the spectrum at 1061 MHz, the \(z = 0.3387\) feature requires confirmation.

Despite the large column densities, no OH absorption was found in either the main or satellite 18 cm lines at these redshifts, although the very red color of the background source suggests large molecular fractions somewhere along the sight line (Curran et al. 2006). Summing the observed \(\text{HI}\) column densities does strengthen the atomic gas abundance/\(V - K\) color correlation (Curran & Whiting 2010), although this remains fairly scattered. Therefore, dense molecular gas at an RFI affected redshift and/or the possibility that J0414+0534 is intrinsically red cannot be ruled out.

However, the fact that this extremely red sight line has yielded at least three intervening gas-rich galaxies (which would likely have remained undiscovered through optical spectroscopy) does have implications for obscured galaxy populations. With the large field of view and instantaneous bandwidths that will be available with the Square Kilometer Array (SKA) and the Australian SKA Pathfinder,\(^\[14\]\) large-scale blind surveys of radio sources with faint optical counterparts will soon be possible, allowing us to quantify the number of such galaxies hidden to optical surveys.

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\[14\] Which will scan \(\text{H}_2\) 21 cm absorption over the \(z \lesssim 1\) redshift range discussed in Section 3.3, through the First Large Absorption Survey in \(\text{H}_2\) (FLASH).

\[13\] Setting the values to \(N_{\text{HI}} = 2.8 \times 10^{19} \cdot T_{\text{spin}}/f_{\text{HI}}\), in order to maintain consistency with the other measurements.

**Figure 4.** The 21 cm line strength vs. optical–near-IR color for the associated \(z \geq 0.1\) absorbers for which the colors are available (Curran & Whiting 2010). The filled circles are the 21 cm detections and the unfilled circles the non-detections. The filled star shows the line strength for the \(N_{\text{HI}} = 7.5 \times 10^{19} \cdot T_{\text{spin}}/f_{\text{HI}}\) absorber associated with the host of J0414+0534 and the hollow stars the total of the line strengths for the four robust detections, including the putative \(z = 0.339\) feature (Table 1).

(A color version of this figure is available in the online journal.)
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