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A 22 GHz search for molecular absorption at $z \sim 3$ with the upgraded ATCA

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ABSTRACT

We report a $\lambda \gtrsim 1$ cm search for rotational molecular absorption towards guasars, now possible with the upgraded Australia Telescope Compact Array (ATCA). The targets were PKS 0201+113, PKS 0336-017 and Q 0537-286, where known damped Lyman-alpha absorption systems (DLAs) could cause redshifted molecular absorption in the 12 mm band of the telescope. We place 3σ upper limits on any HCO⁺ $0 \rightarrow 1$ absorption features of < 30 mJy per 3.4 km s⁻¹ channel. The non-detections could be attributed to the inherent low metallicities in DLAs leading to generally low H_2 , and thus HCO⁺, column densities. In general, the detection of molecular rotational transitions in DLAs could be further hindered by a lower than expected CO-to- H_2 conversion ratio, whether due either to photoionization of carbon or its relative underabundance at high redshift.

Key words: quasars: absorption lines-galaxies: ISM-radio continuum: galaxiescosmology: early universe

INTRODUCTION

Molecular absorption lines at high redshift can provide an excellent probe of cosmological physics such as the cosmic microwave background, values of the fundamental constants and the chemistry of the early Universe (e.g. Wiklind & Combes 1996c, 1997, 2001; Drinkwater et al. 1998). However, such studies are limited to the 4 known high redshift molecular absorption systems, towards TXS 0218+357 (Wiklind & Combes 1995), PKS 1413+135 (Wiklind & Combes 1997), TXS 1504+377 (Wiklind & Combes 1996a) and PKS 1830–211 (Wiklind & Combes 1998). In the search for new systems, one systematic approach is to target high column density absorbers with known redshifts. A convenient sample is the damped Lyman-alpha absorbers, which have neutral hydrogen column densities $N_{\rm HI} \gtrsim 10^{20} {\rm ~cm^{-2}}$. In order to select a sample, we produced a catalogue of all known DLAs (Curran et al. 2002b)¹ and shortlisted those which are illuminated by radio-loud quasars (i.e. those with a measured radio flux density > 0.1 Jy). From this sample of 57 we selected those which have 12 mm or 3 mm fluxes.

Recently, we completed a search for molecular absorption towards 11 DLAs at $\lambda \leq 3$ mm with the SEST 15-m and Onsala 20-m telescopes which, apart from one tentative detection, only lead to upper limits for 18 transitions (Curran et al. 2002a). With the upgraded ATCA it is now possible to improve on these previous attempts. In this paper we present the results of our first search with this telescope - observations towards the known southern centimetre-loud quasars occulted by DLAs in which a commonly detected transition falls into the 12 mm band.

2 **OBSERVATIONS**

The observations were performed in June 2002 with the ATCA at Narrabri, Australia during excellent weather conditions which gave good phase stability. The telescope has recently been upgraded with the addition of 12 mm and 3mm receivers to antennae 2, 3 and 4 (see Wong & Melatos 2002), thus permitting the search for redshifted molecular rotational lines with this instrument. As mentioned above, the 3 mm band has been used quite extensively in previous searches towards DLAs (Wiklind & Combes 1994b, 1995, 1996b; Curran et al. 2002a), although to date no 12 mm searches have been published. At this wavelength we are able to take advantage of the lower system temperature (≈ 60 K) and better atmospheric stability to observe towards the southern ($\delta \leq 30^{\circ}$) guasars of sufficient flux² occulted by

² Originally PKS 0336-017 was confused with Q 0336-019 (J 0339-017), which was then used as a calibrator for the source

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 $^{^1\,}$ A version of this catalogue is continually updated on-line and is available from http://www.phys.unsw.edu.au/~sjc/dla

Table 1. The 22 GHz illuminated DLAs where the redshifted HCO⁺ $0 \rightarrow 1$ falls into either the 16.089–18.888 or 20.089–22.488 GHz ATCA bands. z_{abs} is the DLA redshift and ν_{obs} is the expected frequency of the redshifted HCO⁺ $0 \rightarrow 1$ line, given to the number of significant figures available from the optical data. The red, visible and blue magnitudes of the quasar are given as well as the measured 22 GHz flux densities from both the literature (Lit.) and our observations (Obs.). Any difference between these two values may be due to quasar variability.

Source	Coordinates (J2000)		$z_{\rm abs}$	$\nu_{\rm obs}$	Magnitude			$\approx S_{22}$ (Jy)		Calibrator	$\approx S_{22}$ (Jy)	
	h m s	d ′ ″			В	V	R	$Lit.^a$	Obs.		Lit.	Obs.
0201+113	$02 \ 03 \ 46.7$	$11 \ 34 \ 44$	3.38639	20.331	21.7	19.5	18.8	0.55	0.59	0202 + 149	2.00	1.41
0336 - 017	$03 \ 39 \ 00.9$	-01 33 18	3.0619	21.958	19.5	18.8	19.1	-	0.15	0336 - 019	3.37	2.2
0537 - 286	$05 \ 39 \ 54.3$	$-28 \ 39 \ 56$	2.976	22.43	19.8	19.0	18.9	1.66	0.58	Self ca	libration	

^a The flux density for 0201+113 is from Teräsranta et al. (2001) and for 0202+149, 0336–019 and 0537–286 from the ATCA calibrators site (http://www.narrabri.atnf.csiro.au/calibrators/). The uncertainty of $\approx 15\%$ in these calibrators is the major contributor to the errors in the measured flux densities.

DLAs at redshifts of ~ 3 (Table 1)³. In order to minimize the bias introduced by using such optically selected sources, ideally we would have selected the most visually faint (and hence dusty) objects. However, the ATCA still has a relatively narrow tuning range in the 12 mm band. We therefore selected all of the "high flux" DLAs which can be observed with this restriction (see Table 1). Fortunately, all three are relatively faint (by DLA standards) with 0201+113 and 0537–286 also being red (B – R = 2.9 and 0.9, respectively).

Because of the lack of precision in the optical redshifts (most significant for 0537–286, Table 1), we sacrificed one polarisation in order to overlap two of the widest available (64 MHz) bands. This enabled us to cover an uncertainty of $\approx \pm 0.01$ in redshift while retaining a relatively high spectral resolution of 3.4 km s⁻¹. Finally, post observation, baseline 2–4 was discarded because of phase referencing problems. No other flagging of bad data was required. For 0201+113 and 0336–017 the bandpass of the calibrator was removed from the spectra and in the case of 0537–286, which was self calibrated, we removed a low order polynomial to "flatten" the bandpass.

3 RESULTS AND DISCUSSION

In Figs. 1 to 3 we show the time averaged spectra over both good baselines and note that there are no HCO⁺ 0 \rightarrow 1 absorption features of $\geq 3\sigma$ per 3.4 km s⁻¹ channel in these DLAs. From the r.m.s. noise levels we derive optical depth limits for a resolution of 1 km s⁻¹ and column density limits according to $N_{\rm mm} \propto \int \tau dv$ for an excitation temperature of ≈ 10 K (see Curran et al. 2002a). These are listed in Table 2 together with all previously published results.

From the table we see that, after 3–5 hours per source, our limits are among the lowest of all the searches and



Figure 1. HCO⁺ 0 \rightarrow 1 at $z = 3.386^{+0.013}_{-0.009}$ towards 0201+113. The 1 σ r.m.s. noise is 10 mJy. The overlap between the two spliced bands is 14 MHz. In this and Figs. 2 and 3 the arrow shows the expected absorption frequency according to the published DLA redshift (Table 1).

we achieve the most sensitive search for HCO⁺ absorption in a DLA published to date. However, there are uncertainties in the conversion ratio betweeen $N_{\rm HCO^+}$ and $N_{\rm CO}$ (and thus $N_{\rm H_2}$ which the CO traces⁴). The ratio typical of Galactic star forming clouds is $N_{\rm CO} \gtrsim 10^4 N_{\rm HCO^+}$ (e.g. Wiklind & Combes 1995), whereas that for Galactic absorbers towards extragalactic continuum sources⁵ is $N_{\rm CO} \sim 10^3 N_{\rm HCO^+}$ (Liszt & Lucas 1998). For high redshift clouds, $N_{\rm CO} > 10^3 N_{\rm HCO^+}$ (Wiklind & Combes 1995) or, more specifically, $N_{\rm CO} = 7500 N_{\rm HCO^+}$ for one of the 4 known absorbers (Section 1), the gravitational lens PKS 1830–211 (Menten et al. 1999). Therefore our results are of little use in assigning upper limits to the molecular hydrogen column

⁽Table 1). The measured 22 GHz flux density of $S_{22} = 0.15$ Jy now joins $S_{0.4} = 1.31$, $S_{1.4} = 0.60$, $S_{2.7} = 0.45$ and $S_{5.0} = 0.30$ Jy for the measured radio flux densities of 0336–017 (Curran et al. 2002b).

 $^{^3}$ HCO⁺ is the strongest and most commonly detected molecule in the four known high redshift molecular absorption systems (see Wiklind & Combes references). Note that no CO transitions fell into either of the two sub-bands at these redshifts.

⁴ Although molecular hydrogen constitutes the bulk of the molecular gas in interstellar space, it cannot be observed directly due to its small dipole moment and moment of inertia. Since CO is the next most abundant molecule after H_2 , this "tracer" is extremely useful in the study of the bulk ISM and is therefore the most studied molecule in external galaxies.

⁵ This applies in the regime in which we are interested, i.e. CO column densities of $N_{\rm CO} \lesssim 10^{15} {\rm ~cm^{-2}}$ (Table 2). Above this the CO begins self-shielding and subsequently $N_{\rm CO} > 10^3 N_{\rm HCO^+}$.

Table 2. Summary of published searches for rotational molecular absorption in DLAs. $\nu_{\rm obs}$ is the approximate observed frequency (GHz), V is the visual magnitude of the background quasar, $N_{\rm HI}$ (cm⁻²) is the DLA column density from the Lyman-alpha line and $\tau_{21 \rm \ cm}$ is the optical depth of the redshifted 21 cm H_I line (see Curran et al. 2002b). The optical depth of the relevant millimetre line is calculated from $\tau = -\ln(1 - 3\sigma_{\rm rms}/S_{\rm cont})$, where $\sigma_{\rm rms}$ is the r.m.s. noise level at a given resolution and $S_{\rm cont}$ is the continuum flux density. This is done for a resolution of $\Delta v = 1 \rm \ km\ s^{-1}$ ($\tau_{\rm nm}$), where we quote only the best existing limit. Note that due to simultaneous flux measurements with the ATCA, unlike many of the other results given, we minimize errors due to variable fluxes (see Table 1). For all optical depths, 3σ upper limits are quoted and "–" designates where $3\sigma > S_{\rm cont}$, thus not giving a meaningful value for this limit. Blanks in the $\tau_{21 \rm \ cm}$ field signify that there are no published H_I absorption data for these DLAs. The penultimate column gives the best existing limit of the column density per unit line-width (not to be confused with Δv) estimated for the transition [cm⁻²(km s⁻¹)⁻¹].

DLA	$z_{\rm abs}$	Transition	$\nu_{\rm obs}$	V	$N_{\rm HI}$	$ au_{21~\mathrm{cm}}$	$ au_{ m mm}$	$N_{ m mm}/dv$	Ref.
0201+113	3.38639	$\rm HCO^+ \ 0 \rightarrow 1$	20.3	19.5	2×10^{21}	0.04 - 0.09	< 0.1	$< 9 \times 10^{11}$	7
0235 + 1624	0.52400	CO $0 \rightarrow 1$	75.6	15.5	4×10^{21}	0.05 - 0.5	< 0.06	$< 4 \times 10^{14}$	2
	0.52398	CO $1 \rightarrow 2$	151.3				< 0.09	$< 6 \times 10^{15}$	4
		$\rm HCO^+ \ 3 \rightarrow 4$	234.1				< 0.3	$< 4 imes 10^{12}$	4
	0.523869	CS $2 \rightarrow 3$	96.4				< 0.9	$< 1 \times 10^{13}$	6
0248 + 430	0.3939	CS $2 \rightarrow 3$	105.4	17.7	$4 imes 10^{21}$	0.20	_	-	6
0336 - 017	3.0619	$\rm HCO^+ \ 0 \rightarrow 1$	22.0	18.8	2×10^{21}	< 0.005	< 0.2	$< 2 \times 10^{12}$	7
0458 - 020	2.0397	HCO ⁺ $2 \rightarrow 3$	88.0	18.4	$5 imes 10^{21}$	0.30	< 2	$< 8 imes 10^{12}$	5
	2.0399		88.0				< 0.4	$< 1 \times 10^{12}$	6
	2.0397	$CO \ 2 \rightarrow 3$	113.8				_	-	3
	2.0399	$\mathrm{CO}~3 \to 4$	151.7				< 1	$< 2 \times 10^{16}$	6
0528 - 2505	2.1408	$CO \ 2 \rightarrow 3$	110.1	19.0	4×10^{20}	< 0.2	No published 3 mm fluxes		3
0537 - 286	2.974	$\rm HCO^+~0 \rightarrow 1$	22.4	19.0	$2 imes 10^{20}$		< 0.08	$< 7 \times 10^{11}$	7
0738 + 313	0.2212	$CO \ 0 \rightarrow 1$	94.4	16.1	2×10^{21}	0.07	_	$< 4 \times 10^{15}$	6
0827 + 243	0.5247	CS $2 \rightarrow 3$	96.4	17.3	2×10^{20}	0.007	< 0.4	$< 1 imes 10^{13}$	6
	0.52476	$CO \ 0 \rightarrow 1$	75.6				< 0.2	$< 1 imes 10^{15}$	8
08279 + 5255	2.97364	$\rm HCO^+ \ 0 \rightarrow 1$	44.9	15.2	1×10^{20}		No published 7 mm fluxes		6
		$CO \ 2 \rightarrow 3$	87.0				No published 7 or 3 mm fluxes		6
0834 - 201	1.715	$\rm HCO^+\ 2 \rightarrow 3$	98.6	18.5	3×10^{20}		< 0.4	$< 2 \times 10^{12}$	5
		$\rm HCO^+ \ 3 \rightarrow 4$	131.4				< 0.6	$< 8 imes 10^{12}$	5
		$\mathrm{CO}~3 \to 4$	169.8				_	-	6
1017 + 1055	2.380	CS $2 \rightarrow 3$	43.5	17.2	$8 imes 10^{19}$		No published 7 mm fluxes		6
		$CO \ 2 \rightarrow 3$	102.3				No published 3 mm fluxes		6
1215 + 333	1.9984	$\mathrm{CO}~2 \to 3$	115.3	18.1	1×10^{21}		_	_	3
1229 - 0207	0.3950	CO $0 \rightarrow 1$	82.6	16.8	1×10^{21}		< 1	$< 6 imes 10^{15}$	6
		CO $1 \rightarrow 2$	165.3				_	-	6
	0.39498	CO $1 \rightarrow 2$	165.3				_	-	4
1328 + 307	0.69215	$\rm HCO^+ \ 1 \rightarrow 2$	105.4	17.3	2×10^{21}	0.11	< 0.7	$< 2 \times 10^{12}$	4
		CS $2 \rightarrow 3$	86.9				< 2	$< 4 imes 10^{13}$	6
		CO $1 \rightarrow 2$	136.2				< 1	$< 3 \times 10^{15}$	4
		$CO \ 2 \rightarrow 3$	204.4				_	—	4
1331 + 170	1.7764	${\rm CO}~0 \rightarrow 1$	41.5	16.7	$3 imes 10^{21}$	0.02	_	-	1
	1.7755		41.5				_	-	1
1451 - 375	0.2761	$\rm HCO^+ \ 1 \rightarrow 2$	139.8	16.7	1×10^{20}	< 0.006	< 0.6	$< 2 imes 10^{12}$	6
		CO $0 \rightarrow 1$	90.3				< 0.3	$< 2 \times 10^{15}$	6
2136 + 141	2.1346	HCO ⁺ $2 \rightarrow 3$	85.4	18.9	$6 imes 10^{19}$		< 0.3	$<1\times 10^{12}$	5
		$\mathrm{CO}\ 2 \to 3$	110.3				< 0.6	$< 4 \times 10^{15}$	5
		${\rm CO}~3 \to 4$	147.1				< 0.8	$< 2 imes 10^{16}$	5
		${\rm CO}~5 \to 6$	220.6				-	-	4

References: (1) Takahara et al. (1984); (2) Takahara et al. (1987); (3) Wiklind & Combes (1994a); (4) Wiklind & Combes (1995); (5) Wiklind & Combes (1996b); (6) Curran et al. (2002a); (7) This paper; (8) A. Bolatto (private communication)

density, $N_{\rm H_2}$. In order to bypass this uncertainty, we use the best $N_{\rm CO}$ limit (from Table 2), to estimate an upper limit, though we are still forced to assign an expected line-width to a non-detected feature. For three of the four known high redshift absorbers this is $\approx 20 \text{ km s}^{-1}$ (the FWHM being $\approx 7 \text{ km s}^{-1}$ towards PKS 1413+135⁶, Wiklind & Combes 1994a, 1995, 1996b, 1998). Also, as discussed in Curran et al. (2002a), where non-detections are concerned the spectral resolution of the data have to be taken into account since these determine the r.m.s. noise and thus the values of τ (Table 2).

Nevertheless, using the best available optical depth limit (CO 0 \rightarrow 1 towards 0235+1624, Table 2) gives $N_{\rm CO} \lesssim$ 7×10^{15} cm⁻² for a 20 km s⁻¹ line detected at a resolution of 1 km s⁻¹. This becomes $N_{\rm CO} \lesssim 3 \times 10^{15}$ cm⁻² for the same (barely resolved) line at 10 km s⁻¹ resolution. So for $N_{\rm H_2} \sim 10^4 N_{\rm CO}$ (e.g. Wiklind & Combes 1995), and assum-



Figure 2. HCO⁺ $0 \rightarrow 1$ at $z = 3.062 \stackrel{+0.011}{_{-0.007}}$ towards 0336–017. The 1σ r.m.s. noise is 6 mJy. The overlap between the two spliced bands is 12 MHz.



Figure 3. HCO⁺ 0 \rightarrow 1 at $z = 2.976 \stackrel{+0.010}{_{-0.004}}$ towards 0537–286. The 1 σ r.m.s. noise is 8 mJy. The gap in the spectrum occurs since there was no bandpass calibration and the fitted polynomial is unreliable at these frequencies.

ing that molecular absorption lines have a FWHM of $\lesssim 20$ km s⁻¹, we can assert that $N_{\rm H_2} \lesssim 1\% N_{\rm HI}$ for the DLAs deeply searched for rotational molecular absorption⁷.

For high redshift (z > 1.8) sources, the ultra-violet H₂ lines are redshifted to optical wavelengths and indeed H₂ has been found in absorption in 7 DLAs at $N_{\rm H_2}/N_{\rm HI}$ ratios of $\leq 1\%$ (Ge & Bechtold 1997; Srianand & Petitjean 1998; Levshakov et al. 2000; Petitjean et al. 2000; Levshakov et al. 2002; Ledoux et al. 2002). In the low metallicity environments typical of DLAs ([Zn/H] ≈ -2 to -1, i.e. ~ 0.01 to 0.1 solar, e.g. Prochaska et al. 2001), Liszt (2002) argues that even if the gas is cool, the ambient ionization is sufficient to suppress the formation of H₂. This may offer a potential explanation for our non-detections.

The under-abundance of heavier elements introduces another uncertainty: the application of Galactic CO-to-H₂ conversion ratios. Black et al. (1987) and Chaffee et al. (1988) suggest that the photoionization of carbon would reduce the ratio of $N_{\rm H_2}$ to $N_{\rm CO}$ to a tenth of Galactic values and, from an upper limit of $N_{\rm CO}$ from the A–X molecular bands, Srianand & Petitjean (1998) find $N_{\rm CO}/N_{\rm HI} < 10^{-8}$ in DLAs, which is indeed only 10% of the local ratio. In addition, at earlier epochs of chemical enrichment we would expect that there is simply a lack of raw materials to form significant amounts of tracer molecules (e.g. CO, HCO⁺, HCN and CS) even in cold dark clouds where H₂ readily forms. A reliable conversion ratio could be obtained by searching for CO absorption towards the DLAs in which H₂ has been detected. However, the detection of H₂ biases towards optically bright sources and hence an under-abundance of dust. Furthermore, none of the quasars illuminating the 7 known H₂ absorbing DLAs have appreciable 12 or 3 mm fluxes (Curran et al., in preparation).

In summary, not only do the low metallicities reduce the molecular hydrogen content in DLAs, but they may also further lower the column densities of other molecular tracers, making the detection of these much more difficult than expected. It is clear that further statistics are required in order to identify the factors most crucial (e.g. column density, visual magnitude or metallicity) in determining the molecular content of DLAs. It would be of interest to compare the metallicities of the four known molecular absorbers, especially in the highest redshift case ($z_{abs} = 0.886$, Wiklind & Combes 1998). However, these lie along the lines-of-sight to quasars which, although bright in the millimetre regime, are too optically dim (V> 20 in all cases) to estimate the metal-to-hydrogen ratio.

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 $^{^7\,}$ Note that the $N_{\rm H_2}/N_{\rm CO}$ ratio may exceed 10⁵ (Liszt & Lucas 1998) which could increase this value to $\stackrel{<}{_\sim}$ 10%.

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