Search for cold gas in $z > 2$ damped Ly$\alpha$ systems: 21-cm and H$_2$ absorption

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ABSTRACT

We present the results of a systematic Green Bank Telescope (GBT) and Giant Metre-wave Radio Telescope (GMRT) survey for 21-cm absorption in a sample of 10 damped Lyman-α (DLA) systems at $2 \leq z_{\text{abs}} \leq 3.4$. Analysis of L-band Very Long Baseline Array (VLBA) images of the background QSOs are also presented. We detect 21-cm absorption in only one DLA (at $z_{\text{abs}} = 3.1745$ towards J1337+3152). Thus the detection rate of 21-cm absorption is $\sim 10\%$ when no limit on the integrated optical depth ($\int \tau(v) \, dv$) is imposed and $\sim 13\%$ for a $3\sigma$ limit of 0.4 km s$^{-1}$. Combining our data with the data from the literature (a sample of 28 DLAs) and assuming the measured core fraction at milliarcsecond scale to represent the gas covering factor, we find that the H$_i$ gas in DLAs at $z \geq 2$ is predominantly constituted by warm neutral medium. The detection rate of 21-cm absorption seems to be higher for systems with higher $N$(H$_i$) or metallicity. However, no clear correlation is found between the integrated 21-cm optical depth (or the spin-temperature, $T_S$) and either $N$(H$_i$), metallicity or velocity spread of the low ionization species. There are 13 DLAs in our sample for which high resolution optical spectra covering the expected wavelength range of H$_2$ absorption are available. We report the detection of H$_2$ molecules in the $z_{\text{abs}} = 3.3871$ 21-cm absorber towards J0203+1134 (PKS 0201+113). In 8 cases, neither H$_2$ (with molecular fraction $f$(H$_2$) $\leq 10^{-6}$) nor 21-cm absorption (with $T_S$/$f_c$ $\geq$ 700 K) are detected. The lack of 21-cm and H$_2$ absorption in these systems can be explained if most of the H$_i$ in these DLAs originate from low density high temperature gas. In one case we have a DLA with 21-cm absorption not showing H$_2$ absorption. In two cases, both species are detected but do not originate from the same velocity component. In the remaining 2 cases 21-cm absorption is not detected despite the presence of H$_2$ with evidence for the presence of cold gas. All this is consistent with the idea that the H$_2$ components seen in DLAs are compact (with sizes of $\leq 15$ pc) and contain only a small fraction (i.e typically $\leq 10\%$) of the total $N$(H$_i$) measured in the DLAs. This implies that the molecular fractions $f$(H$_2$) reported from the H$_2$ surveys should be considered as conservative lower limits for the H$_2$ components.

Key words: quasars: active – quasars: absorption lines – galaxies: ISM

1 INTRODUCTION

The Galactic interstellar medium (ISM) has a multiphase structure with neutral hydrogen being distributed between the cold neutral (CNM), warm neutral (WNM) and warm ionized (WIM) media. A large fraction of the gas is also found in diffuse, translucent and dense molecular clouds. Newly formed stars are associated with these dense molecular clouds and strongly influence the physical state of the rest of the gas in different forms through radiative and mechanical inputs. The physical conditions in the multiphase ISM depend on the UV background radiation field, metallic-
ities, dust content and the density of cosmic rays (see Figs. 5, 6 and 7 in Wolffe et al. 1993). In addition, the filling factor of the different phases depends sensitively on the supernova rate (de Avillez & Breitschwerdt 2004). Therefore, detecting and studying the multiphase ISM in external galaxies has great importance for our understanding of galaxy evolution. Damped Lyman-α systems (DLAs) are the highest H I column density absorbers seen in QSO spectra, with N(H i) ≥ 2 × 10^{20} cm^{-2}. These absorbers trace the bulk of the neutral hydrogen at 2 ≤ z ≤ 3 (Prochaska et al. 2003; Noterdaeme et al. 2009) and have long been identified as revealing the interstellar medium of the high-redshift precursors of present day galaxies (for a review see, Wolfe et al. 2007).

The typical dust-to-gas ratio of DLAs, is less than one tenth of that observed in the local ISM, and only a small fraction (< 10%) of DLAs show detectable amounts of molecular hydrogen (Petitjean et al. 2006; Ledoux et al. 2003; Noterdaeme et al. 2008) with the detection rate being correlated to the dust content of the gas (Petitjean et al. 2006). The estimated temperature and molecular fraction in these systems are consistent with them originating from the CNM (Srianand et al. 2003). It has been shown recently that strong C i absorbers detected in low-resolution Sloan Digital Sky Survey (SDSS) spectra are good candidates for H2 bearing systems. Indeed these absorbers have yielded the first detections of CO molecules in high-z DLAs (Srianand et al. 2005; Noterdaeme et al. 2009, 2010, 2011). The properties of these absorbers are similar to those of translucent molecular clouds. The fact that no DLA is found to be associated with a dense molecular cloud, a fundamental ingredient of star-formation, is most certainly related to the large extinction that these clouds are expected to produce and/or the small size of such regions (Zwaan & Prochaska 2006) making detections difficult.

Thus, most DLAs detected in optical spectroscopic surveys seem to probe the diffuse H I gas (Petitjean et al. 2000). However, about 50% of the DLAs show detectable C II absorption (Wolfe et al. 2003), and Wolfe et al. 2003 argued that a considerable fraction of the C II absorption in DLAs originates from CNM gas (see however Srianand et al. 2003). Detection of 21-cm absorption is the best way to estimate the CNM fraction of DLAs as it is sensitive to both N(H i) and thermal state of the gas (Kulkarni & Heiles 1985). This is why it is important to search for 21-cm absorption in DLAs over a wide redshift range. While a good fraction of DLAs/sub-DLAs preselected through Mg II absorption seems to show 21-cm absorption at z ∼ 1.3 (see for example Gupta et al. 2009; Kanekar et al. 2009), searches for 21-cm absorption in DLAs at z_{abs} > 2 have mostly resulted in null detections (see Kanekar & Chengalur 2003; Curran et al. 2014) with only four detections reported till now (see Wolfe et al. 2003; Kanekar et al. 2006, 2007; York et al. 2007). The low detection rate of 21-cm absorption in high-z DLAs can be related to either the gas being warm (i.e high spin temperature, T_S, as suggested by Kanekar & Chengalur (2003)) and/or the low value of covering factor (f_c) through high-z geometric effects (Curran & Webb 2006).

The best way to address the covering factor issue is to perform milliarcsecond scale spectroscopy in the redshifted 21-cm line using very long baseline interferometry (VLBI) to measure the extent of absorbing gas (Lane et al. 2006). Unfortunately due to limited frequency coverage and sensitivity of the receivers available with VLBI such studies cannot be extended to high redshift DLAs. Alternatively, the core fraction measured in the milliarcsecond scale images can be used to get an estimate of the covering factor (see Briggs et al. 1989; Kanekar et al. 2009). Here one assumes that the absorbing gas completely covers at least the emission from the milliarcsec scale core. Therefore, to address this issue, one needs, not only to increase the number of systems searched for 21-cm absorption but also to perform milliarcsecond scale imaging of the background radio sources.

We report here the results of a search for 21-cm absorption in 10 DLAs at z > 2 we have carried out using GBT and GMRT, complemented by L-band VLBA images of the background QSOs. This survey has resulted in the detection of 21-cm absorption in the z_{abs} = 3.1745 DLA towards J1337+3152. A detailed analysis of this system and two sub-DLAs close to this system are presented in Srianand et al. 2010. Section 2 presents the details of our sample. In Section 3 we present the details of GBT and GMRT spectroscopic observations, VLBA continuum observations, and

| Source name | Telescope | Date | Time (hr) | BW (MHz) | Ch. |
|-------------|-----------|------|----------|----------|-----|
| J0407−4410  | GBT       | 2006-10-20 | 4.7     | 0.625    | 512 |
| (CTS247)    |           |      2007-01-05 | 2007-01-06 | 2007-01-08 |      |
| J0733+2721  | GBT       | 2007-12-05 | 10.7    | 1.25     | 512 |
| J0801+4725  | GMRT      | 2006-12-22 | 10.8    | 1        | 128 |
| J0852+2431  | GBT       | 2009-08-07 | 5.6     | 1.25     | 1024|
| J1017+6116  | GBT       | 2008-10-15 | 4.5     | 1.25     | 1024|
| J1242+3720  | GMRT      | 2007-06-08 | 6.1     | 0.5      | 128 |
| J1337+3152  | GMRT      | 2009-01-13 | 6.2     | 1        | 128 |
| J1406+3433  | GBT       | 2009-03-05 | 8.0     | 1.25     | 1024|
| J1435+5435  | GMRT      | 2009-03-08 | 6.7     | 1        | 128 |
Figure 1. SDSS spectra showing the Lyα lines for 12 DLAs in our sample. The best fitted Voigt profiles (solid curves) together with the associated 1σ errors (shaded regions) are over-plotted. The dotted curve gives the best fitted continuum (in some cases the continuum fit includes the emission lines also). We have used VLT UVES spectra to get \( N(H_\alpha) \) in the case of \( z_{\alpha_{\rm abs}} = 3.1745 \) system towards J1337+3152 (see Srianand et al. 2010) and \( z_{\alpha_{\rm abs}} = 2.595 \) and 2.622 systems towards J0407−4410 (CTS 247, see Ledoux et al. 2003).
data reduction. The detection rate of 21-cm absorption in DLAs is discussed in Section 2. In Section 3 we study the correlations between the parameters derived from 21-cm observations, \( N(\text{H} \text{I}) \), metallicity and redshift. In Section 4 we study the relation between 21-cm and \( \text{H}_2 \) absorption. The results are summarized in Section 5. In this work we assume a flat Universe with \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.27 \) and \( \Omega_\Lambda = 0.73 \).

2 THE SAMPLE OF DLAS

To construct our sample, we cross-correlated the overall sample of DLA-bearing QSO sightlines from SDSS-DR7 (Noterdaeme et al. 2009, including systems that are not part of the published statistical sample used to measure \( \Omega \) (Noterdaeme et al. 2009, including systems that are not part of DLA-bearing QSO sightlines from SDSS-DR7). To satisfy these conditions. In addition, there are 4 DLAs along the sight line towards J0407–4410 (also known as CTS 247) at \( z_{\text{abs}} = 1.913, 2.550, 2.595 \) & 2.622. Two of these, at \( z_{\text{abs}} = 2.595 \) and 2.622, have redshifted 21-cm absorption frequency in the relatively RFI free frequency range of GBT. Including these two DLAs towards CTS 247, we have a sample of 15 DLAs for which a search for 21-cm absorption was carried out using either GMRT or GBT. We observed 14 DLAs, (the selection is the \( z_{\text{abs}} = 3.079 \) system towards J1413+4505), but obtained useful spectra for only 10 DLAs. In addition, we have obtained milliarcsecond scale images at 1.4 GHz for all the QSOs except CTS 247 to understand the role of radio structure in detectability of 21-cm absorption in DLAs. The details of the GBT, GMRT and VLBA observations are given below.

The Lyman-\( \alpha \) profiles for 12 DLAs selected from the SDSS-DLA catalog are shown in the Fig. 1. The \( \text{H} \text{I} \) column density for each of these DLAs has been estimated using Voigt profile fits to the Lyman-\( \alpha \) absorption line. The QSO continuum was approximated by a lower order spline using absorption free regions on both sides of the \( \text{H} \text{I} \) trough (dotted curves in each panel). In addition, special care was taken to fit the emission line profiles whenever the Ly\( \alpha \) absorption is close to QSO emission lines. For the remaining three DLAs in our sample, \( z_{\text{abs}} = 3.1745 \) DLA towards J1337+3152 and the two DLAs towards CTS 247, we use the column densities measured by Srianand et al. (2010) and Ledoux et al. (2004) respectively from high resolution VLT UVES spectra.

3 DETAILS OF OBSERVATIONS AND DATA REDUCTION

3.1 The GBT and GMRT observations

We observed our sample of 14 DLAs using the GBT prime focus receivers PFI-340 MHz and PFS-1-450 MHz, and the GMRT P-band receiver. Although we selected DLAs such that the redshifted 21-cm absorption frequencies were not affected by strong RFI, no useful data could be obtained for 4 absorption systems either due to RFI or other technical reasons. The observing log for the remaining 10 DLAs and the spectral set-up used for these observations are provided in Table 1. GBT observations were performed in the standard position-switching mode with typically 5 min spent on-source and 5 min spent off-source. The data were acquired in the orthogonal polarization channels XX and YY. We used the GBT spectral processor as the backend for these observations. The two DLAs towards CTS 247 were observed simultaneously using two bands of 0.625 MHz split into 512 channels. For the GMRT observations, typically a bandwidth of 0.5 or 1 MHz split into 128 frequency channels was used. The data were acquired in the two orthogonal polarization channels RR and LL. For the flux density/bandpass calibration of GMRT data, standard flux density calibrators were observed for 10–15 min every two hours. A phase calibrator was also observed for 10 min every \( \sim 45 \text{ min} \) to get reliable phase solutions.

We used NRAO’s GBTDI package to develop a pipeline to automatically analyse the GBT spectral-line data sets. After excluding time ranges for which no useful data were obtained, the data were processed through this pipeline. The pipeline calibrates each data record individually and flags the spectral channels with deviations larger than 5\( \sigma \) as affected by RFI. After subtracting a second order baseline these data are averaged to produce baseline (i.e. continuum) subtracted spectra for XX and YY. The baseline fit and statistics for the flagging are determined using the spectral region that excludes the central 25% and last 10% channels at both ends of the spectrum. If necessary, a first-order cubic spline was fitted to the averaged XX and YY spectra obtained from the pipeline, which were then combined to produce the Stokes-I spectrum. The spectrum was then shifted to the heliocentric frame. The multi-epoch spectra for a source were then resampled onto the same frequency scale and combined to produce the final spectrum.

The GMRT data were reduced using the NRAO AIPS package following the standard procedures described in Gupta et al. (2004). Special care was taken to exclude the baselines and time stamps affected by RFI. The spectra at the quasar positions were extracted from the RR and LL spectral cubes and compared for consistency. If necessary, a first-order cubic-spline was fitted to remove the residual continuum from the spectra. The two polarization channels were then combined to get the Stokes I spectrum which was then shifted to the heliocentric frame.

The FWHM of the GBT beam at 400 MHz is 30\( '' \) and the rms confusion is 500 mJy. This is comparable to the flux densities of the background radio sources observed with the GBT. Therefore, to correct for the effect of other confusing sources in the GBT beam and determine the QSO flux densities at the redshifted 21-cm frequency, we observed these with the GMRT at 610 and 325 MHz. For these observations we have used 32 MHz bandwidth. Details of these GMRT observations and the measured flux densities are provided in Table 2. For J1406+3433, the 325 MHz flux density is taken from the Westerbork Northern Sky Survey (WENSS). We interpolate these flux density measurements to determine the flux densities at redshifted 21-cm frequencies for the quasars observed with the GBT. Since, flux densities for these 5 QSOs are not measured at the same epoch as the GBT spectroscopic observations, in principle, radio flux density variability can affect our estimates of 21-cm optical
Table 2. GMRT low-frequency flux density measurements for the DLAs observed with the GBT

| Source name | \(S_{610\text{MHz}}\) (\(\text{mJy}\)) | Date       | \(z_{\text{em}}\) | \(N(\text{H}I)\) (\(\text{cm}^{-2}\)) | \(S_{1.4\text{GHz}}\) (\(\text{mJy}\)) | \(\delta\) (\(\text{km s}^{-1}\)) | Spectral rms \(\nu^{1/2}\) (\(\text{mJy \text{ b}^{-1} \text{ c}^{-1}\})) | \(S_{v_{\text{abs}}}\) (\(\text{mJy}\)) | \(\int \tau dv\) (\(\text{km s}^{-1}\)) | \(\bar{\tau}\) (\(\text{K}\)) | \(\bar{\delta}\) (\(\text{K}\)) |
|-------------|------------------|------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| J040718−441013 | 3.020 | 2.595 | 21.05±0.10 | - | 3.7 | 5.9 | 67 | <1.61 | >382 |
| J040718−441013 | - | 2.622 | 20.45±0.10 | - | - | - | 1.6 | >1.93 | >81 |
| J073320.49+272103.5 | 2.938 | 2.7263 | 20.25±0.20 | 240 | 3.8 | 3.4 | 451 | <0.14 | >692 |
| J085257.12+243103.2 | 3.276 | 2.2325 | 20.80±0.15 | 78 | 7.0 | 1.5 | 164 | <0.22 | >1563 |
| J085257.12+243103.2 | 3.617 | 2.7902 | 20.70±0.20 | 160 | 3.9 | 3.9 | 228 | <0.32 | >850 |
| J1101725.89+611627.5 | 2.805 | 2.7263 | 20.60±0.15 | 477 | 3.9 | 4.2 | 268 | <0.29 | >758 |
| J124209.81+372005.7 | 3.839 | 3.4135 | 20.50±0.30 | 662 | 3.6 | 3.6 | 615 | <0.11 | >1567 |
| J133724.69+315254.5 | 3.174 | 3.1745 | 21.36±0.10 | 83 | 6.9 | 1.3 | 69 | 2.08±0.17 | 609^{+220}_{-160} |
| J140653.84+343337.4 | 2.566 | 2.4989 | 20.20±0.20 | 167 | 3.6 | 3.0 | 178 | <0.31 | >356 |
| J143533.78+543559.4 | 3.811 | 3.3032 | 20.30±0.20 | 96 | 7.1 | 1.5 | 145 | <0.26 | >418 |

Table 3. Results from the GBT and GMRT observations

| Source name | \(z_{\text{em}}\) | \(z_{\text{abs}}\) | \(N(\text{H}I)\) (\(\text{cm}^{-2}\)) | \(S_{1.4\text{GHz}}\) (\(\text{mJy}\)) | \(\delta\) (\(\text{km s}^{-1}\)) | Spectral rms \(\nu^{1/2}\) (\(\text{mJy \text{ b}^{-1} \text{ c}^{-1}\})) | \(S_{v_{\text{abs}}}\) (\(\text{mJy}\)) | \(\int \tau dv\) (\(\text{km s}^{-1}\)) | \(\bar{\tau}\) (\(\text{K}\)) | \(\bar{\delta}\) (\(\text{K}\)) |
|-------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| J040718−441013 | 3.020 | 2.595 | 21.05±0.10 | - | 3.7 | 5.9 | 67 | <1.61 | >382 |
| J040718−441013 | - | 2.622 | 20.45±0.10 | - | - | - | 1.6 | >1.93 | >81 |
| J073320.49+272103.5 | 2.938 | 2.7263 | 20.25±0.20 | 240 | 3.8 | 3.4 | 451 | <0.14 | >692 |
| J085257.12+243103.2 | 3.276 | 2.2325 | 20.80±0.15 | 78 | 7.0 | 1.5 | 164 | <0.22 | >1563 |
| J085257.12+243103.2 | 3.617 | 2.7902 | 20.70±0.20 | 160 | 3.9 | 3.9 | 228 | <0.32 | >850 |
| J1101725.89+611627.5 | 2.805 | 2.7263 | 20.60±0.15 | 477 | 3.9 | 4.2 | 268 | <0.29 | >758 |
| J124209.81+372005.7 | 3.839 | 3.4135 | 20.50±0.30 | 662 | 3.6 | 3.6 | 615 | <0.11 | >1567 |
| J133724.69+315254.5 | 3.174 | 3.1745 | 21.36±0.10 | 83 | 6.9 | 1.3 | 69 | 2.08±0.17 | 609^{+220}_{-160} |
| J140653.84+343337.4 | 2.566 | 2.4989 | 20.20±0.20 | 167 | 3.6 | 3.0 | 178 | <0.31 | >356 |
| J143533.78+543559.4 | 3.811 | 3.3032 | 20.30±0.20 | 96 | 7.1 | 1.5 | 145 | <0.26 | >418 |

The GBT and GMRT observations of our DLA sample have resulted in useful 21-cm absorption spectra for 10 DLAs. These spectra are presented in Fig. 2. The 21-cm absorption is detected only for one DLA (i.e. \(z_{\text{abs}} = 3.1745\) DLA towards J1337+3152) and a detailed analysis of this system is presented in Srianand et al. (2010). None of the other “absorption-like features”, marked as shaded regions, are reproduced in spectra from different polarizations and epochs, but are due to RFI. For CTS247b (i.e for \(z_{\text{abs}} = 2.622\) DLA towards CTS247) these features are present only in one polarization at certain times. For J0852+2431 and J1017+6116, using a combination of high spectral resolution (~1 km s\(^{-1}\)) and/or multi-epoch observations we rule out the possibility of these features being real 21-cm absorption. Details of the optical depth measurements and other observational results for all the 10 DLAs are summarized in Table 3.

3.2 Continuum observations with VLBA

The sample of quasars presented here was observed as part of a larger VLBA survey to obtain milliarcsecond scale images for QSOs with foreground DLAs and Mg II systems, and understand the relationship between radio structure and detectability of 21-cm absorption. We have observed using VLBA 21-cm receiver for 11 hrs and 18 hrs on 21/02/2010 and 10/06/2010 respectively. We used eight 8 MHz baseband channels, i.e. the total bandwidth of 64 MHz. Each baseband channel was split into 32 spectral points. Both the right and left-hand circular polarization channels were recorded. Two bit sampling and a post-correlation time resolution of 2 seconds were used.

The observations were done using nodding-style phase-referencing with a cycle time of ~5 min, i.e. 3 min on the source and ~1.5 min on the phase-referencing calibrator. The phase-referencing calibrators were selected from the VLBA calibrator survey (VCS) at 2.3 and 8.6 GHz (Table 4). In order to improve the uv-cover, the total observing time was split into snapshots over a number of different hour angles. Each source, except CTS247 which was excluded due to observational constraints, was typically observed for a total of ~30 min. During both observing runs, strong fringe find-
Figure 2. GBT and GMRT spectra of DLAs in our sample. Shaded regions mark features that are due to RFI. The arrows in the case of non-detections indicate the expected positions of the 21-cm absorption. In the case of $z_{\text{abs}} = 3.1745$ system towards J1337+3152 we show the high resolution 21-cm absorption spectrum only. Two arrows in the case of CTS247a indicate the expected position of 21-cm absorption from the two H$_2$ components.

Non-detection of 21-cm absorption in a DLA could be due to the small covering factor of the absorbing gas. The typical spatial resolution achieved in our VLBA observations is $\sim 8$ mas. If the extent of absorbing gas is of the order of the scales probed by our VLBA observations (i.e. $> 20$ pc) then we expect the detectability of 21-cm absorption to depend on the fraction and spatial extent of radio flux density detected in these images. In column #14 of Table 3.2 we give the ratio of total flux densities detected in the VLBA and FIRST images at 20cm, i.e. $f_{\text{VLBA}}$. The last column of this table gives the largest linear size (LLS), i.e the separation between the farthest radio components, of the radio source at the redshift of the DLA. Out of the 13 QSOs presented in Fig. 3 that have DLAs along their line of sight, we have 21-cm absorption spectra for only 8 DLAs. For the DLA to-
Figure 3. Contour plots of VLBA images at 1.4 GHz. The rms in the images are listed in Table 3.2. At the bottom of each image the restoring beam is shown as an ellipse, and the first contour level (CL) in mJy beam$^{-1}$ and FWHM are noted. The contour levels are plotted as CL×(-1, 1, 2, 4, 8,...) mJy beam$^{-1}$. Depending upon the detailed structure of the radio sources, the emission could be more extended at the redshifted 21-cm frequencies.
Table 5: Results from the VLBA data.

| Source name | $z_{\text{abs}}$ | Right ascension (J2000) | Declination (J2000) | rms | Comp. | $S$ | $r$ | $\theta$ | $a$ | $b/a$ | $\phi$ | $S_T$ | $f_{\text{VLBA}}$ | LLS |
|-------------|-----------------|------------------------|-------------------|-----|-------|----|----|---------|----|----|-------|------|-----|---------|-----|
| J0733+2721  | 2.7263          | 07 33 20.4830          | +27 21 03.430     | 0.3 | 1     | 97 | 0  | -       | 4.52| 0.05| -88   | 240  | 0.62| 348     |
|             |                 |                        |                   |     | 2     | 3  | 9.1 | -129   | 13.24| 0.00| -18   |       |     |         |
|             |                 |                        |                   |     | 3     | 19 | 32.7| -140   | 5.98 | 0.26| 32    |       |     |         |
|             |                 |                        |                   |     | 4     | 29 | 10.8| 51     | 8.37 | 0.44| -17   |       |     |         |
| J0801+4725  | 3.2235          | 08 01 37.6930          | +47 25 28.082     | 0.2 | 1     | 28 | 0  | -       | 6.77 | 0.00| 72    | 78   | 0.67| 342     |
|             |                 |                        |                   |     | 2     | 8  | 9.34| -112   | 7.09 | 0.00| 72    |       |     |         |
|             |                 |                        |                   |     | 3     | 16 | 44.7| -112   | 8.63 | 0.22| 64    |       |     |         |
| J0816+4823  | 08 16 19.0044   | +48 23 28.490          | 0.2               | 1   | 42    | 0  | -  |        | 4.59 | 0.24| 87    | 69   | 0.75| 68      |
|             |                 |                        |                   |     | 2     | 10 | 9.0 | 132    | 8.75 | 0.43| -63   |       |     |         |
| J0839+2002  | 08 39 10.8970   | +20 02 07.391          | 0.2               | 1   | 113   | 0  | -  |        | 4.91 | 0.24| 84    | 130  | 0.87| ≤39     |
|             |                 |                        |                   |     | 2     | 1    | 78 | 0     | 4.92 | 0.31| 71    | 160  | 0.55| 175     |
| J0852+2431  | 08 52 57.1211   | +24 31 03.271          | 0.2               | 2   | 10    | 21.9| 42  | 15.2   | 0.16 | 53  |       |       |     |         |
| J1017+6116  | 10 17 25.8865   | +61 16 27.414          | 0.5               | 1   | 388   | 0  | -  |        | 1.50 | 0.68| 55    | 477  | 0.86| 38      |
|             |                 |                        |                   |     | 2     | 24  | 4.7 | 145    | 2.45 | 0.00| 70    |       |     |         |
| J1223+5037  | 12 23 43.1740   | +50 37 53.344          | 0.5               | 1   | 96    | 0  | -  |        | 2.50 | 0.00| 78    | 229  | 0.60| 554     |
|             |                 |                        |                   |     | 2     | 16  | 13.6| 80     | 3.01 | 0.83| -19   |       |     |         |
|             |                 |                        |                   |     | 3     | 25  | 71.4| 78     | 8.61 | 0.00| 89    |       |     |         |
| J1237+4708  | 12 37 17.4413   | +47 08 06.964          | 0.2               | 1   | 64    | 0  | -  |        | 3.17 | 0.20| -74   | 80   | 0.80| ≤27     |
| J1242+3720  | 12 42 09.8121   | +37 20 05.692          | 0.6               | 1   | 848   | 0  | -  |        | 1.93 | 0.76| 22    | 662  | 1.00| ≤14     |
| J1337+3152  | 13 37 24.6931   | +31 52 54.642          | 0.2               | 1   | 83    | 0  | -  |        | 3.85 | 0.38| 74    | 83   | 1.00| ≤30     |
| J1406+3433  | 14 06 53.8532   | +34 33 37.339          | 0.4               | 1   | 127   | 0  | -  |        | 3.24 | 0.22| -23   | 167  | 0.87| 153     |
|             |                 |                        |                   |     | 2     | 18  | 18.7| -30    | 23.79| 0.23| -25   |       |     |         |
| J1413+4505  | 14 13 18.8652   | +45 05 22.990          | 0.2               | 1   | 105   | 0  | -  |        | 2.19 | 0.42| -67   | 140  | 0.88| 216     |
|             |                 |                        |                   |     | 2     | 12  | 3.4 | -77    | 5.37 | 0.00| -86   |       |     |         |
|             |                 |                        |                   |     | 3     | 6   | 27.9| -72    | 6.28 | 0.03| -67   |       |     |         |
| J1435+5435  | 14 35 33.7812   | +54 35 59.312          | 0.2               | 1    | 31    | 0  | -  |        | 2.66 | 0.17| -29   | 96   | 0.55| 155     |
|             |                 |                        |                   |     | 2     | 17  | 20.4| 155    | 4.00 | 0.47| -36   |       |     |         |
|             |                 |                        |                   |     | 3     | 5   | 7.6 | 153    | 5.52 | 0.00| -7    |       |     |         |

Column 1: Source name. Column 2: absorption redshift. Columns 3 and 4: right ascension and declination of component-1 (see column 6) from the multiple Gaussian fit to the source, respectively. Column 5: rms in the map in mJy beam$^{-1}$. Column 6: component id. Column 7: flux density of the component in mJy. Columns 8 and 9: radius and position angle of the component with respect to component-1, respectively. Columns 10, 11 and 12: major axis, axial ratio and position angle of the deconvolved Gaussian component, respectively. Column 13: flux density in mJy from FIRST/NVSS. Column 14: $c_f$ is the ratio of 1.4 GHz flux density in VLBA image to that in the FIRST image. Column 15: largest projected linear size in pc.
Table 4. Details of phase-referencing calibrators used for the VLBA observations

| Source            | Calibrator     | Separation (degrees) |
|-------------------|----------------|----------------------|
| J0733+2721        | J0732+2548     | 1.5                  |
| J0801+4725        | J0754+4823     | 1.5                  |
| J0816+4823        | J0808+4950     | 1.9                  |
| J0839+2002        | J0842+1835     | 1.6                  |
| J0852+2431        | J0856+2111     | 3.5                  |
| J1017+6116        | J1031+6020     | 2.0                  |
| J1223+5037        | J1227+4932     | 1.3                  |
| J1237+4708        | J1236+4753     | 0.9                  |
| J1242+3720        | J1242+3751     | 0.5                  |
| J1337+3152        | J1329+3154     | 1.6                  |
| J1406+3433        | J1416+4607     | 1.2                  |
| J1435+5435        | J1429+5406     | 1.0                  |

Column 1: Source name. Column 2: Phase-referencing calibrator. Column 3: Separation between the radio source and phase-referencing calibrator.

Figure 3. Continued.

Figure 4. The allowed range of fraction of DLAs having harmonic mean spin temperature $T_S$ greater than a limiting value $T_S^l$ as a function of $T_S^l$. We use only those DLAs for which $c_f$ measurements are available. The lower envelope of the shaded region is obtained considering all the lower limits on $T_S^l$ as measurements. The upper envelope is obtained assuming all the lower limits as measurements with $T_S^l \geq T_S^l$.

4 DETECTABILITY OF 21-CM ABSORPTION

In this Section we investigate the detectability of 21-cm absorption in DLAs and the implication of non-detections for the physical state of the H\textsc{i} gas. It is clear from the last column of Table 3 that for most of the DLAs, our data has good sensitivity to detect $T_S^l/f_c \sim 100$ K gas.

The H\textsc{i} 21-cm absorption is detected only in the $z_{\text{abs}} = 3.1745$ system towards SDSS J1337+3152. This is one of the weakest radio sources in our sample (with a $3\sigma$ $\int \tau dv$ limit of 0.4 km s$^{-1}$). However, thanks to high $N(\text{H}\textsc{i})$ our spectrum is sensitive enough to detect any gas with $T_S^l \leq 3100$ K. This source is unresolved in our VLBA observations (see Fig. 3). The L-band flux density measured in
our VLBA image is consistent with that measured by the FIRST survey. Therefore, the core fraction is, $c_f \sim 1$, and the size of the VLBA beam is less than 30 pc at the redshift of the absorber. The spin-temperature, measured from the ratio of 21-cm optical depth and the $N$(H i) column density derived from the Lyman-α trough, is $600^{+220}_{-160}$ K which is consistent with the upper limit on $T_S$ obtained from the width of the single component Gaussian fit to the 21-cm absorption [Srianand et al. 2010].

In Table 6 we provide various details of our measurements together with the previous measurements at $z \geq 2$ from the literature. We present the results dividing the sample into three groups. These are systems with 21-cm detections (five systems), systems with 21-cm absorption upper limits with (twelve systems) and without (eleven systems) high-resolution optical spectra from which to derive accurate metallicities. The first two groups are used to investigate the connection between UV measurements and 21-cm optical depth. In all cases the 3σ upper limits on the integrated 21-cm optical depth are computed assuming a line width of 10 km s$^{-1}$.

The 21-cm detection rate from our sample, without putting any sensitivity limit, is 10%. This is 13% when we restrict to $\int \tau dv$ of 0.4 km s$^{-1}$ (the limit achieved in the case of J1337+3152 where we have 21-cm detection). Taken at face value, the extended sample listed in Table 6 gives a 21% detection rate for $\int \tau dv$ of 0.4 km s$^{-1}$. For a $\int \tau dv$ limit of 0.2 km s$^{-1}$ we get the detection rate of 28%. However, these may not be representative values as the list of systems compiled from the literature may be biased towards detections as some authors may not have reported their non-detections systematically.

Since we know $N$(H i) from the damped Lyman-α line, the detection limit on the integrated depth implies a lower limit on the ratio $T_S/f_c$. The $T_S/f_c$ measurements are reported in column 7 of Table 6. In column 6 of this table, we give the core fraction $c_f$. As mentioned above, $c_f$ is basically the ratio of flux density in the unresolved core seen in VLBA images to the total flux density measured in the arcsecond scale FIRST images. For the objects from the literature we use the $c_f$ values given in [Kanekar et al. 2002]. These measurements were made at 327 MHz, close to the redshifted 21-cm frequencies. Following [Kanekar et al. 2005] we use core fraction ($c_f$) as the estimate of the covering factor ($f_c$). The $T_S$ measurements given in column 8 of Table 6 are obtained by assuming $f_c = c_f$.

In Fig. 4 we plot the percentage of DLAs having $T_S$ greater than a limiting value $T_S^l$ as a function of $T_S^l$ for systems with $T_S$ measurements given in column 8 of Table 6. The lower envelope of the shaded region is obtained considering all the lower limits on $T_S$ as measurements. The upper envelope is obtained assuming all the lower limits as measurements with $T_S \geq T_S^l$. It is clear from the figure that more than 50% of the DLAs have $T_S \geq 700K$. Remember that the $T_S$ measured in an individual DLA is the harmonic mean temperature of different phases that contribute to the observed $N$(H i). Assuming that the gas is simply a two phase medium with similar covering factors the fraction of H i in the CNM (called $f$(CNM)) can be written as,

$$f$(CNM) = $\frac{1}{T_S^W} \left[ \frac{T_S^C T_S^W}{T_S} - T_S^C \right]$ (1)

where, $T_S^C$ and $T_S^W$ are the spin-temperature of the CNM and WNM respectively [Srianand et al. 2003] have noticed that the H i phase traced by the $T_S$ absorption has temperature typically in the range 100-200 K. Thus we consider the CNM temperature to be 200 K (instead of 70 K as seen in CNM of the Galaxy) so that the $f$(CNM) we get will be a conservative upper limit. Assuming $T_S^C \sim 200$ K and $T_S^W \sim 10^4$ K, $T_S = 700$ K can be obtained for a combination of $f$(CNM) = 0.27 and $f$(WNM) = 0.73. Therefore $f$(CNM) is less than 0.27 in at least 50% of the DLAs. Note that choosing $T_S^W \sim 8000$ K (as suggested for the Galactic ISM) instead of the $10^4$ K used here, does not change the results appreciably.

We estimate $f$(CNM) for the four 21-cm detections (excluding J0501-0159 (B0458-020) for which we do not have the covering factor value). Apart from J0314+4314 (3C082) which seems to be a special case [York et al. 2007], the CNM seems to represent roughly 20 to 30% of the total $N$(H i) measured in these DLAs. For individual non-detections, we can calculate conservative upper limits of the fraction of $N$(H i) in the CNM phase assuming $T_S^C = 200$ K. The values of $f$(CNM) are given in column #9 of Table 6 for systems with $f_c$ measurements. The upper limits vary between 0.10 and 1.0 with a median value of 0.23. Thus the analysis presented here, under the assumption that $f_c = c_f$, suggests that most of the neutral hydrogen in high-$z$ DLAs is warm. This is very much consistent with the conclusion of [Petitjean et al. 2000] based on the lack of H2 detections in most high-$z$ DLAs.

5 RESULTS OF CORRELATION ANALYSIS

In this Section we explore correlations between the 21-cm optical depth and other observable parameters. As we have only a few 21-cm detections and mostly upper limits we use survival analysis and in particular the generalised rank
Table 6. Summary of 21-cm searches in z ≥ 2 DLAs. Column 1: QSO. Column 2: absorption redshift. Column 3: log N(H I). Column 4: Integrated optical depth. Column 5: Reference for f dv given in column 4. Column 6: the core fraction cf. Column 7: the fraction of CNM (see the text for its definition). Column 10: the H2 fraction and Column 11: References for N(H I) and/or f(H2) measurements.

| QSO       | zabs  | log N(H I) | f dv (km s⁻¹) | cf   | T0/f0 (K) | T0 (K) | f(CNM) | log f(H2) | Refs  |
|-----------|-------|-----------|----------------|------|-----------|--------|--------|----------|-------|
| J020346.4+113445 | 3.38714 | 21.26±0.08 | 0.71±0.02       | 1    | 0.76      | 1397   | 1062   | ~0.19    | ~6.2  |
| J031443.6+431405 | 2.8977 | 20.30±0.11 | 0.82±0.09      | 2    | ....      | 133    | ....    | ~1.00    | ....  |
| J044017.2–33309 | 2.3747 | 20.78±0.10 | 0.22±0.03      | 3    | 0.59      | 1493   | 881    | ~0.23    | ....  |
| J050112.8–015914 | 2.03955 | 21.70±0.10 | 7.02±0.16      | 4    | ....      | 390    | ....    | ....     | ~6.40 |
| J133732.6+031534 | 3.17447 | 21.36±0.10 | 2.08±0.17      | 5    | 1.00      | 600    | 600    | ~0.33    | ~7.00 |

21-cm non-detections having metallicity measurements

| QSO       | zabs  | log N(H I) | f dv (km s⁻¹) | cf   | T0/f0 (K) | T0 (K) | f(CNM) | log f(H2) | Refs  |
|-----------|-------|-----------|----------------|------|-----------|--------|--------|----------|-------|
| J033755.7–120142 | 3.1799 | 20.65±0.10 | 0.06           | 6    | 0.62      | 4057   | 2515   | ≤0.08    | ≤5.10 |
| J033901.0–013318 | 3.0619 | 21.10±0.10 | 0.06           | 6    | 0.68      | 11435  | 7775   | ≤0.03    | ≤6.90 |
| J040739.9–330346 | 2.569  | 20.60±0.10 | 0.12           | 7    | 0.44      | 1807   | 795    | ≤0.25    | ....  |
| J040718.0–411013 | 2.5975 | 21.05±0.10 | 0.16           | 8    | ....      | 380    | ....    | ≤2.61    | ≤0.20 |
| J040718.0–411013 | 2.6214 | 20.45±0.10 | 0.19           | 8    | ....      | 80     | ....    | ≤0.20    | ....  |
| J044403.4–435550 | 2.30197 | 20.95±0.10 | 0.33           | 7    | ....      | 1471   | ....    | ≤5.15    | ....  |
| J053007.9–250330 | 2.81115 | 21.35±0.07 | 0.58           | 9    | 0.94      | 2103   | 1977   | ≤0.10    | ≤2.83 |
| J091551.7–000713 | 2.7434 | 20.74±0.10 | 0.37           | 7    | ....      | 809    | ....    | ....     | ....  |
| J135646.8–110129 | 2.96680 | 20.80±0.10 | 0.33           | 6    | ....      | 1042   | ....    | ≤6.75    | ....  |
| J135706.1–174402 | 2.77990 | 20.30±0.15 | 0.14           | 7    | ....      | 777    | ....    | ≤5.99    | ....  |
| J142107.7–064356 | 3.44828 | 20.50±0.10 | 0.14           | 7    | 0.69      | 1233   | 2489   | ≤0.24    | ≤6.59 |
| J23451.2+343348 | 2.90910 | 21.11±0.10 | 0.21           | 6    | 0.71      | 3343   | 2373   | ≤0.08    | ≤6.19 |

References in column #5: 1) Kanekar et al. (2007), 2) York et al. (2007), 3) Kanekar et al. (2008), 4) Briggs et al. (1984), 5) Srianand et al. (2010), 6) Kanekar & Chengalur (2003), 7) Kanekar et al. (2004), 8) This paper, and 9) Curran et al. (2011). † Archival data from GBT08A+03 (PI: Curran) were processed through our pipeline. See text for details.

5.1 Metallicity vs T0/f0

Firstly we study the importance of the metallicity of the gas. Only 3 DLAs in our sample have measurements of metallicity from high resolution optical spectroscopy. In the extended sample at z ≥ 2 (see Table 5) there are 17 systems with metallicity measurements and 21-cm spectra. In Fig. 5 we plot T0/f0 versus metallicity. The vertical long-dashed line marks the median metallicity of the points plotted in the figure. The only detection found in the low metallicity half is for zabs = 3.1745 towards J1337+3152 reported from our survey. The other four detections are from the high metallicity half. The non-parametric generalized Kendall rank correlation test suggests only a weak correlation between Z and T0/f0 (at the 1.42σ level) with the probability that it can arise due to chance being 0.15. The significance is even lower (i.e. 0.9σ with a chance probability of 0.37) when we use T0 (instead of T0/f0) for cases where we have estimated f0 measurements. We wish to point out that a correlation between T0/f0 and metallicity is reported in the literature (Curran et al. 2007, Kanekar et al. 2008, Curran et al. 2011). The lack of correlation in our sample (with systems in a restricted redshift range) could either reflect redshift evolution of the relationship or small range in metallicity covered by the sample. Metallicity measurements for the remaining 11 systems in Table 6 would allow us to address this issue in a statistically significant manner.
5.2 Redshift dependence

In the left hand side panels of Fig. 6 we plot $T_s/f_c$ and integrated 21-cm optical depth vs redshift. No clear correlation is evident in this figure. The non-parametric Kendall test finds no significant correlation between $\int \tau dv$ (or $T_s$) and $z$. Note our sample probes only a restricted redshift range in terms of time interval probed. However, the lack of correlation found here is consistent with the near constancy of $T_s/f_c$ as a function of redshift found by Curran et al. (2010). Understanding the redshift dependence of $T_s$ is very important in particular to address whether there is any evolution in $T_s$ (Kanekar & Chengalur 2003) or geometric effects (Curran & Webb 2006). To make an unbiased comparison we need to have 21-cm measurements at low $z$ for a well defined sample of DLAs detected based on Ly$\alpha$ absorption.

5.3 Dependence on $N(H\,\text{i})$

Recently Curran et al. (2010) have found a 3σ level correlation between $N(H\,\text{i})$ and $T_s/f_c$. To check whether this correlation holds at $z > 2$, we plot, in the top panels of Fig. 6 the integrated 21-cm optical depth as a function of redshift and $N(H\,\text{i})$. We note that there is a tendency for more 21-cm detections in DLAs with higher $N(H\,\text{i})$. However, the non-parametric Kendall test finds no significant correlation between $\int \tau dv$ and $N(H\,\text{i})$. In the bottom right
6 21-CM ABSORPTION AND H$_2$

As 21-cm absorption and H$_2$ molecules can give complementary information on the physical state of the gas. In this Section, we study the relationship between these two indicators. There are 13 DLAs in our extended sample for which the expected optical wavelength range of redshifted H$_2$ absorptions has been observed at high spectral resolution. Nine of these sources are part of the UVES sample of Noterdaeme et al. (2008). Srianand et al. (2010) have reported the detection of H$_2$ in J1337+3152 and here we report the search for H$_2$ in the remaining three DLAs (z$_{abs}$ = 3.3871 towards J0203+1134, z$_{abs}$ = 2.7799 towards J1357−1744 and z$_{abs}$ = 2.9091 towards J2344+3433). In the 10th column of Table 6 we summarize the molecular fraction f(H$_2$) = 2N(H$_2$)/(2N(H$_2$)+N(H I)) derived for these 13 systems.

In 8 systems, neither 21-cm absorption nor H$_2$ molecules are detected with typical upper limits of the order of $10^{-6}$ for f(H$_2$). Apart from the system at z$_{abs}$ = 2.6214 towards J0407−4410, the lower limits on T$_S$/f$_e$ for the remaining 7 systems are higher than 700 K. There are 4 cases where f$_e$ measurements are available. In three cases (z$_{abs}$ = 3.1799 towards J0337−1204, z$_{abs}$ = 3.0619 towards J0339−0133 and z$_{abs}$ = 2.9019 towards J2344+3433), the lower limit on T$_S$ is more than 2000 K. These are in line with the suggestion by Petitjean et al. (2000) that the absence of H$_2$ in most of the DLAs is due to the low density and high temperature of the gas.

In two cases (z$_{abs}$ = 2.5947 towards J0407−4410 (CTS 247) and z$_{abs}$ = 2.8112 towards J0530−2503 (PKS 0528−250)), strong H$_2$ absorption is detected with rotational excitations consistent with the H$_2$-bearing gas being a CNM. However, 21-cm absorption is not detected in either case. We discuss these two systems in detail below.

Among the five 21-cm absorbers, high resolution UVES spectra covering the expected wavelength range of H$_2$ absorption are available for four systems. The exception is the z$_{abs}$ = 2.28977 system towards J0314+4314 (B0311+430). For the z$_{abs}$ = 2.3474 system towards J0440−4333 (B0438−436) the continuum flux in the expected wavelength range is removed by high ionization lines from an associated system, as well as by a high-z Lyman limit system present along the line of sight. Below we discuss the five systems where simultaneous analysis of H$_2$ and 21-cm absorption is possible.

6.1 z$_{abs}$ = 3.3868 DLA towards J0203+1134 (PKS 0201+113)

Searches for 21-cm absorption in this system have yielded conflicting results (de Bruyn et al. 1996, Briggs et al. 1997). Based on GMRT spectra taken at three different epochs, Kanekar et al. (2007) reported the detection of 21-cm absorption in two components at z$_{abs}$ = 3.38714(17) and 3.386141(45). Using N(H I)~ (1.8±0.3)×10$^{21}$ cm$^{-2}$ they obtained T$_S$ = [955 ± 160/(f$_e$/0.69)] K. Using high resolution optical spectrum, Ellison et al. (2001) have found a gas phase metallicity of 1/20 of solar with very little dust depletion. The gas cooling rate, log l$_c$ = −26.67 ± 0.10 erg s$^{-1}$ Hz$^{-1}$, derived using C ii$^+$ absorption is consistent with this DLA being part of high-cool population defined by Wolfe et al. (2003). From Kanekar et al. (2002) we can see that the strongest 21-cm absorption does not correspond to the strongest velocity component in either C ii$^+$ or Fe ii.

Here we report the detection of H$_2$ absorption from J=0 and J=1 levels originating from both Lyman and Werner bands (see Fig 7). A single component Voigt profile fit reproduces the data well. As the Lyman-α forest is dense and the spectral signal-to-noise ratio is not very high due to the faintness of the QSO, we considered a range of b values (i.e between 1 and 5 km s$^{-1}$) to get the best fit values of log[N(H$_2$, J=0)] in the range 16.10−14.48 and log[N(H$_2$, J=1)] = 16.03−14.57. We estimated the kinetic temperature using the ortho-to-parai ratio (i.e T$_{kin}$) and found it to be in the range 48−108 K for the range of b parameters considered above. We note that for b parameters greater than 2 km s$^{-1}$, the H$_2$ lines are mainly in the linear portion of the curve of growth and the column density estimate is insensitive to the assumed value. The average molecular fraction, log f(H$_2$), in the range, −4.6 ≤ log f(H$_2$) ≤ −6.2.

Despite the gas being cold, there is no 21-cm absorption detected at the position of the H$_2$ component (at z = 3.38679) which is well separated from the 21-cm absorption component. If we use f$_e$ = 0.76, as found by Kanekar et al. (2003) using 326 MHz observations, we find log N(H I) < 19.12. This is less than 1% of the total H I column density measured in this DLA.

Unlike most of the strong H$_2$ systems, this system does not show detectable C i absorption. This means we do not have, unfortunately, an independent estimate of the density from fine-structure excitation.

6.2 z$_{abs}$ = 2.5948 towards J0407−4410 (CTS 247)

As the radio source is faint, our GBT spectrum only gives a weak limit on the spin temperature, T$_S$ ≥ 380 K when we use a line width of 10 km s$^{-1}$. Srianand et al. (2003) have reported log N(C ii$^+$) = 13.66±0.13. This, together with log N(H I) = 21.05±0.10, gives a gas cooling rate of log l$_c$ = 26.92±0.16. This is very close to the value l$_c^{\text{crit}}$ that seems to demarcate between the high and low cool systems defined by Wolfe et al. (2003). Ledoux et al. (2003) reported the detection of H$_2$ from this system. The H$_2$ absorption is well fitted with two components at z$_{abs}$ = 2.59471 and 2.49846 with log N(H$_2$) = 18.14 and 15.51 respectively (Srianand et al. 2003). These components have T$_{01}$ = 121±10 and 91±6 K respectively. The average molecular fraction, log f(H$_2$), is found to be −2.42±0.07 with an average metallicity of −1.02 ± 0.12 and moderate dust depletion (Ledoux et al. 2003).

The absence of 21-cm absorption from this system is intriguing as H$_2$ components have T~100 K. With the same b parameters as used to fit the H$_2$ lines and the rms from the GBT spectrum, we get a 3σ upper limit of ∣τdv ∣ = 0.88 km s$^{-1}$. This translates to a constraint, f$_e$×N(H I) ≤
Figure 7. Voigt profile fits to H$_2$ Lyman and Werner band absorption lines in the $z_{\text{abs}} = 3.3868$ DLA system towards J0203+1134 (PKS 0201+113). The zero of the velocity scale is defined at $z = 3.38716$. The two vertical lines at $v = 0$ and $-68$ km s$^{-1}$ show the locations of two 21-cm absorption components reported by Kanekar et al. (2007). The vertical dotted line indicates the location of H$_2$ absorption. In each panel we also show the error spectrum with dotted curves.

$2 \times 10^{20}$ cm$^{-2}$ in the H$_2$ components where we have assumed $T_S = T_0$. Unfortunately we do not have a VLBA image of this source and it is difficult to constrain the covering factor of the gas. If we assume $f_c \sim 1$ then the upper limit on $N$(H i) implies that the H$_2$ component is a sub-DLA with log $f$(H$_2$) $> -1.85$.

From the column densities of the C i fine-structure lines, Srianand et al. (2005) have constrained the particle density in the gas to be in the range $4.5 < n_H$(cm$^{-3}$) $< 57.3$. For $n_H = 4.5$ cm$^{-3}$ and $f_c = 1$, we estimate the thickness of the H$_2$ cloud (i.e $N$(H i)/$n_H$) along the line of sight to be $\leq 15$ pc.

6.3 $z_{\text{abs}} = 2.0395$ towards J0501–0159 (B0458-020)

21-cm absorption in two velocity components was reported by Wolfe et al. (1983). The background radio source shows structure over a wide range of scales and the absorbing cloud seems to cover most of these components (Briggs et al. 1984). The estimated extent of the H i absorber is $\sim 8$ kpc and the spin-temperature of the system is 390 K.

C ii absorption is detected and the measured cooling rate is $l_c = -26.41 \pm 0.10$ (Wolfe et al. 2008). This is consistent with the high cool population. H$_2$ molecules are not detected with an upper limit of the molecular fraction of log $f$(H$_2$) $\leq -6.52$. This is one of the rare DLAs to show Lyman-$\alpha$ emission in the middle of the DLA absorption (Mølmer et al. 2004; Heinmüller et al. 2006).

Based on the star formation rate derived from the Lyman-$\alpha$ flux, Heinmüller et al. (2006) argued that the ambient radiation field is 10 times higher than the Galactic UV background. This excess radiation could be the main reason for the absence of H$_2$ in the gas. This picture is also confirmed by the lack of associated C i absorption.

6.4 $z_{\text{abs}} = 2.8111$ towards J0530-2503 (PKS 0528–250)

Carilli et al. (1996) searched for 21-cm absorption in this system using the WSRT and did not find any significant absorption. Recently Curran et al. (2010) have reported GBT observations of this source with a better signal-to-noise. They obtain a lower limit of the spin temperature of 700 K for $f_c = 1$, again assuming a width of 10 km s$^{-1}$. This source was found to be compact in the low frequency VLBA images with $f_c = 0.94$ (Kanekar et al. 2009).

No measurement of cooling rate is possible for this sys-
system as the the C II* absorption is blended with other saturated lines.

This system has log \( N(\text{H} \; \text{i}) = 21.35 \pm 0.07, \ Z = -0.91 \pm 0.07 \) and \( z_{abs} \) higher than \( z_{em} \). This is the first high redshift DLA where \( \text{H} \; \text{ii} \) absorption has been detected \( \text{[Levshakov & Varshalovich 1985; Srianand & Petitjean 1998; Srianand et al 2005].} \)

The high resolution UVES spectrum reveals two strong \( \text{H} \; \text{II} \) components at \( z_{abs} = 2.81100 \) and 2.81112 with log \( N(\text{H} \; \text{ii}) = 17.93 \pm 0.20 \) and 17.90 \pm 0.14, and \( T_01 = 167 \pm 7 \) and 138 \pm 12 K respectively.

We re-reduced the GBT data of \( \text{[Curran et al 2010]} \) in the same way as our GBT data and found the r.ms in the frequency range expected for the 21-cm absorption associated with the \( \text{H} \; \text{II} \) components to be 6.7 mJy. This, together with the temperature \( T_01 \) and the \( \text{H} \; \text{II} \) b parameter give a constraint of log \( N(\text{H} \; \text{i}) \leq 20 \) in the \( \text{H} \; \text{II} \) components.

\( \text{C I} \) absorption is detected only in one of the \( \text{H} \; \text{II} \) components (i.e at \( z_{abs} = 2.81112 \) \( \text{[Srianand et al 2005].} \)). From the \( \text{C I} \) level populations and for the above temperature, we derive that the particle density is in the range 25 < \( n_\text{H} \; \text{(cm}^{-3}\text{)} < 270 \). If we use the N(\( \text{H} \; \text{i} \)) limit of \( 10^{20} \; \text{cm}^{-2} \) derived from the 21-cm absorption, and use the constraint we get for the hydrogen density in the case of the \( z_{abs} = 2.81112 \) component, we get a limit on the thickness of the gas along the line of sight to be 1.33 pc.

\[ 6.5 \quad z_{abs} = 3.1745 \quad \text{towards J1337+3152} \]

Detection of 21-cm and \( \text{H} \; \text{II} \) in this system was reported in \( \text{[Srianand et al 2010].} \) The weak \( \text{H} \; \text{II} \) absorption is well aligned with the strongest metal line component but is slightly shifted by 2.5 km s\(^{-1}\) with respect to the 21-cm absorption component. This again suggests that the two transitions do not originate exactly from the same gas and that the absorptions arise from an inhomogeneous absorbing region.

As the \( \text{H} \; \text{II} \) column density is very low and the ratio of \( \log (N(\text{H} \; \text{II} \; J=0) / N(\text{H} \; \text{II} \; J=1)) \) is close to the maximum value allowed by the Boltzmann distribution, we cannot constrain the kinetic temperature of the gas.

\[ \text{C II}^* \] absorption is detected with a total column density log \( N(\text{C II}^*) = 13.61 \pm 0.08 \). Using log \( N(\text{H} \; \text{i}) = 21.36 \pm 0.10 \) we derive a gas cooling rate of \( log L = -27.28 \pm 0.13 \). Thus the system belongs to the low cool part of the DLA population. The quasar is unresolved in our 1420 MHz VLBA image with a total flux density consistent with the measurement from FIRST observations. This suggests that most of the emission is in the unresolved component. Using Gaussian fits we estimate the limit on the largest angular size to be \( \leq 3.8 \; \text{mas} \) (or \( \leq 30 \; \text{pc} \) at \( z_{abs} \)). Given the compact nature of the radio source it is intriguing to see the difference between the \( \text{H} \; \text{II} \) and 21-cm absorptions. This clearly shows that the absorbing gas contains a mixture of different phases at parsec scales.

7 RESULTS AND DISCUSSION

We have carried out a systematic search for 21-cm absorption in 10 DLAs at \( z_{abs} > 2 \) using GMRT and GBT. We detect 21-cm absorption in only one of them. From our sample we find the 21-cm detection rate is 13\% for a \( f \tau dv \) limit of 0.4 km/s (the detection limit reached in the case of J1337+3152). We also obtained 1420 MHz VLBI images for the sources in our sample.

The 21-cm detection at \( z \geq 2 \) seems to favour systems with high metallicity and/or high N(\( \text{H} \; \text{i} \)) (see also \( \text{[Kanekar et al 2004; Curran et al 2010].} \)). This basically means that the probability of detecting cold components that can produce detectable 21-cm absorption is higher in systems with high values of N(\( \text{H} \; \text{i} \)) and \( Z \). However, we do not find any correlation between the integrated optical depth (or \( T_01 / f_c \)) and N(\( \text{H} \; \text{i} \)) or metallicity.

It is important to address the covering factor issue before drawing any conclusions on \( T_01 \). Ideally one should do high spatial resolution VLBA spectroscopy for this purpose (see for example \( \text{[Lane et al 2000].} \)). However, this is not possible at present specially for \( z \geq 2 \) absorbers. Therefore, we proceed by assuming that the core fraction found in the VLBA images as the covering factor of the absorbing gas (as in the case of \( \text{[Kanekar et al 2004].} \)) We find that more than 50% of DLAs have weighted mean spin temperature (\( T_S \)) in excess of 700 K. For the assumed temperature of the CNM gas \( T_S^{CNM} = 200 \; \text{K} \) (as seen in \( \text{H} \; \text{II} \) components in high-z DLAs) we find that more than 73% of \( \text{H} \; \text{i} \) in such systems is originating from WNM. The median value CNM fraction (i.e \( f(CNM) \)) obtained for the detections and the median value of upper limits in the case of non-detections are in the range 0.2 to 0.25.

We study the connection between 21-cm and \( \text{H} \; \text{II} \) absorption in a sub-sample of 13 DLAs where both these species can be searched for. We report the detection and detailed analysis of \( \text{H} \; \text{II} \) molecules in the \( z_{abs} = 3.3871 \) DLA system towards J0203+1134 where 21-cm absorption is also detected. For a b parameter in the range 1-5 km s\(^{-1}\) we find 14.57 \( \leq \log (N(\text{H} \; \text{ii})) \leq 16.03 \). The inferred kinetic temperature is in the range 48-108 K based on \( T_01 \) of \( \text{H} \; \text{II} \). However no 21-cm absorption is detected at the very position of this \( \text{H} \; \text{II} \) component. This suggests that the \( \text{H} \; \text{i} \) column density associated with this component is \( \leq 10^{15} \; \text{cm}^{-2} \). However, the lack of proper coincidence between 21-cm and any of the strong UV absorption components may also mean that the radio and optical sight lines probe different volumes of the gas.

In the case of 8 DLAs, neither 21-cm nor \( \text{H} \; \text{II} \) are detected. Typical upper limits on the molecular fraction (\( f_{\text{H}_2} \)) in these systems are \( \leq 10^{-6} \). The lack of \( \text{H} \; \text{II} \) in DLAs can be explained if the \( \text{H} \; \text{i} \) gas originates from low density regions photoionized by the metagalactic UV (see for example \( \text{[Petitjean et al 1992; 2000]; [Hirashita & Ferrari 2003].} \)). This also indicates that the volume filling factor of \( \text{H} \; \text{II} \) in DLAs is small (\( \text{[Zwaan & Prochaska 2006].} \)). Typical limits obtained for \( T_01 \) in these systems are consistent with only a small fraction of the \( \text{H} \; \text{i} \) gas originating from the CNM phase as suggested by the lack of \( \text{H}_2 \) absorption.

In two cases strong \( \text{H}_2 \) absorption is detected and kinetic temperatures are in the range 100-200 K, but 21-cm absorption is not detected. Even in two cases where both the species are detected they do not originate from the same velocity component. The lack of 21-cm absorption directly associated with \( \text{H}_2 \) indicates that only a small fraction (typically \( \leq 10\% \)) of the neutral hydrogen seen in the DLA is associated with the \( \text{H}_2 \) components (see also...
This implies that the molecular fractions $f(H_2)$ reported from the H$_2$ surveys should be considered as conservative lower limits for the H$_2$ components.

For two of the H$_2$-bearing DLAs with density measurements based on C I fine-structure excitation we derive an upper limit on the line of sight thickness of $\leq 15$ pc. This is consistent with the size estimate for the H$_2$-bearing gas in $z_{abs} = 2.2377$ DLA towards Q1232+082 based on partial coverage [Balashev et al. 2011].

In principle, the presence of H$_2$ and 21-cm absorptions in a single component provides a unique combination to simultaneously constrain the variation of the fine-structure constant ($\alpha$), the electron-to-proton mass ratio ($\mu$) and the proton G-factor. As shown here, DLAs with 21-cm and H$_2$ detections are rare. Even in these cases the presence of multiphase structure at parsec scale is evident, introducing velocity shifts between the different absorption components that will affect the constraints on the variation of constants.

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