The covering factor of high-redshift damped Lyman-α systems

N. Kanekar,1* W. M. Lane,2 E. Momjian,1 F. H. Briggs3 and J. N. Chengalur4

1National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA
2Naval Research Laboratory, Code 7213, 4555 Overlook Ave SW, Washington, DC 20375, USA
3Australian National University, Weston, ACT 2611, Australia
4National Centre for Radio Astrophysics, Ganeshkhind, Pune, 411007, India

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ABSTRACT
We have used the Very Long Baseline Array to image 18 quasars with foreground damped Lyman-α systems (DLAs) at 327, 610 or 1420 MHz, to measure the covering factor $f$ of each DLA at or near its redshifted H$\text{I}$ 21 cm line frequency. Including six systems from the literature, we find that none of 24 DLAs at $0.09 < z < 3.45$ has an exceptionally low covering factor, with $f \sim 0.45–1$ for the 14 DLAs at $z > 1.5$ and $f \sim 0.41–1$ for the 10 systems at $z < 1$, and consistent covering factor distributions in the two subsamples. The observed paucity of detections of H$\text{I}$ 21 cm absorption in high-$z$ DLAs thus cannot be explained by low covering factors and is instead likely to arise due to a larger fraction of warm H$\text{I}$ in these absorbers.

Key words: galaxies: ISM – quasars: individual: images.

1 INTRODUCTION
Damped Lyman-α systems (DLAs), selected on the basis of their high H$\text{I}$ column densities ($N_{\text{HI}} \geq 2 \times 10^{20} \text{cm}^{-2}$) in quasar absorption spectra, have long been identified as the progenitors of normal present-day galaxies (Wolfe et al. 1986), and have hence been the subject of much research. Despite this, the nature of high-$z$ DLAs, physical conditions in them and their evolution with redshift are still matters of dispute today (e.g. Wolfe, Gawiser & Prochaska 2009). An issue of recent controversy is the temperature distribution of H$\text{I}$ in DLAs. For radio-loud background quasars, a comparison between the H$\text{I}$ column density and the optical depth in the redshifted H$\text{I}$ 21 cm line yields the DLA spin temperature ($T_\text{s}$). For optically thin multiphase absorption, $T_\text{s}$ is the column-density-weighted harmonic mean of the spin temperatures of the different phases along the line of sight. For nearly three decades, the spin temperatures of high-$z$ DLAs have been found to be systematically higher than values seen in the Milky Way or local spiral discs (e.g. Wolfe & Davis 1979; Carilli et al. 1996; Kanekar & Chengalur 2003, hereafter KC03); the first low-$T_\text{s}$ DLA at high redshift was only detected very recently (York et al. 2007). The simplest interpretation of the observations is that H$\text{I}$ in high-$z$ DLAs is predominantly warm, unlike the situation in the Galaxy (Carilli et al. 1996; Chengalur & Kanekar 2000; KC03). Conversely, Wolfe, Gawiser & Prochaska (2003) used C$\text{II}\np$ absorption lines to argue that roughly half the DLAs at $z \geq 2$ contain significant fractions of cold H$\text{I}$.

A problem in measuring DLA spin temperatures is that low-frequency radio emission is often extended over large angular scales, far larger than the size of a galaxy. Redshifted H$\text{I}$ 21 cm absorption studies are usually carried out with single dishes or short-baseline interferometers, of fairly poor angular resolution, $\geq 10$ arcsec or $\geq 80$ kpc at $z \sim 3$. It is hence often uncertain that the quasar radio emission is entirely covered by the foreground DLA. If some fraction of the quasar emission leaks out around the DLA, the inferred spin temperature will be an overestimate. The fraction of the radio emission occulted by the DLA is referred to as the covering factor $f$ (e.g. Briggs & Wolfe 1983).

Recently, Curran et al. (2005) have emphasized the problem of unknown covering factors in high-$z$ DLAs, pointing out that the high-estimated $T_\text{s}$ values of KC03 could merely stem from very low DLA covering factors, $f \ll 1$. Curran & Webb (2006) also argued that low DLA covering factors at high redshifts arise due to a geometrical effect, as the similarity in angular diameter distances of the high-$z$ DLAs and their background quasars implies that a high-$z$ DLA is ‘less effective’ at covering the quasar than a low-$z$ absorber. Note that Curran et al. (2005) found that quasars of angular extent $\lesssim 0.1$ arcsec are adequately covered even by compact foreground DLAs.

The most direct way of resolving this issue is by high spatial resolution very long baseline interferometry (VLBI) studies in the redshifted H$\text{I}$ 21 cm line (e.g. Briggs et al. 1989; Lane, Briggs & Smette 2000). Unfortunately, the low-frequency coverage of current VLBI facilities is quite limited, implying that such observations are only possible for very few sources. Alternatively, one could measure the compact flux density arising from the quasar core in VLBI continuum images at or near the redshifted H$\text{I}$ 21 cm line frequency and then estimate the DLA covering factor by comparing the VLBI flux density with the flux density measured with short baseline interferometers or single dishes (e.g. Briggs & Wolfe 1983; Kanekar, Chengalur & Lane 2007). This is the approach that we follow here, based on Very Long Baseline Array (VLBA) imaging of 18 quasars with foreground DLAs at $z \sim 0.24–3.45$.
2 OBSERVATIONS, DATA ANALYSIS AND RESULTS

The VLBA 1.4 GHz, 610 and 327 MHz receivers were used to observe the 18 quasars of our sample between 2002 March and 2006 June (projects BK89 and BK131), with observing frequencies close to the redshifted H\textsc{i} 21 cm line frequency of the foreground DLA. Three quasars with DLAs at $z \sim 0.24$–0.44 were observed at 1.4 GHz, two, with DLAs at $z \sim 0.52$–0.86, at 610 MHz, and 13, with DLAs at $z \sim 1.78$–3.45, at 327 MHz. Total bandwidths of 4, 8 and 16 MHz were used for the observations at 610, 327 and 1420 MHz, respectively, with two-bit sampling, two polarizations, 16 spectral channels and on-source integration times of 1–4 h. Strong fringe finders (3C 345, 3C 454.3 or 3C 286) were observed every few hours to calibrate the shape of the passband. Phase referencing was not used. The $U$–$V$ coverage was poor in some cases, as all the VLBA antennas were not available, resulting in asymmetric or larger synthesized beams.

The data were analysed in ‘classic’ AIPS, using standard techniques. Initial procedures included ionospheric corrections, editing of radio frequency interference, amplitude calibration (using the measured antenna gain and system temperatures), passband calibration and fringe-fitting for the delay rates, before the data for each target were averaged in frequency to a single-channel data set. For each source, this was followed by a number of cycles of self-calibration and imaging to determine the antenna gains, until no improvement was seen on further self-calibration. The final images obtained from the above procedure are shown in Fig. 1, in the order of increasing redshift, with the synthesized beams listed in Column 6 of Table 1. The rms noise in off-source regions in the images was measured to be $\sim 0.5$–3 mJy Beam$^{-1}$.

The UVS FIT was used to fit elliptical Gaussian models to the visibility data to measure the compact flux density. Most sources in Fig. 1 are core-dominated, with only a small fraction of the flux density in extended structure. For some sources with visible extensions (e.g. 1229–021, 1243–072 and 2021+113), a single-component model was found sufficient to recover the ‘cleaned’ flux density. The only exceptions are 0952+179 ($\tau_{abs} \sim 0.238$, 1157+014 ($\tau_{abs} \sim 1.944$) and 0438–436 ($\tau_{abs} \sim 2.347$), where all the ‘cleaned’ flux density could be recovered only with a two-component model.

Table 1 summarizes the results of the VLBA observations, grouping the sources by observing band, in the order of increasing redshift. For each source, the first four columns contain the observing band, source name, DLA redshift and redshifted H\textsc{i} 21 cm frequency. Column 5 lists the total flux densities at the VLBA observing frequency. For the three 1.4 GHz targets, this was obtained from the 1.4 GHz National Radio Astronomy Observatory (NRAO) Very Large Array Sky Survey (Condon et al. 1998). For most 327 MHz targets (11/13), we use the flux density measured at nearby frequencies [e.g. at 327 MHz from the Westerbork Northern Sky Survey (Renglink et al. 1997), at 365 MHz from the Texas survey (Douglas et al. 1996; Carilli et al. 1996 or KC03)]. Four sources (0827+243, 0454+039, 0405–331 and 0438–436) do not have measurements in the literature near the VLBA observing frequencies; their flux densities were hence estimated from their low-frequency (<1 GHz) spectral indices.

Columns 6–10 contain the VLBA synthesized beam (6), the flux density obtained on fitting a Gaussian model with UVS FIT (7), the deconvolved angular sizes of the Gaussian components (8), the corresponding spatial extents of these components, at the redshift of the foreground DLA (9) [we use $(\Omega_\lambda, \Omega_\text{ext}, h) = (0.7, 0.3, 0.7)$ in this Letter] and the covering factor of the compact radio emission at the observing frequency (10), obtained by dividing the ‘core’ flux density by the total flux density. In three cases of two source components, the one that is more compact is identified with the core. We emphasize that the deconvolved sizes listed in Columns 8 and 9 are upper limits, due to the possibility of residual phase errors in the data (e.g. due to fluctuations on time-scales shorter than the self-calibration interval). This is especially true for the 327 and 610 MHz results.

3 OTHER SOURCES

A few other quasars with foreground DLAs have estimates of the covering factor from VLBI studies. These are discussed below.

(1) 0738+313 ($\tau_{abs} \sim 0.0912$, 0.2212): Lane et al. (2000) used 1302 MHz VLBA observations to estimate that the covering factor of the foreground DLAs is $f \sim 0.98$.

(2) 1127–145 ($\tau_{abs} \sim 0.3127$): Bondi et al. (1996) measured a flux density of $\sim 5.0$ Jy in their 1.6 GHz VLBI image, compared to a single-dish flux density of $\sim 5.6$ Jy. This gives $f \sim 0.89$.

(3) 0235+164 ($\tau_{abs} \sim 0.524$): Wolfe et al. (1978) used 931 MHz VLBI observations to show that the size of the quasar core is $\lesssim 6$ mas. More recently, Frey et al. (2000) found that the 1.6 GHz VLBI core flux density (with a submas beam) is very similar to that measured simultaneously with a single dish. This implies $f \sim 1$.

(4) 3C 286 ($\tau_{abs} \sim 0.692$): Wilkinson et al. (1979) used 609 MHz VLBI observations to find that 17.5 Jy of the 609 MHz flux density ($\sim 20$ Jy) arises in the central 55 mas. This implies $f \sim 0.9$.

(5) 0458–020 ($\tau_{abs} \sim 2.039$): Briggs et al. (1989) used 608 MHz VLBI observations to estimate that the compact quasar core contains $\sim 1.15$ Jy at the redshifted H\textsc{i} 21 cm line frequency of $\sim 467$ MHz, with an additional $\sim 1.3$ Jy in two extended components, on scales of $\sim 0.2$–0.5 arcmin and $\sim 1$–2 arcsec. They found the H\textsc{i} 21 cm optical depths measured in VLBI and single-dish studies to be in an excellent agreement and used this to argue that the entire 2 arcsec radio emission is likely to be covered, i.e. $f \sim 1$.

There are four DLAs with searches for H\textsc{i} 21 cm absorption where the core fraction in the background quasar is very small, implying a low covering factor ($f \lesssim 0.1$). These are at $z \sim 0.437$ towards 3C 196, $z \sim 1.391$ towards 0957+561A, $z \sim 1.4205$ towards 1354+258 and $z \sim 0.656$ towards 3C 336. Boisse et al. (1998) noted that the optical and radio sightlines towards 3C 196 are clearly different, due to which $T_c$ cannot be estimated. Similarly, KC03 found very small core fractions in 0957+561A and 1354+258, and argued that covering factor uncertainties preclude an estimate of the spin temperature. Conversely, Curran et al. (2007) do quote a (low) spin temperature for the DLA towards 3C 336. However, the quasar is strongly lobe-dominated with the lobes extended over $\sim 190$ kpc, and only a small fraction of the flux density arises from the core (Bridle et al. 1994). As in the case of 3C 196, the difference between radio and optical sightlines implies that it is not possible to estimate $T_c$ in this absorber.

4 DISCUSSION

For H\textsc{i} 21 cm absorption studies of DLAs towards radio-loud quasars, the H\textsc{i} 21 cm optical depth $\tau_{21}$, H\textsc{i} column density $N_{\text{H}i}$ (cm$^{-2}$) and spin temperature $T_c$ (K) are related by the expression

$$N_{\text{H}i} = 1.823 \times 10^{18} \times (T_c/f) \int \tau_{21} \, dV,$$

(1)

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Figure 1. VLA images of the 18 quasars of the sample, ordered (from top left panel) by DLA redshift. The map frequency is at the top right of each panel.
The HI 21 cm line is redshifted to frequencies typically low covering factors, the high-
low. If, as argued by Curran et al. 1992, this suggests that high-
DLAs are based on covering factors estimated either from VLBI
sample were all determined at

| v_{21cm} (MHz) | S_{int} (mJy) | Beam (mas × mas) | Spatial extent (pc × pc) | f |
|----------------|--------------|------------------|--------------------------|---|
| 0.238          | 14 × 6       | 330 ± 1          | 1.66 ± 0.1               | 1.06 |
| 0.395          | 17 × 6       | 303 ± 1          | 1.69 ± 0.1               | 0.42 |
| 0.437          | 22 × 8       | 483 ± 1          | 6.9 (1.01)               | 0.88 |
| 0.525          | 38 × 13      | 626 ± 6          | 11.3 ± 0.4               | 0.70 |
| 0.860          | 41 × 15      | 251 ± 9          | 9 (1.01)                 | 0.50 |
| 1.776          | 53 × 32      | 444 ± 5          | 2 ± 2                    | 0.72 |
| 1.944          | 74 × 25      | 565 ± 15         | 58 (1.01)                | 0.63 |
| 2.193          | 65 × 25      | 290 ± 9          | 24 (1.01)                | 0.57 |
| 2.347          | 120 × 34     | 4533 ± 15        | 34 (1.01)                | 0.59 |
| 2.462          | 56 × 28      | 510 ± 6          | 51 (1.01)                | 0.98 |
| 2.569          | 332 ± 13     | 367 ± 5          | 0.7 (0 ± 0.1)            | 0.44 |
| 2.811          | 102 × 13     | 132 ± 5          | 0 (8 ± 3)                | 0.94 |
| 2.908          | 52 × 16      | 219 ± 10         | 42.2 (0 ± 0)             | 0.71 |
| 2.974          | 105 × 67     | 495 ± 1          | 10 ± 1                   | 0.47 |
| 3.062          | 99 × 48      | 636 ± 7          | 23 (1.01)                | 0.68 |
| 3.180          | 157 × 77     | 419 ± 8          | 69 (1.01)                | 0.62 |
| 3.387          | 98 × 50      | 321 ± 8          | 6 (4 ± 0)                | 0.76 |
| 3.448          | 294 × 57     | 302 ± 11         | 38 (2 ± 3)               | 0.69 |

where f is the covering factor of the foreground DLA and the HI 21 cm line is assumed to be optically thin. For a DLA, where \( N_{HI} \) is known from the Lyman-\( \alpha \) profile, a measurement of the HI 21 cm optical depth hence yields \( T_s / f \). Estimates of the covering factor can then be used to infer \( T_s \) for the DLA. High-
DLAs have long
index of core emission is usually inverted or flat, while extended
of Table 1, fitted by an elliptical Gaussian model, the 'size' is the
of the core emission plotted against DLA redshift; for the sources

Table 1. Results from VLBA low-frequency imaging of quasars behind high-z DLAs (see text for details and discussion).

| v_{abs} | QSO | z_{abs} | \( v_{21cm} \) (MHz) | S_{abs} (Jy) | Beam (mas × mas) | S_{int} (mJy) | Angular size (mas × mas) | Spatial extent (pc × pc) | f |
|---------|-----|---------|---------------------|--------------|------------------|--------------|--------------------------|--------------------------|---|
| 0.238   | 14  | 1.16    | 14 × 6              | 762 ± 1      | (1.7 ± 0.1) × (13.9 ± 0.1) | (6.4 ± 0.1) × (52.2 ± 0.1) | 0.66 |
| 0.395   | 17  | 1.65    | 689 ± 1             | 303 ± 1      | (4.5 ± 0.1) × (9.1 ± 0.1) | (17.1 ± 0.1) × (34.1 ± 0.1) | – |
| 0.437   | 22  | 2.88    | 483 ± 1             | 104 ± 1      | (7.7 ± 0.1) × (6.9 ± 0.1) | (43.6 ± 0.2) × (39 ± 1) | 0.88 |
| 0.525   | 38  | 13.3    | 626 ± 6             | 23.4 ± 0.4   | (11.3 ± 0.4) | (16 ± 2) × (71 ± 3) | 0.70 |
| 0.860   | 41  | 5.0     | 251 ± 9             | 31 ± 1       | (9 ± 1) | (241 ± 9) × (66 ± 9) | 0.50 |
| 1.776   | 53  | 3.2     | 444 ± 5             | 26 ± 1       | (2 ± 2) | (223 ± 3) × (19 ± 14) | 0.72 |
| 1.944   | 74  | 2.5     | 565 ± 15            | 39 ± 1       | (58 ± 1) | (327 ± 8) × (488 ± 9) | 0.63 |
| 2.193   | 65  | 2.5     | 290 ± 9             | 39 ± 2       | (24 ± 1) | (322 ± 18) × (196 ± 6) | 0.57 |
| 2.347   | 120 | 3.4     | 4533 ± 15           | 19 ± 1       | (34 ± 1) | (156 ± 2) × (277 ± 2) | 0.59 |
| 2.462   | 56  | 2.8     | 510 ± 6             | 10 (1 ± 0.1) | (56 ± 5) | (0 ± 15) | 0.44 |
| 2.569   | 332 | 0.8     | 367 ± 5             | 0 ± 1        | (0 ± 0.1) | (0 ± 15) | 0.94 |
| 2.811   | 102 | 1.4     | 132 ± 5             | 49 ± 5       | (8 ± 3) | (384 ± 42) × (65 ± 20) | 0.94 |
| 2.908   | 52  | 1.6     | 219 ± 10            | 49 ± 2       | (42 ± 2) | (372 ± 13) × (329 ± 12) | 0.71 |
| 2.974   | 105 | 1.0     | 495 ± 1             | 10 ± 1       | (10 ± 1) | (77 ± 2) × (79 ± 10) | 0.47 |
| 3.062   | 99  | 0.9     | 636 ± 7             | 37 ± 1       | (23 ± 2) | (286 ± 17) × (176 ± 18) | 0.68 |
| 3.180   | 157 | 0.8     | 419 ± 8             | 31 ± 6       | (69 ± 2) | (233 ± 45) × (521 ± 11) | 0.62 |
| 3.387   | 98  | 0.4     | 321 ± 8             | 21 ± 2       | (6 ± 4) | (152 ± 12) × (41 ± 28) | 0.76 |
| 3.448   | 294 | 0.4     | 302 ± 11            | 23 ± 3       | (38 ± 2) | (167 ± 240) × (208 ± 11) | 0.69 |
The covering factor of high-$z$ DLAs

Figure 2. (A) Left-hand panel: the covering factor of the 24 DLAs of the present VLBI sample, plotted against DLA redshift, $z_{\text{DLA}}$. (B) Right-hand panel: the spatial extent of the compact radio emission of the background quasars (at $z_{\text{abs}}$) plotted versus $z_{\text{abs}}$. The dashed line in (B) is at 400 pc (see text for discussion).

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The covering factor of high-$z$ DLAs

$\geq 2$ kpc-sized) galaxies. The only exception is the $z \sim 2.039$ DLA towards 0458–020, where Briggs et al. (1989) find that the entire $\sim 2$ arcsec radio emission is covered by the foreground DLA, implying an absorber size $\geq 17$ kpc. Note that the larger deconvolved sizes typically obtained at high redshifts are at least partly due to the fact that all high-$z$ DLAs were observed at 327 MHz, where residual phase errors in the data are likely to be an issue; as mentioned earlier, the deconvolved sizes should be treated as upper limits.

19 out of the 24 systems plotted in Fig. 2 (of which 10 are at $z > 1.5$) have $T_s$ estimates in the literature (e.g. Wolfe & Davis 1979; Carilli et al. 1996; KC03; Kanekar et al. 2006). It thus appears that the high-$T_s$ estimates in high-$z$ DLAs are not the result of very low covering factors. The inferred high spin temperatures in high-$z$ DLAs could then arise due to (i) a preponderance of warm H I in these systems (Carilli et al. 1996; KC03) or (ii) systematically lower H I column densities on the radio sightlines than those measured towards the optical quasi-stellar object (QSO), due to small-scale (subkpc) structure in the H I (Wolfe et al. 2003). The spatial resolution of the present VLBA data is not sufficient to rule out the possibility of differences between the radio and optical sightlines. However, good agreement (within a factor of $\sim 2$) has been found between H I column densities measured along the same sightline from Lyman-$\alpha$ absorption and low-resolution H I 21 cm emission studies, both in the Galaxy (Dickey & Lockman 1990) and in the $z \sim 0.009$ DLA towards SBS 1549+593 (Chengalur & Kanekar 2002). This suggests that systematic large differences in H I column density between radio and optical sightlines in DLAs are unlikely. The high spin temperatures in high-$z$ DLAs are thus more likely to be the result of a larger fraction of warm H I in these absorbers.

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