Discovery of 21-cm absorption in a $z_{\text{abs}} = 2.289$ damped Lyman $\alpha$ system towards TXS 0311+430: the first low spin temperature absorber at $z > 1$

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ABSTRACT
We report the detection of H I 21-cm absorption from the $z = 2.289$ damped Lyman $\alpha$ system (DLA) towards TXS 0311+430 with the Green Bank Telescope. The 21-cm absorption has a velocity spread (between nulls) of $\sim 110$ km s$^{-1}$ and an integrated optical depth of $\int \tau \, dV = (0.818 \pm 0.085)$ km s$^{-1}$. We also present new Giant Metrewave Radio Telescope 602-MHz imaging of the radio continuum. TXS 0311+430 is unresolved at this frequency, indicating that the covering factor of the DLA is likely to be high. Combining the integrated optical depth with the DLA H I column density of $N(\text{H} \text{I}) = (2 \pm 0.5) \times 10^{20}$ cm$^{-2}$ yields a spin temperature of $T_s = (138 \pm 36)$ K, assuming a covering factor of unity. This is the first case of a low spin temperature ($< 350$ K) in a $z > 1$ DLA and is among the lowest temperatures ever measured in any DLA. Indeed, the $T_s$ measured for this DLA is similar to values measured in the Milky Way and local disc galaxies. We also determine a lower limit ($\text{Si/H} > 1/3$ solar for the DLA metallicity, amongst the highest abundances measured in DLAs at any redshift. Based on low-redshift correlations, the low $T_s$, large 21-cm absorption width and high metallicity all suggest that the $z \sim 2.289$ DLA is likely to arise in a massive, luminous disc galaxy.

Key words: galaxies: high-redshift – galaxies: ISM – radio lines: galaxies.

1 INTRODUCTION
Damped Lyman $\alpha$ systems (DLAs) are the highest column density absorbers seen along quasi-stellar object (QSO) lines of sight, with neutral hydrogen column densities $N(\text{H} \text{I}) \geq 2 \times 10^{20}$ cm$^{-2}$. They have long been identified as the precursors of today’s galaxies and the primary gas reservoir for star formation at high redshifts. Despite the recognized importance of the absorbers, their typical size, structure and internal physical conditions remain issues of controversy (e.g. Wolfe, Gawiser & Prochaska 2005). For example, DLA metallicities, now measured in over 100 absorbers, show very little evolution between $z \sim 3$ and $z \sim 0$, with low-metallicity ($-2 < [Z/H] < -1$, where $Z \equiv \text{Zn, S or Si I}$) absorbers the norm at all redshifts (e.g. Kulkarni et al. 2005). This lack of metallicity evolution runs contrary to expectations that the interstellar metallicity should rise towards lower redshifts if DLAs trace the bulk of gas in galaxies. Moreover, only a few tens of DLAs have their galactic counterparts identified, of which only a small fraction have been spectroscopically confirmed (e.g. Chen & Lanzetta 2003). Our understanding of the basic physical properties of the absorbing galaxies, such as their mass, size, star formation rates and luminosity, remains very limited.

H I 21-cm absorption studies of DLAs towards radio-loud quasars provide an independent probe of physical conditions in the absorbers. They can be combined with optical measurements of the H I column density of the DLA (from the Lyman $\alpha$ line) to obtain the column-density-weighted harmonic mean spin temperature $T_s$ of the absorbing gas, allowing one to determine the temperature distribution of the H I along the line of sight. Measurements of $T_s$ in a large number of DLAs may ultimately be used to infer other galactic properties of high-redshift systems. For example, in the local Universe, large spiral discs such as the Milky Way and M31 typically have low $T_s$ values ($\lesssim 300$ K; Braun & Walterbos 1992) while high $T_s$ values ($\sim 1000$ K; Young & Lo 1997) are more common in dwarf galaxies. Tentative evidence for a similar trend has been found in low-z DLAs, out to $z \sim 0.7$ (Kanekar & Chengalur 2003). If such correlations hold for DLAs at all redshifts, measurements of $T_s$ and its evolution, would provide interesting insights into galaxy evolution.

Unfortunately, despite a number of searches over the past two and a half decades (e.g. Briggs & Wolfe 1983; Carilli et al. 1996; Chengalur & Kanekar 2000; Kanekar & Chengalur 2003), spin temperature estimates are available for only 15 DLAs (of which 10 are lower limits) at $z \gtrsim 1.7$ (Kanekar et al., in preparation). All of

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these previous high z measurements yield high spin temperatures of $T_e \gg 300$ K. There are a number of reasons why the crop of $T_e$ estimates has increased slowly over the last 25 years, including observational issues such as the frequency coverage of radio telescopes and widespread radio frequency interference (RFI) at the low frequencies ($\lesssim 1$ GHz) of the redshifted 21-cm line. However, an additional important reason for the relatively small present 21-cm absorption sample is simply the dearth of known DLAs towards radio-loud QSOs suitable for 21-cm absorption follow-up. We have hence been conducting an optical survey of low-frequency-selected radio-loud quasars, specifically designed to increase the number of $T_e$ estimates in the redshift range $2 < z < 4$. While the survey is still in progress, we report here its first results, the detection of 21-cm absorption from the $z \sim 2.289$ DLA towards TXS 0311+430, the first case of a low spin temperature in a high-z DLA.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Optical observations

Optical observations of $\sim 50$ QSOs selected from the Texas 365-MHz survey (Douglas et al. 1996) have been conducted at various facilities in order to identify DLAs suitable for 21-cm follow-up. As part of this campaign, we observed TXS 0311+430 ($B = 21.5$, $z_{em} = 2.87$) with the Gemini Multi-Object Spectrograph (GMOS) on the Gemini-North telescope. We obtained seven 2300-s and one 1700-s long-slit spectra of TXS 0311+430, using a 1.0-arcsec slit and the B600_G5303 disperser. The central wavelength was set to 4590 Å for four of the exposures and to 4620 Å for the other four, so as to achieve continuous wavelength coverage despite the gap between CCD chips in the GMOS detector. The CCD was binned $2 \times 2$. The final spectrum has a resolution of 4.1 Å (full width at half-maximum) and extends from $\sim 3550$ to 6050 Å; this range allows the detection of DLAs in the redshift interval $1.92 \lesssim z \lesssim 2.87$, with the upper limit set by the quasar redshift.

The GMOS data were reduced using standard IRAF routines including bias subtraction, flat-field correction, extraction using APALL, wavelength fitting (the root mean square (rms) error on the wavelength fits was $\lesssim 0.14$ Å), and finally, vacuum and heliocentric velocity wavelength corrections; the full procedure for this and the other optical spectra of our survey will be described in York et al. (in preparation). The final signal-to-noise ratio (S/N) ranged from $\sim 8$ per pixel at 3600 Å to $\sim 20$ per pixel at 6000 Å. The GMOS observations resulted in the detection of a DLA at $z \sim 2.289$ (see Section 3.1).

2.2 Radio observations

An initial search for 21-cm absorption at the DLA redshift was carried out with the PFI-450 MHz receiver of the Green Bank Telescope (GBT; programme AGBT-06B-042) on 2006 September 12. We used the GBT Spectral Processor as the back-end, with a bandwidth of 1.25 MHz centred at 431.808 MHz, two circular polarizations, 1024 spectral channels and a spectral resolution of $\sim 0.85$ km s$^{-1}$ (before any smoothing). The data were taken in total power mode, with On/Off position switching (with a 10-min On/Off cycle made up of 2-s integrations) and online measurements of the system temperature using a noise diode. The total on-source time was $\sim 35$ min.

Weak absorption was detected at the expected redshifted 21-cm frequency ($\sim 431.8$ MHz) in the September run. We hence repeated the observations on 2006 October 20 and 2007 January 4 to confirm the feature. The same observational set-up was used in these observing sessions, except for the use of linear instead of circular polarizations (as laboratory calibration information was not available for the circular polarizations; we will hence not further discuss the September data). The total on-source time on TXS 0311+430 was $\sim 50$ min and $\sim 65$ min in October and January, respectively. A calibrator, PKS B0316+162, was also observed during the October session, with the same setup, to test for RFI at the observing frequency. The calibrator was observed for a total of 25 on-source minutes, broken into two runs, alternating with two runs on TXS 0311+430.

The GBT data were analysed in AIPS++ using the DTHS package of single-dish routines. After the initial data-editing, to remove scans with correlator problems and RFI, the data were calibrated (assuming a telescope gain of 2 K Jy$^{-1}$) and averaged together to measure the flux density of TXS 0311+430. This yielded flux densities of $(6.2 \pm 0.7)$ Jy in October and $(6.7 \pm 0.7)$ Jy in January, where the errors include those from confusing sources in the primary beam [note that Ficarra, Gruen & Tomassetti (1985) measured $(4.94 \pm 0.10)$ Jy at 408 MHz]. A second-order spectral baseline was then fitted to RFI- and line-free channels for each 2-s spectrum (during calibration) and subtracted out. The residual 2-s spectra were then averaged together and Hanning-smoothed to obtain the final spectrum for each epoch. A similar procedure was followed to obtain the final spectrum towards PKS B0316+162; the flux density of which was measured to be $(9.4 \pm 0.7)$ Jy in the October session. Intermittent low-level RFI was seen near the absorption frequencies in all three runs and careful data-editing was hence necessary, especially for the January data.

We also obtained a 602-MHz continuum image of TXS 0311+430 with the Giant Metrewave Radio Telescope (GMRT) in 2007 March, to determine the spatial structure of the quasar radio emission and derive an estimate of the covering factor. The total on-source time was 1.5 h, with a 16-MHz bandwidth centred at a frequency of 602 MHz and subdivided into 128 channels. The standard calibrator 3C48 was used for flux density and bandpass calibration. These data were analysed in classic AIPS, using standard procedures (e.g. Kanekar, Chengalur & Lane 2007).

3 SPECTRA AND RESULTS

3.1 Lyman $\alpha$ and metals

Damped Lyman $\alpha$ absorption is clearly visible in the GMOS spectrum towards TXS 0311+430, at $z = 2.289 \pm 0.002$. The Lyman $\alpha$ profile, shown in Fig. 1(a), yields an HI column density of $N$(HI) = $(2.0 \pm 0.5) \times 10^{20}$ cm$^{-2}$, derived by overlying damped profiles using the Starlink tprso software. We quote a conservative error of 25 per cent, to encompass the range of reasonable ‘by-eye’ profiles as well as systematic errors from the continuum fit. Next, although our spectral coverage was such that only a few metal lines associated with the DLA are outside the Lyman $\alpha$ forest, we were able to detect the Si $\equiv$ λ1526, Si $\equiv$ λ1808 and Al $\equiv$ λ1670 transitions at the DLA redshift; their equivalent widths are listed in Table 1 and the Si $\equiv$ λ1808 profile shown in Fig. 1(b). Despite the low resolution of our spectrum ($\sim 200$ km s$^{-1}$), all three metal lines have resolved structure, indicating a large velocity width and multiple spectral components. Both the Al $\equiv$ λ1670 and Si $\equiv$ λ1526 lines are usually very strong and heavily saturated in DLAs, and the high rest frame equivalent widths indicate that this is indeed the case for the absorber towards TXS 0311+430. Conversely, Si $\equiv$ λ1808
is often unsaturated in DLA spectra and can therefore be used to
derive an abundance for silicon. However, in the present case, the
high rest frame equivalent width of the Si\(\text{II}\) line suggests
that it too is likely to be saturated. None the less, by assuming that
the Si\(\text{II}\) line is in the linear part of the curve of growth, it
is possible to obtain a lower limit on the Si\(\text{II}\) column density and
hence, on the metallicity of the DLA. The Si\(\text{II}\) column density is
\(N(\text{Si}\text{II}) \geq 2.7 \times 10^{15}\ \text{cm}^{-2}\), giving \([\text{Si}/\text{H}] \geq -0.48\). This is an unusually
high metallicity among DLAs, including those in radio-selected
QSOs (Akerman et al. 2005). Among the 104 DLAs at \(z_{\text{abs}} > 1.6\)
in the compilation by Prochaska et al. (2007), there are only three
absorbers with higher values of the silicon abundance.

Our estimates of \(N(\text{Si}\text{II})\), and hence \([\text{Si}/\text{H}]\), may be lower limits,
because we have assumed no line saturation and no depletion of
Si on to dust grains. On the other hand, it is possible that we may
have overestimated the equivalent width of the Si\(\text{II}\) line through unrecognized blending with other features in our
low-resolution GMOS spectrum. The work of Herbert-Fort et al.
(2006) – see, in particular, fig. 5 – shows that in low-resolution
spectra from the Sloan Digital Sky Survey this effect can lead one
to overestimate \(N(\text{Si}\text{II})\) by as much as a factor of three. Higher
resolution spectra, and observations of other spectral lines such as
Zn\(\text{II}\) at \(\lambda 2026, 2062\), should help resolve these ambiguities.

We also examined the GMOS spectrum for possible absorption
at other redshifts and detected a strong Mg\(\text{II}\) system at \(z \sim 1.069\).
The large rest-frame equivalent widths of the Mg\(\text{II}\)\(\lambda\lambda 2796, 2803\)
doublet (>3 \(\AA\)) and the Fe\(\text{II}\)\(\lambda 2600\) line (>2.3 \(\AA\)) in this absorber
(see Table 1) imply that it too is likely to be a DLA (Rao, Turnshek
& Nestor 2006).

### 3.2 Radio spectroscopy and imaging

The final H\(\text{I}\) 21-cm spectra from the October and January observing
sessions are shown in panels (a) and (b) of Fig 2, with the

<table>
<thead>
<tr>
<th>Transition</th>
<th>(z)</th>
<th>EW (m(\text{A}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si(\text{II})(\lambda 1526)</td>
<td>2.290 ± 0.003</td>
<td>761 ± 58</td>
</tr>
<tr>
<td>Al(\text{II})(\lambda 1670)</td>
<td>2.290 ± 0.002</td>
<td>787 ± 45</td>
</tr>
<tr>
<td>Si(\text{II})(\lambda 1808)</td>
<td>2.289 ± 0.002</td>
<td>169 ± 32</td>
</tr>
<tr>
<td>Fe(\text{II})(\lambda 2344)</td>
<td>1.069 ± 0.002</td>
<td>2606 ± 80</td>
</tr>
<tr>
<td>Fe(\text{II})(\lambda 2374)</td>
<td>1.069 ± 0.002</td>
<td>1385 ± 98</td>
</tr>
<tr>
<td>Fe(\text{II})(\lambda 2382)</td>
<td>1.069 ± 0.002</td>
<td>2374 ± 84</td>
</tr>
<tr>
<td>Fe(\text{II})(\lambda 2586)</td>
<td>1.069 ± 0.002</td>
<td>1595 ± 68</td>
</tr>
<tr>
<td>Fe(\text{II})(\lambda 2600)</td>
<td>1.068 ± 0.002</td>
<td>2313 ± 61</td>
</tr>
<tr>
<td>Mg(\text{II})(\lambda 2796)</td>
<td>1.068 ± 0.001</td>
<td>3115 ± 70</td>
</tr>
<tr>
<td>Mg(\text{II})(\lambda 2803)</td>
<td>1.069 ± 0.001</td>
<td>3109 ± 72</td>
</tr>
<tr>
<td>Mg(\text{I})(\lambda 2852)</td>
<td>1.069 ± 0.001</td>
<td>–</td>
</tr>
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Figure 1. (a) The damped Lyman \(\alpha\) profile at \(z \sim 2.289\) towards
TXS 0311+430. The dashed line shows our fit to the profile, which yields
\(N(\text{H}\text{I}) = (2.0 \pm 0.5) \times 10^{20}\ \text{cm}^{-2}\). The dotted lines show the 1\(\sigma\) errors on
the fit. The dashed vertical line here (and in the lower panel) indicates \(z = 2.289\). (b) The Si\(\text{II}\)\(\lambda 1808\) line from the \(z \sim 2.289\) DLA.

Figure 2. GBT H\(\text{I}\) 21-cm spectra towards TXS 0311+430, with optical
depth (in units of \(10^3 \times \tau\)) plotted against barycentric frequency, in MHz.
The dashed vertical line is at \(z = 2.289766\). Panels (a) and (b) show the
spectra from the October and January runs while panel (c) shows the final
GBT spectrum, obtained by combining the spectra of panels (a) and (b). The
shaded regions in the top two panels show frequency ranges affected by RFI.
Both these ranges have been blanked out in panel (c).
towards the calibrator source, combined with the expected Doppler shift over a 3-month period, rules out RFI as a possible cause for the absorption seen towards TXS 0311+430.

Fig. 2(c) shows the final GBT 21-cm spectrum towards TXS 0311+430, obtained by averaging the spectra from October and January with appropriate weights (based on the rms noise values), after scaling the January spectrum to a flux density of 6.2 Jy. Regions affected by RFI in either spectrum have been blanked out (note that these are well-removed from the absorption feature and thus do not affect our optical depth measurement). The rms noise on this spectrum is ∼ 10.4 mJy, i.e. at z = 2.289766(19). The integrated optical depth is T ∝ V dV = (0.818 ± 0.085) km s⁻¹, with the error dominated by the uncertainty in the source flux density.

Fig. 3 shows the GMRT 602-MHz continuum image of TXS 0311+430. The image has a resolution of 6.0 × 4.1 arcsec (i.e. a spatial resolution of ∼ 50 × 34 kpc² at z = 2.289) and an rms noise of 0.6 mJy Bm⁻¹; no evidence for extended structure can be seen. A single elliptical Gaussian component provides a good fit, yielding an integrated flux density of 3.58 Jy and a deconvolved size of 4.1 arcsec. Further, while the continuum image is at a somewhat different frequency from the redshifted 21-cm line, the lack of any detected extended emission suggests that the quasar is also very compact at the latter frequency.

### 3.3 The spin temperature

For 21-cm absorption studies of DLAs towards radio-loud QSOs, the 21-cm optical depth, HI column density, and spin temperature Tₜ, are related by the expression

$$N(HI) = 1.823 \times 10^{18} \left( \frac{T}{T_r} \right) \int \tau dV,$$

where N(HI) is in cm⁻², T in K, dV in km s⁻¹ and the 21-cm absorption is assumed to be optically thin. In the case of multiple H I clouds along the line of sight, Tₜ is the column-density-weighted harmonic mean of the spin temperatures of the individual clouds. Note that the use of the above equation to estimate the spin temperature of the DLA implicitly assumes that the H I column densities along the optical and the (usually more extended) radio lines of sight are the same. The covering factor f gives the fraction of the radio flux density covered by the foreground DLA; this can be estimated by very long baseline interferometric (VLBI) observations at or near the redshifted 21-cm line frequency, to measure the fraction of flux density arising from the compact radio core, as well as its spatial extent (e.g. Kanekar et al. 2007).

The z = 2.289 DLA towards TXS 0311+430 has an H I column density N(HI) = (2 ± 0.5) × 10²⁰ cm⁻² and an integrated 21-cm optical depth of ∫ dV = (0.818 ± 0.085) km s⁻¹. No VLBI measurements are available in the literature at any radio frequency. However, the sub-arcsec size estimate from the GMRT 602-MHz image indicates that the quasar is strongly core-dominated and suggests a high covering factor, f ∼ 1. Using this, we obtain Tₜ = (138 ± 36) fK, one of the lowest spin temperatures ever found in a DLA and the only low value currently known at z > 1.

### 4 DISCUSSION

Spin temperature estimates have so far been obtained in more than thirty DLAs at all redshifts, including fifteen detections of 21-cm absorption (Kanekar et al., in preparation). Only four absorbers, all at z < 0.6, show low spin temperatures, Tₜ < 350 K, typical of lines of sight through the Milky Way and local discs (Kanekar & Chengalur 2003). Another 11 systems, all with Tₜ > 500 K, have been detected in 21-cm absorption (of which only four are at z ≥ 2; Wolfe & Davis 1979; Wolfe & Briggs 1981; Kanekar et al. 2006, 2007) while the remaining DLAs without detectable 21-cm absorption all have 3σ lower limits of > 700 K on the spin temperature.

The preponderance of high spin temperature estimates in high-z DLAs has usually been attributed to a relatively low fraction of the cold neutral phase of HI (the CNM), with most of the gas in the warm phase (the WNM) (e.g. Carilli et al. 1996; Chengalur & Kanekar 2000). This assumes that the absorbers have a similar two-phase structure to that seen in the ISM of the Milky Way (e.g. Wolfe, Gawiser & Prochaska 2003). The low spin temperature of the z = 2.289 DLA towards TXS 0311+430 would then imply that a higher fraction of the H I along the line of sight is in the CNM compared with the majority of DLAs at z ≥ 2. Chengalur & Kanekar (2000) argued that the high derived Tₜ values of high-z DLAs could be due to the low metallicities of typical high-z DLAs, with the paucity of metals resulting in fewer radiation pathways for gas cooling (see also Young & Lo 1997). If this is correct, one would expect DLAs with low spin temperatures (such as the absorber towards TXS 0311+430) to be less common at high redshifts.

3 Note that this does not include the z = 0.656 DLA towards 3C336 (Curran et al. 2007), where the background radio source is strongly lobe-dominated, with a very small core fraction. The very extended radio structure (corresponding to a spatial extent of ∼ 195 kpc² at z = 0.656) implies that the radio and optical absorption almost certainly arise from very different lines of sight (a possibility discussed by Curran et al.).
to have significantly higher metallicities than those of the general DLA population (Kanekar & Chengalur 2001). As expected, and assuming that the Si ii $\lambda 1808$ equivalent width has not been overestimated, the $z \sim 2.289$ DLA has [Si/H] $\geq -0.4$ 8, one of most metal-rich DLAs yet discovered.

It has also been suggested that the observed low 21-cm optical depth in high-$z$ DLAs arises due to covering factor effects (e.g. Curran et al. 2005). In the present case, any reduction in the covering factor below the assumed value of unity can only strengthen the case for a low spin temperature [as $T_s = (138 \pm 36) K$]. The only way to alter the conclusion that a sizeable fraction of H i along the line of sight is in the cold phase is if there are large spatial differences in the H i column densities along the optical and radio lines of sight (e.g. Wolfe et al. 2003). For example, if the optical QSO lies behind a ‘hole’ in the H i column density distribution, the average H i column density against the radio QSO could be larger than that measured from the Lyman $\alpha$ line, implying a higher spin temperature from equation (1). Unfortunately, it is very difficult to directly test this possibility. While Galactic H i column densities derived from Lyman $\alpha$ absorption studies are in excellent agreement with those obtained from H i 21-cm emission observations in the same directions, despite the very different spatial resolutions in the two methods, such comparisons have only been carried out for a fairly small number of high latitude lines of sight (Dickey & Lockman 1990). A similar comparison between $N$(H i) values derived from Lyman $\alpha$ absorption and 21-cm emission has only been possible in one DLA, the $z \sim 0.009$ absorber towards SBS 1543+593. Here, the H i column densities agree within a factor of ~2, despite the extremely poor spatial resolution ($\sim 5.3 h_{70}^{-1}$ kpc) of the radio observations (Chengalur & Kanekar 2002). While both of these studies suggest that the $N$(H i) values along the radio and optical lines of sight are likely to be comparable, we cannot formally rule out the possibility of differences in an individual absorber. However, the fact that the expected high metallicity is indeed seen in the $z \sim 2.289$ DLA (assuming that our $N$(Si ii $\lambda 1808$ measurement is accurate) is consistent with the interpretation of a high CNM fraction.

Finally, Kanekar & Chengalur (2003) noted a relationship between spin temperature and absorber morphology, in that, at low redshifts, low $T_s$ values are only found in DLAs identified with luminous disc galaxies, while low-$z$, low-luminosity DLAs, associated with dwarf or LSB galaxies, are all found to have high spin temperatures ($T_s \geq 700$ K). It has not been possible to test this empirical relationship at $z > 1$, as the host galaxies of high-$z$ DLAs are rarely detectable. However, if the relationship does extend out to high redshifts, we would expect the $z \sim 2.289$ DLA to be a massive, luminous disc galaxy. We note that both the high metallicity and the large velocity spreads seen in the optical low-ionization metal lines and the 21-cm absorption are consistent with the absorption arising in a massive galaxy. If so, it should be possible to detect the absorber host with deep imaging; this would be the first direct test of the $T_s$-morphology relationship at high redshifts.

In summary, we have detected damped Lyman $\alpha$ and H i 21-cm absorption at $z = 2.289$ towards the quasar TXS 0311+430. We obtain a DLA spin temperature of $T_s = (138 \pm 36) K$, the first case of a low spin temperature estimate in a high-redshift DLA. The low spin temperature, high metallicity and large velocity spread of the 21-cm and metal lines all suggest that the absorber is likely to be a massive disc galaxy.

**ACKNOWLEDGMENTS**

We thank Carl Bignell and Bob Garwood for much help with the GBT observations and AIPS++ data analysis. The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the NSF. We thank the staff of the GMRT who made these observations possible; the GMRT is run by NCRA-TIFR. Based on observations obtained at the Gemini Observatory (programme ID GN-2005B-Q-60), which is operated by the AURA, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the NSF (United States), the STFC (United Kingdom), the NRC (Canada), CONICYT (Chile), the ARC (Australia), CNPq (Brazil) and CONICET (Argentina). BAY was supported in part by a grant from the NSERC (Canada).

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