Relationships between the H\textsc{i} 21-cm line strength, Mg \textsc{ii} equivalent width and metallicity in damped Lyman-\textalpha absorption systems

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ABSTRACT

We present the results of a survey for 21-cm absorption in four never previously searched damped Lyman-\textalpha absorption systems (DLAs) with the Westerbork Synthesis Radio Telescope. The one detection is presented and discussed in Curran et al. (2007b) and here we add our results to other recent studies in order to address the important issues regarding the detection of cold gas, through 21-cm absorption, in DLAs: Although, due to the DLAs identified with spiral galaxies, there is a mix of spin temperature/covering factor ratios at low redshift, two recent high redshift end points (Kanekar et al. 2006, 2007) confirm that this ratio does not generally rise much above $T_{\text{spin}}/f \sim 10^3$ K over the whole redshift range searched (up to $z_{\text{abs}} = 3.39$). That is, if the covering factors of many of these galaxies were a factor of $\geq 2$ smaller than for the spirals (which span $120 \leq T_{\text{spin}}/f \leq 520$ K), then no significant difference in the spin temperatures between these two classes would be required.

Furthermore, although it is difficult to separate the relative contributions of the spin temperature and covering factor, the new results confirm that 21-cm detections tend to occur at low angular diameter distances, where the coverage of a given absorption cross section is maximised. This indicates a dominant contribution by the covering factor. Indeed, the two new high redshift detections occur towards two extremely compact radio sources ($\leq 0.04 \arcsec$), although the one other new detection, which may have an impact parameter in excess of $75 \text{ kpc}$, occurs towards one of the largest radio sources (Curran et al. 2007b).

Finally, we also find an apparent 21-cm line strength–Mg \textsc{ii} equivalent width correlation, which appears to be due to a coupling of the velocity structure between the components that each species traces. That is, the gas seen in 21-cm absorption could be the same as that seen in optical absorption. Combined with the known equivalent width–metallicity relation, this may be manifest as a spin temperature–metallicity anti-correlation, which is non-evolutionary in origin.

Key words: quasars: absorption lines -- cosmology: observations -- cosmology: early Universe -- galaxies: ISM

1 INTRODUCTION

Although currently relatively rare\textsuperscript{1}, redshifted absorption systems lying along the sight-lines to distant quasars are important probes of the early to present day Universe. Of particular interest are damped Lyman-\alpha absorption systems (DLAs), which contain at least 80\% of the neutral gas mass density in the Universe (Prochaska et al. 2005).

DLAs are believed to be the precursors of modern-day galaxies and studies over a range of redshifts are important to establish the link between the early stages of galaxy formation and the galaxies known in detail today. However, despite their importance in the context of galactic evolution, the typical size and structure of DLAs has long been an issue of much controversy, with models ranging from large, rapidly rotating protodisks (e.g. Prochaska & Wolfe 1997) to small, merging sub-galactic systems (e.g. Haehnelt et al. 1998). Moreover, imaging of DLA host galaxies at $z \lesssim 1.6$ (where the galaxy can be distinguished against the point spread function of the background QSO), reveals a mixed bag of spiral, irregular, low surface brightness (LSB) and dwarf galaxies (e.g. Bergeron & Boissé 1991; Le Brun et al. 1997; Chen & Lanzetta 2003; Rao et al. 2003). This variety being confirmed by a blind 21-cm emission survey of local galaxies (Ryan-Weber et al. 2003).

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\textsuperscript{1} See table 3 of Curran et al. (2006).
Whatever their morphologies, the high abundance of cold neutral gas in DLAs is expected to provide a reservoir for star formation at high redshift. However, abundances of (the star forming) molecular gas in DLAs are exceedingly low, H$_2$ only being detected in a very few cases (Levshakov and Varshalovich 1985; Levshakov et al. 2000; Levshakov et al. 2002; Ge et al. 2001; Ledoux et al. 2002, 2003, 2004; Petitjean et al. 2002, 2006; Lopez & Ellison 2003; Reimers et al. 2003; Cui et al. 2003; Noterdaeme et al. 2007), which calls into question the ability of DLAs to contribute significant star formation activity to the earlier Universe (Ledoux et al. 2003). Despite this, DLAs exhibit a weak evolution of elemental abundance with redshift (Pettini et al. 2001; Ledoux et al. 2002, 2003, 2006; Petitjean et al. 2002, 2006; Prochaska et al. 2003), which would be expected from the enrichment of the interstellar medium in each galaxy by successive generations of stars. Additionally, for the H$_2$-bearing DLAs, the molecular fraction also exhibits an anti-correlation with redshift, and the fact that the metallicity evolution is significantly steeper for these DLAs may suggest that these actually constitute a narrower class of objects (or sight-lines) than the general DLA population (Curran et al. 2004). Furthermore, the decrease of molecular fraction with look-back time indicates an evolution in the dust abundance, which is also evident through a decrease in the dust depletion factor with redshift in the H$_2$-bearing DLAs (Murphy et al. 2004).

Where the DLA occults a radio-loud QSO, the 21-cm transition can provide complementary data to that obtained from the ultra-violet Lyman-α observations (which are redshifted into the optical band at $z \gtrsim 1.7$). The former transition traces the cold gas, whereas the latter traces all of the neutral gas, thus providing a potential thermometer of the absorber. Provided that the 21-cm and Lyman-α absorption arise in the same cloud complexes, the spin temperature, $T_{\text{spin}}$ [K], of a homogeneous cloud can be derived from the column density, $N_{\text{HI}}$ [cm$^{-2}$], obtained from the Lyman-α, via

$$
N_{\text{HI}} = 1.823 \times 10^{18} T_{\text{spin}} \int \tau \, dv,
$$

where $\int \tau \, dv$ is the integrated optical depth of the 21-cm line. However, obtaining the spin temperature from a 21-cm observation is not quite so straightforward, since the observed optical depth of the 21-cm line also depends upon on how effectively the background radio continuum is covered by the absorber. Specifically, $\tau \equiv -\ln (1 - \frac{f}{\sigma})$, where $\sigma/S$ is the depth of the line relative to the flux density and $f$ is the covering factor of the flux by the absorber.

Of the DLAs searched (and published) in 21-cm absorption, there is currently a detection rate of slightly less than 50%. Most of these occur at $z_{\text{abs}} \lesssim 2$, where there is a roughly equal number of non-detections. Chengalur & Kanekar (2000; Kanekar & Chengalur 2001, 2003) attribute this distribution to the low redshift DLAs having a mix of spin temperatures, whereas the high redshift absorbers have exclusively high spin temperatures, resulting in the large number of non-detections at high redshift (note then detected at $z_{\text{abs}} > 2.04$). Since all of the DLAs identified as large spirals have low spin temperatures, whereas those identified with LSBs and dwarf galaxies, have higher spin temperatures, Kanekar & Chengalur (2003) conclude that the DLA host population consists mainly of the warmer dwarfs and LSBs at high redshift, which evolves to include a higher proportion of spirals at low redshift. However, there are several caveats regarding this conclusion:

(i) Although Kanekar & Chengalur (2003) have undertaken a careful analysis in order to obtain the most likely covering factors, estimating this from the flux of the compact unresolved component to the total flux of the quasar or by examining the quasar’s spectral energy distribution, none of these methods provides any information on the size of the absorbing region.

(ii) When such information is unavailable, more often than not in the literature the covering factor is usually assumed to have its maximum value of unity (notable exceptions are Brown & Roberts 1973; Wolfe et al. 1984; Briggs & Wolfe 1983; Wolfe et al. 1985; Carilli et al. 1992; Lane et al. 2004). In the case of Kanekar & Chengalur (2003), half of the 12 detections have $f < 1$ and half $f = 1$, whereas for the non-detections, 10 out of 11 have $f < 1$, the vast majority of which (8) are at $z_{\text{abs}} > 1$ (see figure 1 of Curran et al. 2003).

(iii) If the $T_{\text{spin}}/f$ degeneracy is left intact, there still remains a mix of values at low redshift, with exclusively high values at high redshift (figure 5 of Curran et al. 2003). However, of the non-detections only one morphology is actually known (see Fig. 5, and although, due to their high “spin temperatures”, it is tempting to count these as non-spirals, this is not actually known. In fact, there are no host identifications at $z_{\text{abs}} \gtrsim 0.9$.

(iv) Furthermore, figure 3 (Kanekar & Chengalur 2003) suggests that at $z_{\text{abs}} \gtrsim 3$ spin temperatures in DLAs are expected to exceed $\sim 2000$ K, with half of these $\gtrsim 3000$ K, rendering these very difficult to detect. However, since then, 21-cm absorption has been detected at $z_{\text{abs}} = 3.39$ towards 0201+113 (Kanekar et al. 2007) at a spin temperature of $T_{\text{spin}} \lesssim 1950$ K (for $f < 1$), when this was previously believed to have $T_{\text{spin}} > 3300$ K (Kanekar & Chengalur 2003).

Additionally:

(v) Curran et al. (2003) find that $\approx 70$ per cent of the non-detections occult large background ($\gtrsim 1$ arc-sec) sources and that 21-cm absorption tends to be detected towards these large sources only when the DLA host has been identified as a spiral.

(vi) Again, although for the non-detections the morphologies are essentially unknown, lower covering factors, resulting in non-detections at high redshift, would also be consistent with hierarchical galaxy formation scenarios, where compact galaxies at high redshift evolve to include a higher proportion of larger galaxies in the more immediate Universe.

(vii) Most recently, Curran & Webb (2006) find that all of the $z_{\text{abs}} \gtrsim 1$ absorbers have large DLA-to-QSO angular diameter distance ratios ($D_{\text{DLA}}/D_{\text{QSO}} \approx 1$), whereas the $z_{\text{abs}} \lesssim 1$ absorbers have a mix of ratios. Thus reproducing the “spin temperature” segregation of Kanekar & Chengalur (2003) through geometrical effects alone. Since the DLAs with low ratios are almost always detected in 21-cm absorption, this and the other points suggest that the covering factor, rather than the spin temperature (which could range from 170 to $> 9240$ K, Kanekar & Chengalur 2003), is the important criterion in determining whether 21-cm absorption is detected in a DLA.

We therefore expect 21-cm absorption to be readily detectable.
in DLAs located along the sight-lines towards compact radio sources. In order to further address this, as well as finding new sources in which to pursue our primary objective, the measurement of cosmological variations in the fundamental constants at large look-back times (e.g. Tzanavaris et al. 2007), we are undertaking a survey for H\text{I} 21-cm absorption in the suitably radio-illuminated DLAs yet to be searched: In Section 2 we present the results of the first phase of this survey, observations of both low and high redshift DLAs with the Westerbork Synthesis Radio Telescope (WSRT). In Section 3 we discuss these and the other new results (since Curran et al. 2005) in the context of factors affecting the detectability of 21-cm in DLAs, as well as investigating correlations between the 21-cm line strength, Mg\text{II} equivalent width and metallicity in these absorbers.

2 OBSERVATIONS AND RESULTS

2.1 Sample Selection

The DLAs were selected from the Sloan Digital Sky Survey Damped Lyman-\alpha Survey Data Release 1 (Prochaska & Herbert-Fort 2004) and the known systems also occulting radio-loud quasars ($S \gtrsim 0.1$ Jy) as yet unsearched (Curran et al. 2002). Of those redshifted into the WSRT’s Ultra High Frequency (UHF) receiver bands, we selected an initial sample which gave a mix of low and high redshifts in order to test the arguments presented above. Since we require deep observations in order to, at the very least, obtain useful limits, each absorber was observed for 12.5 hours, which limited the number of sources to four, although a further two candidate sub-DLAs were also observed along the line-of-sight to 1402+044 (Table 1). With two DLAs each at $z_{abs} < 1$ and $z_{abs} > 2$, we prioritised according to highest neutral hydrogen column density, the largest background radio flux ($> 1$ Jy) and the most compact background source size, in order to maximise the covering factor. Unfortunately, this sample, prioritised by the first two criteria, gave a range of values for the radio source size ($\theta_{\text{QSO}} \approx 15''$), see Table 1, none of which are especially compact. However, in order to shed light on the above arguments, DLAs occulting all radio source sizes should be searched. Furthermore, at the time of application, the DLA at $z_{abs} = 0.6561$ towards 1622+238 was believed to be due to a spiral galaxy (Chen et al. 1998, although see Curran et al. 2007b) and the background radio source size of 15.3$''$ is similar to that of the other spirals detected in 21-cm absorption (Curran et al. 2005 and references therein).

2.2 Observations, Data Reduction and Results

All of the observations were performed in June and July of 2006 with the Westerbork Synthesis Radio Telescope in the Netherlands. To cover the redshifted 21-cm line, the UHF and 92-cm receivers were backed by a band-width of 5 MHz over 2048 channels (dual polarisation), giving channel spacings of 0.85 to 1.9 km s$^{-1}$ (for $z_{abs} = 0.66$ to 2.7). This ensured that the observations not only covered uncertainties in the optical redshifts, but gave a fine enough resolution to avoid resolving out any possibly narrow absorption lines; the full-width half maxima (FWHMs) range from 4 to 53 km s$^{-1}$ for the DLAs already detected in 21-cm (see Curran et al. 2005). The two orthogonal polarisations (XX & YY) were used in order to allow the removal of any polarisation dependent radio frequency interference (RFI). Upon the removal of this, the polarisations were combined in order to maximise the signal-to-noise ratio. For all of the observations, the quasars 3C48, 3C147 and 3C286 were used for bandpass and flux calibration. The data were reduced using the MIRIAD interferometry reduction package, with which we extracted a summed spectrum from the emission region of the continuum maps.

2.2.1 0149+336

0149+336 was observed in 29 × 0.42 hour slots on 25 June 2006, with the UHF-low receiver. However, in this band the RFI was severe, particularly in the XX polarisation. Upon flagging this and the worst affected channels out of the YY data, RFI still dominated on each baseline at all time intervals and the remaining data were of too poor a quality to obtain an image (Fig. 1).

2.2.2 0809+483

After realising that 0149+336 was mistakenly observed in 10 second integrations, we switched to the default 60 seconds, making each slot 2.5 hours long, for which 0809+483 and the other remaining sources were observed for 5 slots. 0809+483 (3C 196) was observed on 2 July 2006, with the UHF-high receiver. Severe RFI in this band (783.8 to 788.2 MHz) meant that one of the slots had to be removed completely. Furthermore, for all of the slots, the XX polarisation had to be completely flagged from the baselines involving antenna 3, leaving 76 full and partial (XX or YY) baseline pairs, over a total observing time of 7.5 hours, after the flagging of further time dependent RFI. The source was unresolved by the $60'' \times 39''$ beam and the final extracted spectrum is shown in Fig. 2.

2.2.3 1402+044

1402+044 was observed on 1 July 2006 with the 92-cm receiver. Although the strongest absorber towards this quasar would exhibit 21-cm absorption at $\approx 383.06$ MHz, the central frequency was offset from this (as shown in Fig. 3) in order to also cover the other two absorbers in this band (see Table 1). The observations were...
RFI free, except the last 2.5 hour slot, which was rejected along with the calibrator used after the run, 3C 48. This left 9.3 hours of good data and the RFI-free observations of 3C 286 were used for the bandpass and flux calibration. Thanks to the low degree of interference in this band, 91 full baseline pairs could be used. The source was unresolved by the 708′′ × 72′′ beam.

All but one of the features in the extracted spectrum (Fig. 3) were noted to be due to RFI during the reduction process and occurred in one polarisation only. The exception is the “absorption feature” closest to $v = 0 \text{ km s}^{-1}$ (Fig. 3) and thus the only confirmed DLA (with $N_{\text{HI}} = 8 \times 10^{20} \text{ cm}^{-2}$, Table 1). This feature was present in both polarisations, each of which can be fitted by similar Gaussians, giving $\Delta v = -90.2 \pm 89.3 \text{ km s}^{-1}$ and FWHMs of $12.7 \pm 11.2 \text{ km s}^{-1}$ for the XX and YY polarisations, respectively. These values agree to less than one channel width and give a redshift of $2.707$, cf. the quoted DLA value of $z_{\text{abs}} = 2.708$ (Prochaska & Herbert-Fort 2004). $z_{\text{abs}} = 2.7069 \pm 0.0003$ (Si II, 1526 Å) and $z_{\text{abs}} = 2.7072 \pm 0.0003$ (Al II, 1670 Å), from the Sloan Digital Sky Survey. However, the fact that the depth of the feature differs significantly between each polarisation ($-0.26 \text{ Jy in XX \& } -0.13 \text{ Jy in YY}$), as well as these features also appearing at other locations in the image remote from the continuum source, forces us to conclude that this absorption feature is an artifact.

### 2.2.4 1622+238

1622+238 (3C 336) was observed on 9–10 July 2006 with the UHF-high receiver. After flagging of time dependent RFI, 12.0 hours of good data remained, although there was some RFI remaining on some baselines, particularly in the XX polarisation. After further flagging, 63 full and partial pairs remained, resulting in a detection (Fig. 3). Further details are given in Curran et al. (2007b), where this detection is reported and discussed.

### 3 DISCUSSION

#### 3.1 These and other recent results

In Table 1 we present our observations and derived results. In the optically thin regime $(\sigma / f.S \lesssim 0.3)$, Equation 1 reduces to $N_{\text{HI}} = 1.823 \times 10^{18} \frac{T_{\text{spin}}}{f} \int \frac{S}{v} dv$, thus giving a direct measure of the spin temperature of the gas for a known column density and covering factor. However, as recalled in the introduction, in the absence of any direct measurement of the size of the radio absorbing region, this latter value cannot be determined. Therefore in Table 1 we quote our derived results in terms of $T_{\text{spin}}/f$.

In Fig. 3 we add these and the other recent results to the $T_{\text{spin}}/f$–redshift distribution of Curran et al. (2008). Like Kanekar & Chengalur (2003), for the detections we see that at low redshift we have a mix of ratios (cf. spin temperatures) and at high redshift exclusively high values, although not segregated to the extent seen in figure 3 of Kanekar & Chengalur (2003). We also see that the low values are dominated by the identified spirals, although by no means does this irrefutably indicate that the lower redshifts do indeed have a mix of spin temperatures: If the larger spirals have larger covering factors than the dwarfs and LSBs, then the spin temperatures of these non-spirals would be correspondingly lower.
As stated, however, in view of the uncertainty in determining the covering factor and spin temperature, we prefer to retain the degeneracy. Through the two new high redshift end points (Kanekar et al. 2005; 2007), which nearly double the number of detections at \( z_{\text{abs}} > 1 \), it appears as though \( T_{\text{spin}}/f \) does not increase indefinitely with redshift. This supports our previous hypothesis that 21-cm absorption should be readily detectable towards compact radio sources at \( z_{\text{abs}} \gtrsim 2 \) (Curran et al. 2005). Since \( f \lesssim 1 \), the ordinate values in Fig. 5 can be considered as the maximum permissible values of \( T_{\text{spin}}/f \), and so the very high spin temperatures at \( z_{\text{abs}} \gtrsim 3 \) (Kanekar & Chengalur 2003) are not seen. Ironically, the largest \( T_{\text{spin}}/f \) value (10,000 K) is obtained in one of the lowest redshift DLAs of the sample, at \( z_{\text{abs}} = 0.238 \) towards 0952+179.

3.2 The detection of 21-cm absorption

3.2.1 Radio source sizes

If \( T_{\text{spin}}/f \) generally levels off at high redshift, as suggested by Fig. 5, we reiterate that 21-cm absorption should be readily detectable (especially towards compact radio sources, thus maximising \( f \)). In Table 4 we show the sizes of the background continuum sources, as obtained from the highest resolution radio images available, closest in frequency to the redshifted 21-cm values. From this, we see that the two new high redshift end points (0201+113 & 0438–436) occur towards the most compact background radio sources (which are also compact in comparison to all of the DLAs searched, Table 2 of Curran et al. 2005). This may indicate that the spin temperatures in these two DLAs, whose host types are unidentified, are indeed higher than in the low redshift spirals, although still \( \lesssim 2000 \) K. However, in the absence of any knowledge of the absorption cross section, this is still inconclusive.

Apart from these two new high redshift examples, the radio source sizes do not reveal much, with a very similar range of values between the detections and non-detections. While the only two significantly smaller radio sources illuminate DLAs de-

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**Table 1.** Our search results. \( z_{\text{abs}} \) is the redshift of the DLA with the optical identification (ID) given: S–spiral (Chen et al. 1998), U–unknown. \( z_{\text{em}} \) is the redshift of the background QSO, \( S \) is the flux density at the observed frequency, \( \nu_{\text{obs}} \), \( S_{\text{HI}} \) is the peak flux of the line and \( \Delta \nu \) is the channel width of the observations. Since the measured r.m.s. noise is dependent upon the spectral resolution, as per (Curran et al. 2005), for the non-detections the 3σ upper limits of \( \tau_{\text{peak}} \) at a velocity resolution of 3 km s\(^{-1}\) are quoted, since this is a fairly typical resolution for the previous and new (Gupta et al. 2005) searches. The total neutral hydrogen column density, \( N_{\text{HI}} \) (cm\(^{-2}\)), is given with the corresponding reference, which yields the quoted spin temperature/covering factor ratio. In the case of the non-detections, like Curran et al. (2005), we assume a FWHM of 20 km s\(^{-1}\) for the line width (the mean value of the detections, excluding 1622+238).

| QSO | \( z_{\text{abs}} \) | ID | \( z_{\text{em}} \) | \( \nu_{\text{obs}} \) [MHz] | \( S \) [Jy] | \( S_{\text{HI}} \) [mJy] | \( \Delta \nu \) [km s\(^{-1}\)] | \( \tau_{\text{peak}} \) | \( \log_{10} N_{\text{HI}} \) | Ref. | \( T_{\text{spin}}/f \) [K] |
|-----|----------------|----|----------------|----------------|--------|----------------|----------------|----------------|----------------|------|-------------------|
| 0149+336 | 2.1413 | U | 2.431 | 452.17 | – | – | 1.6 | 20.6 | 1.2 | – | – |
| 0809+483 | 0.80787 | U | 0.871 | 785.68 | 20.5 | < 110 | 0.93 | < 0.0090 | > 20.3 | 3 | > 600 |
| 1402+044 | 2.688 \(^b\) | U | 3.215 | 385.14 | 1.12 | < 32 | 1.9 | < 0.068 | – | 2 | – |
| ... | 2.708 | U | ... | 383.07 | ... | ... | ... | ... | ... | ... | 20.9 | 4 | > 300 |
| ... | 2.713 \(^b\) | U | ... | 382.55 | ... | ... | ... | ... | ... | ... | – | 2 | – |
| 1622+238 \(^c\) | 0.6561 | S | 0.927 | 857.68 | 3.55 | 31 | 0.85 | 0.0088 | 20.4 | 5 | 60 |

Notes: \(^a\) \( 3C \) 196 (candidate DLA at \( z_{\text{abs}} = 0.808 \)); \(^b\) candidate sub-DLAs (Turnshek et al. 1989), although possibly due to blends of narrower features (figure 3 of Wolfe et al. 1986); \(^c\) \( 3C \) 336. References: (1) Wolfe et al. (1996); (2) Turnshek et al. (1989); (3) Le Brun et al. (1998); (4) Prochaska & Herbert-Fort (2004); (5) Rao & Turnshek (2000).

**Table 2.** Summary of the new (since Curran et al. 2005) 21-cm absorption searches in DLAs (\( N_{\text{HI}} \gtrsim 2 \times 10^{20} \) cm\(^{-2}\)) and sub-DLAs (\( N_{\text{HI}} < 2 \times 10^{20} \) cm\(^{-2}\)). In the top panel we list the detections and in the bottom panel the non-detections (quoted as 3σ).

| Reference | No. | \( z_{\text{abs}} \) | \( z_{\text{cm}} \) | \( N_{\text{HI}} \) [cm\(^{-2}\)] | \( T_{\text{spin}}/f \) [K] |
|-----------|-----|----------------|----------------|----------------|-------------------|
| Previous detections \(^a\) | 15 | 0.09–2.04 | 0.64–2.85 | 0.2 – 6 × 10\(^{21}\) | 100 – 10,000 |
| Kanekar et al. (2006) | 1 | 2.347 | 2.852 | 6 × 10\(^{20}\) | 1500 |
| Gupta et al. (2007) \(^b\) | 3 | 1.17–1.37 | 1.37–1.64 | 0.4 – 2 × 10\(^{19}\). \( (T_{\text{spin}}/f) \) | unknown |
| Kanekar et al. (2007) \(^c\) | 1 | 3.386 | 3.610 | 2.5 × 10\(^{21}\) | 1600 |
| This paper | 1 | 0.6561 | 0.927 | 2.3 × 10\(^{20}\) | 60 |
| Previous non-detections \(^a\) | 16 | 0.10–3.18 | 0.31–3.61 | 0.1 – 3 × 10\(^{21}\) | > 200 – > 6000 |
| Gupta et al. (2007) \(^b\) | 6 | 1.31–1.45 | 1.40–2.17 | < 2 – 4 × 10\(^{17}\). \( (T_{\text{spin}}/f) \) | unknown |
| Srianand et al. (2007) | 1 | 1.365 | 2.22 | 2 × 10\(^{19}\) | > 900 |
| This paper | 2 | 0.81–2.71 | 0.87–3.22 | > 2 – 8 × 10\(^{20}\) | > 300 – > 600 |

Notes: \(^a\) See Kanekar & Chengalur (2003); Curran et al. (2007) for full details. Note that 0438–436 has now graduated from a non to a detection (Kanekar et al. 2004). \(^b\) DLA candidates only and so neutral hydrogen column densities are unavailable, hence the upper limits in \( N_{\text{HI}} \) for the non-detections. Note that the sub-DLA 0237–223 is common to both Gupta et al. (2007) and Srianand et al. (2007). \(^c\) We quote the most recent result as this was previously detected by de Bruyn et al. (1996); Briggs et al. (1997).
Figure 5. The spin temperature/covering factor ratio versus the absorption redshift for the DLAs searched in 21-cm absorption. The symbols represent the 21-cm detections and the shapes represent the type of galaxy with which the DLA is associated: circle–unknown type, star–spiral, square–dwarf, triangle–LSB. The arrows show the lower limits and all of these bar one (0454+039 at $z_{\text{abs}} = 0.8596$) have unknown host identifications (our values are shown in red, Table 1). The unfilled symbols show the new detections since Curran et al. (2005), from which the figure is updated: The two new high redshift detections of Kanekar et al. (2004, 2007) and the possible spiral towards 1622+238 (Curran et al. 2007b).

Table 3. The radio source sizes, $\theta_{\text{QSO}}$ [arc-sec] at $\nu_0$ [GHz], of the QSOs illuminating the recent DLAs searched (Table 1).

| QSO       | Study          | $\theta_{\text{QSO}}$ [arc-sec] | $\nu_0$ [GHz] |
|-----------|----------------|---------------------------------|---------------|
| J0108−0037| G07            | 0.98                            | 1.4           |
| B0201+113 | K07            | 0.018                           | 0.33          |
| B0438−436 | K06            | 0.0039                          | 1 & 5         |
| J0804+3012| G07            | $\approx 22 < 16$.5             | 0.65,1.4      |
| B1622+238 | C07            | 15.33                           | 1.4           |
| J2338−1020| G07            | 0.95                            |               |
| J0214+1405| G07            | $< 18.8$                        | 1.4           |
| J0240−2309| G07            | $< 18.8, < 0.05$                | 1.4,2.3       |
| J0748+3006| C07            | 1.93                            | 1.4           |
| B0809+483 | C07            | 5.27                            | 0.4           |
| J0845+4257| C07            | 1.06                            | 1.4           |
| J1017+3536| G07            | 3.84                            | 1.4           |
| B1402+044 | C07            | 1.35                            | 1.4           |
| J1411−0300| G07            | $\approx 35,6.98$               | 0.59,1.4      |
| J1604−0019| G07            | $\approx 37, 2.13$              | 0.61,1.4      |

References: K06: Kanekar et al. (2006), C07: Gupta et al. (2007), K07: Kanekar et al. (2007), C07: This paper. VLBI: Very Long Baseline Interferometry (see table 2 of Curran et al. 2005) for details. EVN: (European VLBI Network) Dallacasa et al. 1998. FIRST: The Very Large Array’s “Faint Images of the Radio Sky at Twenty Centimetres”, NVSS: “NRAO VLA Sky Survey”.

3.3 The strength of the 21-cm absorption

3.3.1 Correlation with Mg II equivalent width

Now that we have recapped the factors which could determine whether 21-cm absorption is detected or not, we turn our attention to what could possibly determine the strength of the absorption, where detected. Curran & Webb (2006) noted that, although the strength of the absorption appears to be correlated with the equivalent width of the Mg II 2796 Å line, this is not decisive in whether absorption is detected or not: In Fig. 3 (top panel) we see that the non-detections span a similar range of equivalent widths as the detections and that 21-cm absorption is detected down to $W_{\lambda=2796}^\text{Mg II} = 0.33$ Å. Although there is a strong tendency for 21-cm absorption to occur in DLAs originally identified through the Mg II doublet, Curran & Webb (2006) argue that this is a mere consequence of the Mg II selection bias towards low redshift absorbers and thus lower angular diameter distance ratios (see their figure 3). Therefore the deciding criteria in regards to detectability may be

5 Since the ordinate of Fig. 5 is proportional to $(N_{\text{H I}}, S)/(\text{FWHM}, \sigma)$, this gives an accurate indication of the limits, although if the FWHM of the any non-detected 21-cm absorption is $< 20 \text{ km s}^{-1}$, the limits would be better than shown. The plot nevertheless gives a truer representation of the limits reached than the spin temperature plots of Chengalur & Kanekar (2000), Kanekar & Chengalur (2001, 2003), where a covering factor is assigned.

6 $D_{\text{DLA}}/D_{\text{QSO}} = 0.8$ splits the low redshift sample approximately in half and is where the increase in $D_{\text{DLA}}/D_{\text{QSO}}$ with redshift begins to lose its linearity.

7 The possible candidates at $z_{\text{abs}} = 2.688$ and $z_{\text{abs}} = 2.713$ absorbers towards 1402+044 are not included.
related to the coverage, as discussed above. Of course, if the fit in Fig. 6(top) is an accurate indicator, again the non-detections may not have been searched sufficiently deep to overcome these low covering factors.

For strong (\(W_\lambda^{2796} > 0.3 \text{ Å}\)) Mg II absorption, characteristic of the DLAs searched in 21-cm, the line is completely saturated and above these equivalent widths the profile traces the number of absorbing components (e.g. Ellison 2006). Therefore the strength of the Mg II absorption is dominated by the velocity structure. On the other hand, the 21-cm absorption is optically thin, and therefore less susceptible to the same kinematics, although the top panel of Fig. 6 suggests that this may nevertheless be important in determining the strength of the 21-cm profile. In order to verify this, in the lower two panels of Fig. 6 we show the full width half maximum and the total velocity spread (\(\Delta V\)) of the 21-cm absorption profiles (obtained from the references given in table 1 of Curran et al. 2005). The fact that the non-parametric correlations are considerably more significant than for the line-strength correlation, suggests that the strength of the 21-cm absorption may indeed be dominated by the velocity structure, although the spirals do introduce some scatter, perhaps due to a contribution from the large-scale galactic dynamics. In particular, 1622+238 (FWHM = 235 km s\(^{-1}\)) and \(\Delta V \approx 560\) km s\(^{-1}\)), which is more reminiscent of a large-scale emission profile, rather than the typical pencil beam absorption profile (Curran et al. 2007b).

### 3.3.2 Correlation with metallicity and implications

In addition to the correlation between the Mg II and 21-cm profile widths, a relationship between the velocity spreads of low ionisation lines and the metallicity has been well documented: Wolfe & Prochaska (1998) originally noted a tentative correlation in a sample of 17 DLAs, over the redshift range \(z_{\text{abs}} = 1.6 - 3.0\), with a similarly tentative correlation between [Zn/H] and \(\Delta V_{\text{ion}}\) being found in a sample of 72, over the range \(z_{\text{abs}} = 1.4 - 4.5\), by Péroux et al. (2003). From composites of 370 SDSS spectra, Nestor et al. (2003) found higher metallicities in the \(W_\lambda^{2796} \geq 1.3 \text{ Å}\) sample than for \(1.0 \leq W_\lambda^{2796} < 1.3\), over both low and high redshift regimes. This was confirmed by Turnshek et al. (2005) with composites from nearly 6000 SDSS spectra and metallicities obtained from Zn, Si, Cr, Fe and Mn abundances. A correlation between the metallicity and velocity spread from individual systems was found by Ledoux et al. (2006), using several low ionisation species (O I, Si II, Fe II, Cr II & S II), in 70 DLAs and sub-DLAs (with \(N_{\text{HI}} \geq 10^{20} \text{ cm}^{-2}\)) over the redshift range \(z_{\text{abs}} = 1.7 - 4.3\). Like Wolfe & Prochaska (1998) [and Khare et al. 2007; Prochaska et al. 2007], the velocity spread is attributed to the galactic dynamics, indicating that the metallicity traces the mass of the galaxy with which the DLA is associated. However, Bouche et al. (2006) find, from a sample of 1806 Mg II absorbers with \(W_\lambda^{2796} \geq 0.3 \text{ Å}\), that the halo mass and equivalent width are anti-correlated, thus leading Murphy et al. (2007) [see Fig. 7].
Figure 7. The metallicity versus the rest frame equivalent width of the Mg II 2796 Å line for the DLAs illuminated at radio frequencies, where available. The black symbols represent the 21-cm detections and the coloured (green/blue) symbols the non-detections/unsearched DLAs. The errors are from the literature as given in Murphy et al. (2007) and are not shown in the other plots for the sake of clarity. Since we use the same [M/H] and $W_{2796}^\lambda$ range in each plot, these give a clear indication of what the uncertainties are. Even in this sub-sample, we see the correlation exhibited for all of the 49 DLAs and sub-DLAs (over $S_{21} = 0.2 - 2.6$) for which both measurements exist (with $S_{21} > 0.009$, in fact it was the above correlation which prompted this investigation of the general DLA population. As per Fig. 6 in this and the following plots we give the non-parametric correlation estimator and the resulting significance.

Figure 8. As figure 1 of Curran et al. (2005), which shows the spin temperature against absorption redshift as given in Kanekar & Chengalur (2003), but with metallicity shown on the abscissa. In this and Figs. 9 and 10, the other new measurements are for 0201+113 (Ellison et al. 2001) and 0438–436 (Akerman et al. 2005) and, as per Fig. 7, the metallicities are from the references given in Murphy et al. (2007), with the few available limits added from Akerman et al. (2005); Ellison (2006). Kendall’s $\tau$ two-sided probability is shown for both the detections only (with and without 1622+238) and the detections + the non-detections (the least-squares fit is for the detections only). In the bottom panel, which shows the covering factors applied to derive the spin temperatures (Kanekar & Chengalur 2003 [Kanekar et al. 2006, 2007]), the coloured symbols represent the non-detections (which show that $f$ is set to unity in all cases). For 1622+238 we have assumed $f = 1$, since $f < 1 \Rightarrow T_{spin} < 60$ K in this DLA (Curran et al. 2007b).

Note also that the abundance of metals appears to be anti-correlated with the neutral hydrogen column density, which when combined with a mass–metallicity relationship, suggests that sub-DLAs arise in more massive galaxies than DLAs, perhaps due a deficit of neutral gas in the central regions of these larger galaxies. This may suggest that it is the sub-DLAs which contribute star forming activity, and thus elemental abundances, to the early Universe (Wolfe & Prochaska 1995, Khare et al. 2007), perhaps bypassing the inconsistency raised by the low abundance of cold, star forming, molecular gas observed in DLAs (Sect. 1).

Interestingly, in 40% of the absorbers the C IV gas exceeds the escape velocity, suggesting that the absorption occurs in outflows. Unlike, the outflows of Murphy et al. (2007), however, these consist of photoionised and collisionally excited gas.

10 Note also that the abundance of metals appears to be anti-correlated with the neutral hydrogen column density, which when combined with a mass–metallicity relationship, suggests that sub-DLAs arise in more massive galaxies than DLAs, perhaps due a deficit of neutral gas in the central regions of these larger galaxies. This may suggest that it is the sub-DLAs which contribute star forming activity, and thus elemental abundances, to the early Universe (Wolfe & Prochaska 1995, Khare et al. 2007), perhaps bypassing the inconsistency raised by the low abundance of cold, star forming, molecular gas observed in DLAs (Sect. 1).

11 Although the two non-detections with upper limits to their metallicities could be located closer to the fit, the metallicities would have to be $[M/H] \lesssim -2$ if taking these limits as the spin temperature values.
ably less scatter and the fit suggests that we may be close to the sensitivities required to detect 21-cm in these DLAs. It should be borne in mind, however, that these are still lower limits, although they are, on the whole, several factors lower than the “spin temperatures” implied by Fig. 5 thus being more consistent with the implied correlation. More to the point, through retaining the $T_{\text{spin}}/f$ degeneracy, only observed measurements are used.

From the enrichment of the interstellar medium by successive generations of stars, a metallicity–redshift anti-correlation is expected. In conjunction with a possible spin temperature–metallicity correlation (Fig. 5), this could explain an increase in the spin temperature with redshift (Kanekar & Chengaluri 2003). However, from the results of Curran et al. (2005), Curran & Webb (2006) and the flattening of $T_{\text{spin}}/f$ at $\approx 2000$ K (Fig. 5), we believe that this may be artificial. In Fig. 10 we show the metallicity–redshift distribution for this sample, which due to the limited dataset, does not exhibit the metallicity–redshift relation, present in much larger (Prochaska et al. 2003) or more homogeneous (Curran et al. 2004) datasets. So, although a spin temperature–metallicity correlation may be expected, we suggest that this is not due to the spin temperature evolving with redshift.

3.3.3 The cause of the correlations

In the optically thin regime, the normalised 21-cm line strength is

$$f \frac{\tau dv}{N_{\text{HI}}} \propto f \frac{T_{\text{spin}}}{S},$$

where here $\tau \equiv \sigma/S$ (Sect. 3.1). Therefore one has to be wary of over-interpreting the spin temperature (as well as the covering factor): According to Equation 2, Fig. 6 (top) exhibits an increase in $f/T_{\text{spin}}$ with the Mg II rest frame equivalent width, which when combined with the metallicity-equivalent width relation (Fig. 7), would suggest that $f/T_{\text{spin}}$ is correlated with metallicity, giving the anti-correlation between $T_{\text{spin}}/f$ and [M/H] (Fig. 9).

However, $f/T_{\text{spin}}$ is but a measure of the normalised 21-cm line strength (Equation 2), which, as seen from Fig. 6 (middle, bottom), may be a consequence of the kinematics, as is the Mg II equivalent width. So what we are seeing here is that the velocity structure of the cold neutral atomic gas does share a degree of coupling with that of the singly ionised species. This confirms that the neutral and singly ionised gas are spatially coincident, as suggested by the correspondence of their strongest absorption components (Tzanavaris et al. 2007). Therefore, any correlation with the metallicity could well be dominated by the left, rather than right, hand side of Equation 2 more specifically $\int dv$, which, through its tracing of the Mg II velocity spread will also trace the metallicity. In order to determine which term on the left hand side of the equation is dominating the correlation with $W_{\lambda 2796}$, and thus $[M/H]$, in Fig. 11 (top) we show the optical depth of the 21-cm absorption against the Mg II rest frame equivalent width and, as noted by Briggs & Wolfe (1983), there appears to be little correlation between these two quantities. It therefore appears that the relationship between the 21-cm line strength and the Mg II equivalent width (Fig. 6 top), is predominately due to the 21-cm velocity spread (Fig. 6 middle & bottom).

This confirms (as shown by the statistics in Fig. 5) that the kinematics of the 21-cm line is the key factor in giving a correlation between the 21-cm line strength and the Mg II equivalent width, and therefore the metallicity. How this itself ties in with the right hand side of Equation 2 is more complicated, since, as discussed at length above, it is very hard to determine the degeneracy between these two unknowns. For example, a larger covering factor could well be manifest in larger observed velocity spreads of the 21-cm profiles, as seen for the spirals (Fig. 6, particularly 1622+238, Curran et al. 2007b), Conversely, the spin temperature could be anti-correlated with the velocity spread, although this would be counter-intuitive if the spin temperature is related to the kinetic temperature of the gas, a problem further compounded if

\[^{13}\] Such a coupling of the cold atomic and molecular gases towards reddened quasars has also recently been found by Curran et al. (2007).

\[^{14}\] In fact, including the optical depth on its own actually has a destabilising effect on the correlation; Fig. 11 (bottom) cf. Fig. 6 (middle & bottom), which is somewhat neutralised by normalising this by the column density (Fig. 6 top). Interestingly, although DLAs at $z < 1.65$ arise almost entirely from the Mg II absorbers with $W_{\lambda 2796} > 0.6$ Å (Rao & Turnshek 2004) also find little direct correlation between $N_{\text{HI}}$ and $W_{\lambda 2796}$. 

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**Figure 9.** The spin temperature/covering factor ratio versus the metallicity for the DLAs searched in 21-cm absorption. As in Fig. 8, Kendall’s $\tau$ two-sided probability is shown for both the detections only (with and without 1622+238) and the detections + the non-detections.

**Figure 10.** The metallicity versus the absorption redshift for the DLAs under discussion. No overwhelming trend is seen for this sample, verifying that the relation seen in Fig. 9 is not redshift dependent. Although, like Fig. 9 the spirals are grouped together at high metallicities.
the relationship in Fig. 8 rather than Fig. 9 were used. On the other hand, as expected, the spin temperature could indeed be
directly anti-correlated with the metallicity (through higher cooling
rates), or the covering factor correlated, due to larger covering fac-
tors being associated with larger, more evolved galaxies. Either, or
both, of these scenarios could explain the relation seen in Fig. 9
although we know that for this sample the ratio between these two
parameters shows no significant redshift evolution (Fig. 5).

In light of these various possibilities, once again it is prudent
to leave the degeneracies intact and only conclude as far as

$$ f \frac{\tau}{dv} \propto \frac{f}{T_{\text{spin}}} \propto \frac{\lambda^{12796}}{[M/H]}, $$

where the first and third terms are essentially $\Delta V_{21-\text{cm}}$ and
$\Delta V_{\text{MgII}}$, respectively.

4 SUMMARY

We have searched four sight-lines for 21-cm absorption in four
DLAs and two candidate sub-DLAs with the Westerbork Synthe-
sis Radio Telescope. This has resulted in one detection and four
non-detections, with one observation being lost to severe radio fre-
tency interference at 452 MHz. Adding these to the results from
the two new high redshift detections (Kanekar et al. 2006, 2007), is
consistent with the suggestion by Curran et al. (2005) that the spin
temperature does not increase indefinitely with redshift.

(ii) Occulting extremely compact radio sources ($\lesssim 0.04''$),
these two new high redshift detections vindicate the prediction
of Curran et al. (2005) that, despite extremely high "spin tem-
peratures", DLAs should be detectable at high redshift, particu-
larly through the targetting of those located towards compact ra-
dio sources. However, the radio sources illuminating the other new
(intermediate redshift) detections, are not significantly smaller than
those illuminating the non-detections ($\sim 1''$).

(iii) The addition of the new search results increases the signifi-
cance that the 21-detections generally have smaller angular diame-
ter distances than their background quasars, thus maximising the
covering factor through line-of-sight geometry (Curran & Webb
2006). This results in a mix of distance ratios at low redshift, but ex-
clusively high ratios at high redshift, as per the "spin temperature"
distribution of Kanekar & Chengalur (2003).

As suggested by Curran & Webb (2006), since DLAs originally
identified through the Mg II doublet generally have lower redshifts
($0.2 \lesssim z_{\text{abs}} \lesssim 2.2$, in the optical bands of ground based telescopes)
than those identified through the Lyman-$\alpha$ line ($z_{\text{abs}} \gtrsim 1.7$), these
will usually have low angular diameter distance ratios. This man-
ifests itself as 21-cm absorption being more likely to be detected
in Mg II selected absorbers. This is evident in the fact that, al-
though the 21-cm line strength is correlated with the Mg II equiv-
alent width, it is not decisive in whether 21-cm absorption is de-
tected or not, with the non-detections spanning a similar range of
equivalent widths as the detections. Investigating this and other cor-
relations further, we find:

(iv) The relationship between the 21-cm line strength and the
Mg II equivalent width (significant at $\lesssim 1.9\sigma$) is dominated by the
velocity width of the 21-cm line, thus indicating a correlation be-
tween the 21-cm and Mg II velocity profiles ($\lesssim 2.8\sigma$).

(v) Since the Mg II equivalent width is also correlated with the
metallicity, this would suggest a 21-cm line strength–metallicity
relation, which we find at $\lesssim 2.8\sigma$ significance.

(vi) Such a correlation has previously been suggested, on evolu-
tionary grounds, by Kanekar & Briggs (2004). However, although
the metallicity is known to decrease with redshift for larger or more
homogeneous samples of DLAs, no metallicity–redshift correlation is
seen for this sample, suggesting that this relationship may be
non-evolutionary in origin for the 21-cm absorbing DLAs. This is
confirmed by our finding that the $T_{\text{spin}}/f$ ratio does not appear to
exhibit an overall increase with redshift.

Although the relationships between these various parameters are
expected to be complex and intricately interconnected, we suggest
since $[M/H] \propto \lambda^{12796} \propto \Delta V_{\text{MgII}} \propto \Delta V_{21-\text{cm}}$, that the ob-
served 21-cm line strength–metallicity correlation is a consequence
of the coupling between the velocity structure of the cold neutral
(HI 21-cm) and the singly ionised (Mg II) gas.

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10,000 K, but at redshift of $z_{\text{abs}} = 0.238$ this definitely does not con-
tribute to an increase in the spin temperature with redshift.
REFERENCES

Akerman C. J., Ellison S. L., Pettini M., Steidel C. C., 2005, A&A, 440, 499
Bergeron J., Boissé P., 1991, A&A, 243, 344
Bouché N., Murphy M. T., Péroux C., Csabai I., Wild V., 2006, MNRAS, 371, 495
Briggs F. H., Brinks E., Wolfe A. M., 1997, AJ, 113, 467
Briggs F. H., Wolfe A. M., 1983, ApJ, 268, 76
Brown R. L., Roberts M. S., 1973, ApJ, 184, L7
Carilli C. L., Perlman E. S., Stocke J. T., 1992, ApJ, 400, L13
Chen H., Lanzetta K. M., Webb J. K., Barcons X., 1998, ApJ, 498, 77
Chen H.-W., Lanzetta K. M., 2003, ApJ, 597, 706
Chengalur J. N., Kanekar N., 2000, MNRAS, 318, 303
Cui J., Bechtold J., Ge J., Meyer D. M., 2005, ApJ, 633, 649
Curran S. J., Darling J. K., Bolatto A. D., Whiting M. T., Bignell C., Webb J. K., 2007a, MNRAS, in press (arXiv:0708.1636)
Curran S. J., Murphy M. T., Pihlström Y. M., Webb J. K., Purcell C. R., 2005, MNRAS, 356, 1509
Curran S. J., Tzanavaris P., Murphy M. T., Webb J. K., Pihlström Y. M., 2007b, MNRAS, in press (arXiv:0706.2692)
Curran S. J., Webb J. K., 2006, MNRAS, 371, 356
Curran S. J., Webb J. K., Murphy M. T., Bandiera R., Corbelli E., Flambaum V. V., 2002, PASA, 19, 455
Curran S. J., Webb J. K., Murphy M. T., Carswell R. F., 2004, MNRAS, 351, L24
Curran S. J., Whiting M., Murphy M. T., Webb J. K., Longmore S. N., Pihlström Y. M., Athreya R., Blake C., 2006, MNRAS, 371, 431
Dallacasa D., Bondi M., Alef W., Mantovani F., 1998, A&AS, 129, 219
deBruyn A. G., O’Dea C. P., Baum S. A., 1996, A&A, 305, 450
Ellison S. L., 2006, MNRAS, 368, 335
Ellison S. L., Pettini M., Steidel C. C., Shapley A. E., 2001, ApJ, 549, 770
Fox A. J., Ledoux C., Petitjean P., Srianand R., 2007, A&A, accepted (arXiv:0707.4065)
Ge J., Bechtold J., Kulkarni V. P., 2001, ApJ, 547, L1
Gupta N., Srianand R., Petitjean P., Khare P., Saikia D. J., York D. G., 2007, ApJ, 654, L111
Haehnelt M. G., Steinmetz M., Rauch M., 1998, ApJ, 495, 647
Kanekar N., Briggs F. H., 2004, Science with the Square Kilometer Array, New Astronomy Reviews. Elsevier, Amsterdam, pp 1259–1270
Kanekar N., Chengalur J. N., 2001, A&A, 369, 42
Kanekar N., Chengalur J. N., 2003, A&A, 399, 857
Kanekar N., Chengalur J. N., Lane W. M., 2007, MNRAS, 375, 1528
Kanekar N., Subrahmanyan R., Ellison S. L., Lane W., Chengalur J. N., 2006, MNRAS, 370, L46
Khare P., Kulkarni V. P., Péroux C., York D. G., Lauroesch J. T., Meiring J. D., 2007, A&A, 464, 487
Kulkarni V. P., Fall S. M., 2002, ApJ, 580, 732
Lane W. M., 2000, PhD thesis, University of Groningen
Lane W. M., Briggs F. H., Smette A., 2000, ApJ, 532, 146
Le Brun V., Bergeron J., Boissé P., Deharveng J. M., 1997, A&A, 321, 733
Le Brun V., Vito M., Milliard B., 1998, A&A, 340, 381
Ledoux C., Petitjean P., Fynbo J. U., Møller Pand Srianand R., 2006, A&A, 457, 71
Ledoux C., Petitjean P., Srianand R., 2003, MNRAS, 346, 209
Ledoux C., Petitjean P., Srianand R., 2006, ApJ, 640, L25
Ledoux C., Srianand R., Petitjean P., 2002, A&A, 392, 781
Levshakov S. A., Dessauges-Zavadsky M., D’Odorico S., Molaro P., 2002, ApJ, 565, 696
Levshakov S. A., Molaro P., Centurião M., D’Odorico S., Bonifacio P., Vladilo G., 2000, A&A, 361, 803
Levshakov S. A., Varshalovich D. A., 1985, MNRAS, 212, 517
Lopez S., Ellison S. L., 2003, A&A, 403, 573
Lu L., Sargent W. L. W., Barlow T. A., Churchill C. W., Vogt S. S., 1996, ApJS, 107, 475
Meiring J. D., Lauroesch J. T., Kulkarni V. P., Péroux C., Khare P., York D. G., Crots A. P. S., 2007, MNRAS, 376, 557
Murphy M. T., Curran S. J., Webb J. K., 2004, in Duc P.-A., Braine J., Brinks E., eds, Recycling Intergalactic and Interstellar Matter, IAU Symposium No. 217 H2-bearing damped lyman-α systems as tracers of cosmological chemical evolution. ASP Conf. Ser., San Francisco, p. 252
Murphy M. T., Curran S. J., Webb J. K., Méniager H., Zych B. J., 2007, MNRAS, 376, 673
Murphy M. T., Liske J., 2004, MNRAS, 354, L31
Nestor D. B., Rao S. M., Turnshek D. A., Vanden Berk D., 2003, ApJ, 595, L5
Noterdaeme P., Ledoux C., Petitjean P., Pettit F. L., Srianand R., Smette A., 2007, A&A, accepted (arXiv:0707.4479)
Péroux C., Dessauges-Zavadsky M., D’Odorico S., Kim T.-S., McMahon R. G., 2003, MNRAS, 345, 480
Petitjean P., Ledoux C., Noterdaeme P., Srianand R., 2006, A&A, 456, L9
Petitjean P., Srianand R., Ledoux C., 2002, MNRAS, 332, 383
Pettini M., King D. L., Smith L. J., Hunstead R. W., 1995, in Meylan G., ed., QSO Absorption Lines The Chemical Evolution of Damped Lyman-Alpha Galaxies. Springer-Verlag, Berlin, p. 71
Prochaska J. X., Chen H.-W., Wolfe A. M., Dessauges-Zavadsky M., Bloom J. S., 2007, ApJ, submitted (astro-ph/0703701)
Prochaska J. X., Gawiser E., Wolfe A. M., Castro S., Djorgovski S. G., 2003, ApJ, 595, L9
Prochaska J. X., Herbert-Fort S., 2004, PASP, 116, 622
Prochaska J. X., Herbert-Fort S., Wolfe A. M., 2005, ApJ, 635, 123
Prochaska J. X., Wolfe A. M., 1997, ApJ, 487, 73
Rao S., Nestor D. B., Turnshek D., Lane W. M., Monier E. M., Bergeron J., 2003, ApJ, 595, 94
Rao S. M., Turnshek D. A., 2000, ApJS, 130, 1
Reimers D., Baade R., Quast R., Levshakov S. A., 2003, A&A, 410, 785
Ryan-Weber E. V., Webster R. L., Staveley-Smith L., 2003, MNRAS, 343, 1195
Srianand R., Gupta N., Petitjean P., 2007, MNRAS, 375, 584
Steidel C. C., Dickinson M., Meyer D. M., Adelberger K. L., Semi-
bach K. R., 1997, ApJ, 480, 568
Turnshek D. A., Rao S. M., Nestor D. B., Belfort-Mihalyi M., Quider A., 2005, in Williams P. R., Shu C., Ménard B., eds, Probing Galaxies through Quasar Absorption Lines, Proceedings IAU Colloquium No. 199 (astro-ph/0506701)
Turnshek D. A., Wolfe A. M., Lanzetta K. M., Briggs F. H., Cohen R. D., Foltz C. B., Smith H. E., Wilkes B. J., 1989, ApJ, 344, 567
Tzanavaris P., Murphy M. T., Webb J. K., Flambaum V. V., Curran S. J., 2007, MNRAS, 374, 634
Vladilo G., Bomfaco P., Centurión M., Molaro P., 2000, ApJ, 543, 24
Wolfe A. M., Briggs F. H., Jauncey D. L., 1981, ApJ, 248, 460
Wolfe A. M., Briggs F. H., Turnshek D. A., Davis M. M., Smith H. E., Cohen R. D., 1985, ApJ, 294, L67
Wolfe A. M., Lanzetta K. M., Foltz C. B., Chaffee F. H., 1995, ApJ, 454, 698
Wolfe A. M., Prochaska J. X., 1998, ApJ, 494, L15
Wolfe A. M., Prochaska J. X., 2000, ApJ, 545, 591
Wolfe A. M., Turnshek D. A., Smith H. E., Cohen R. D., 1986, ApJS, 61, 249
Wolfire M. G., Hollenbach D., McKee C. F., Tielens A. G. G. M., Bakes E. L. O., 1995, ApJ, 443, 152