DETECTING COLD GAS AT INTERMEDIATE REDSHIFTS: GIANT METREWAVE RADIO TELESCOPE SURVEY USING Mg II SYSTEMS

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ABSTRACT

Intervening H i 21 cm absorption systems at \( z \geq 1.0 \) are very rare, and only four confirmed detections have been reported in the literature. Despite their scarcity, they provide interesting and unique insights into the physical conditions in the interstellar medium of high-\( z \) galaxies. Moreover, they can provide independent constraints on the variation of fundamental constants. We report three new detections based on our ongoing Giant Metrewave Radio Telescope (GMRT) survey for 21 cm absorbers at 1.10 \( \leq z_{\text{abs}} \leq 1.45 \) from candidate damped Ly\( \alpha \) systems. The 21 cm lines are narrow for the \( z_{\text{abs}} = 1.3710 \) system toward SDSS J0108−0037 and \( z_{\text{abs}} = 1.1726 \) system toward SDSS J2358−1020. Based on line FWHM, the kinetic temperatures are \( \leq 5000 \) and \( \leq 800 \) K, respectively. The 21 cm absorption profile of the third system, \( z_{\text{abs}} = 1.1908 \) system toward SDSS J0804+3012, is shallow, broad, and complex, extending up to 100 km s\(^{-1} \). The centroids of the 21 cm lines are found to be shifted with respect to the corresponding centroids of the metal lines derived from SDSS spectra. This may mean that the 21 cm absorption is not associated with the strongest metal-line component.

Subject headings: quasars: absorption lines — radio lines: galaxies

Online material: color figures

1. INTRODUCTION

The diffuse interstellar medium exhibits a wide range of physical conditions such as temperature, density, and radiation field that are influenced by in situ star formation, cosmic-ray energy density, photoelectric heating by dust, as well as mechanical energy input from impulsive disturbances such as supernova explosions and the steady injection of energy in the form of stellar winds. Therefore, understanding the physical conditions in the gas and the processes that maintain these is important for understanding galaxies and their evolution. The damped Ly\( \alpha \) systems (DLAs), with log \( N(H\ i) \geq 20.3 \), are a major reservoir of H i at high \( z \) and possibly the progenitors of present-day galaxies (see Wolfe et al. 2005). At high \( z \), despite many attempts, only a handful of DLA galaxies have been detected based on line and/or continuum emission (see Möller et al. 2004).

Our understanding of physical conditions in DLAs at \( z \geq 1.8 \) is based primarily on the absorption lines of H\( \text{ii} \) molecules and atomic fine-structure lines. A systematic search for H\( \text{ii} \) in DLAs at \( z_{\text{abs}} > 1.8 \) has resulted in a detection in \(-15\%\) of the cases (see Ledoux et al. 2003). Usually, the DLAs with H\( \text{ii} \) absorption also show absorption lines of C i, C ii, C iii, and C iv. Detailed investigations show that H\( \text{ii} \) components have properties similar to that of the cold neutral medium (CNM) in a radiation field of moderate intensity originating from local star formation activity (Srianand et al. 2005). Using C ii absorption lines, Wolfe et al. (2004) have concluded that most of the DLAs at high \( z \) consist of CNM gas. However, the above techniques cannot be used to probe the nature of the gas at low and intermediate redshifts. In this case detecting 21 cm absorption line is one complementary way to probe the nature of absorbing gas.

There have been several systematic searches for 21 cm absorption in DLAs undertaken by various groups (Briggs & Wolfe 1983; Lane 2000; Kanekar & Chengalur 2003; Curran et al. 2005) with limited success. To date, in the literature 38 DLAs have been searched for 21 cm absorption, resulting in 17 detections most of which occur at \( z < 1 \) (see Fig. 1).

The column density of H i for an optically thin cloud that covers a fraction \( f_c \) of the background source is related to the optical depth \( \tau(v) \) in a velocity interval \( v \) and \( v + dv \) and to the spin temperature \( (T_s) \) by

\[
N(H\ i) = (1.835 \times 10^{18} \text{ cm}^{-2}) \frac{T_s}{f_c} \int \tau(v)dv. \tag{1}
\]

The low detection rate at high \( z \) can therefore be attributed to either the gas being warm (high \( T_s \)) or a low value of the covering factor \( (f_c) \) through high-\( z \) geometry effects (see Kanekar & Chengalur 2003 and Curran & Webb 2006, respectively). However, the redshift coverage is sparse and measurements are available only for a few systems at \( 1 \leq z \leq 2 \) (Fig. 1). To improve the statistics we have started a systematic survey of 21 cm absorption at 1.10 \( \leq z \leq 1.45 \) using the 610 MHz receiver at GMRT. Here we report the results from the first phase of this survey that has resulted in three new detections.

Obtaining a new DLA sample at \( z \leq 1.6 \) is virtually impossible in the absence of UV spectrographs in space as the redshifted wavelength of Ly\( \alpha \) line falls below the atmospheric cutoff. However, Rao & Turnshek (2000) have shown that the DLAs can be preselected on the basis of equivalent widths of Mg ii, Fe ii, and Mg i absorption lines. Specifically, they found that 30% of the absorbers with rest-frame W(Fe ii \( \lambda 2600 \)) and W(Mg ii \( \lambda 2796 \)) greater than 0.5 \( \text{ Å} \) were confirmed DLAs. The detection rate becomes 100% when W(Mg i) \( \geq 0.5 \) \( \text{ Å} \). It is also clear from Fig. 3.4 of Lane (2000) that such a selection will also ensure that 50% of these candidates are detected in 21 cm absorption. Motivated by this, we have begun a GMRT 21 cm survey of DLA candidates selected on the basis of W(Mg ii) in the redshift range 1.10 \( \leq z \leq 1.45 \). Our complete sample is drawn from the catalog of 7421 Mg ii systems with W(Mg ii) \( \geq 1 \) \( \text{ Å} \) and 0.3 \( \leq z \leq 1.9 \), detected along the line of sight toward 45,023 QSOs in the Sloan Digital Sky Survey (SDSS) Data Release 3.
Fig. 1.—Line histogram is the redshift distribution of the DLAs for which redshifted 21 cm observations are reported (Table 1 of Curran et al. 2005 and \( z = 2.347 \) toward PKS 0438–436 from Kanekar et al. 2006). Shaded histogram is for the confirmed 21 cm absorption systems. The redshift range covered in our GMRT survey is also marked.

There are 2857 systems at \( 1.10 \leq z \leq 1.45 \). Of these, we have selected the 26 systems that have an estimated 610 MHz flux density in excess of 100 mJy from the NVSS and FIRST catalogs. These form our main sample. In addition to this, we have also observed three other sources (J0108–0037 [York et al. 2006], J0240–2309, and J1604–0019 [Lanzetta et al. 1987]) that have total flux density at 610 MHz in excess of 1 Jy and have strong Mg II systems.

2. OBSERVATIONS AND RESULTS

In the first phase of our GMRT survey we have observed 10 systems (Table 1) from our sample. Usually, a 1 MHz bandwidth split into 128 frequency channels was used to acquire data in the systems (Table 1) from our sample. Usually, a 1 MHz bandwidth redshifted 21 cm observations are reported (Table 1 of Curran et al. 2005 and Prochter et al. 2006). There are 2857 systems at 1.10

### TABLE 1

| Name                | \( z_{\text{abs}} \) | Time (hr) | Peak Flux | rms | \( \tau \) |
|---------------------|----------------------|-----------|-----------|-----|-----|
| J0108–0037          | 1.3710               | 4.4       | 1276      | 2.9 | 0.07 |
| J0214+1405          | 1.4463               | 4.4       | 220       | 2.7 | <0.012 |
| J0240–2309          | 1.3647               | 8.0       | 5100      | 5.2 | <0.001 |
| J0748+3006          | 1.4470               | 5.5       | 347       | 3.5 | <0.010 |
| J0804+3012          | 1.1908               | 6.0       | 2050      | 1.9 | 0.006 |
| J0845+4257          | 1.1147               | 5.0       | 224       | 3.0 | <0.013 |
| J1017+5356          | 1.3055               | 4.4       | 127       | 2.3 | <0.018 |
| J1411–0500          | 1.4160               | 3.9       | 244       | 3.0 | <0.012 |
| J1604–0019          | 1.3245               | 3.3\(^{\text{ii}}\) | 375       | 3.9 | <0.010 |
| J2358–1020          | 1.1726               | 3.9\(^{\text{iii}}\) | 443       | 1.4 | 0.033 |
|                     | ...                  | 5.0\(^{\text{iv}}\) | 420       | 2.5 | 0.035 |

\(^{\text{a}}\) Peak flux (mJy beam\(^{-1}\)).

\(^{\text{b}}\) Spectral rms (mJy beam\(^{-1}\) channel\(^{-1}\)).

\(^{\text{c}}\) Peak optical depth or \( \tau \) peak.

\(^{\text{d}}\) 2 MHz bandwidth.

\(^{\text{e}}\) The two spectra correspond to peaks P1 and P2.

\(^{\text{f}}\) 256 channels used.

\(^{\text{g}}\) 0.5 MHz bandwidth.

Fig. 2.—GMRT \( \text{H} \alpha \) spectra of the sources with 21 cm absorption. Single Gaussian fits are overplotted in the case of J0108–0037 and J2358–1020. Arrows mark the expected positions of 21 cm absorption based on the metal absorption lines. See the electronic edition of the Journal for a color version of this figure.

In most of the cases the background quasar is unresolved for the typical 5\(^{\prime\prime} \times 5\(^{\prime\prime}\) synthesized beam achieved in our observations. However, for J0804+3012, J1411–0300, and J1604–0019 the radio sources are extended (see Fig. 4). For J0804+3012, 21 cm absorption is detected in the spectrum extracted toward the radio peak (Fig. 2). Higher spatial resolution as well as S/N observations will be required to investigate its variation across the source. In the case of J1411–0300, the radio peak is not consistent with the location of the optical source. The 21 cm absorption is not detected toward either the strongest radio peak (P1) or another peak (P2) northeast to P1 (Figs. 3 and 4). No 21 cm absorption is detected toward any of the three prominent radio peaks seen in J1604–0019. Figure 3 shows the spectrum toward the central component. A narrow absorption is present with \( \tau_{\text{peak}} \sim 0.04 \pm 0.01 \) and FWHM = 6.1 ± 2.3 km s\(^{-1}\) near the expected frequency toward J0845+4257 (see Fig. 3). The feature is present in both the polarizations and in the spectra extracted using different baselines and time ranges. At this stage we consider this as a tentative detection.

2.1.  \( z_{\text{abs}} = 1.3710 \) System toward J0108–0037

The 21 cm absorption profile is well fitted with a single Gaussian having \( \tau_{\text{peak}} = 0.068 \pm 0.002 \) and FWHM = 15.4 ± 0.6 km s\(^{-1}\). From the observed optical depth we get the integrated column
Thus is uncertain. Assuming thermal broadening, gives a gas density, \( N(H\ i) = 2.1 \times 10^{18} T_c (f_c) \) cm\(^{-2}\). High-frequency VLBA observations suggest structures extending over 60 mas (~50 pc; \( H_o = 71 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.27\), \( \Omega_{\Lambda} = 0.73\)) with significant flux density in extended emission (Beasley et al. 2002). Thus \( f_c \) is uncertain. Assuming thermal broadening, gives a gas kinetic temperature \( T_K = 21.86 \times (\text{FWHM/km s}^{-1})^2 \leq 5200 \) K. This is an upper limit as various other effects also could contribute to the line width. Now we can assume \( T_K = T_c \) as is the case for thermodynamic equilibrium. If the gas is a typical CNM (say \( T_K = 100 \) K) then \( \log [f_c N(H\ i)] = 20.50\). Thus, \( N(H\ i) \) in the 21 cm component is consistent with it being a DLA. The 21 cm centroid is within 4 km s\(^{-1}\) to that expected from the metal lines detected in the SDSS spectrum. The Zn \( \Pi + \) Cr \( \Pi \) blend at \( \lambda = 2062 \) Å, the Si \( \Pi \lambda 1808\) and the Mn \( \Pi \) lines are clearly detected even in the low-dispersion SDSS spectrum.

2.2. \( \zeta_{\text{abs}} = 1.1908\) System toward J0804+3012

The 21 cm absorption is clearly detected toward J0804+3012 which is partially resolved in our observations (Fig. 4). The absorption profile is consistent with a main component (with FWHM ~ 44 ± 19 km s\(^{-1}\) and \( \tau_{\text{peak}} = 0.006 \pm 0.001\)) and a broad wing (extending up to ~100 km s\(^{-1}\)) toward higher frequency. Our two-epoch observations with different spectral resolution confirm the main component which also shows the expected Doppler shift. However, deeper observations are required to ascertain the strength of the wing. It is interesting to note that the expected position of 21 cm absorption based on the SDSS spectrum coincides with the wing of the 21 cm absorption and not the stronger main component. Based on the profile obtained on 15–16 September 2006, we get an integrated column density of \( N(H\ i) = 6.5 \times 10^{17} (T_c/f_c) \) cm\(^{-2}\). Unlike the other two 21 cm absorbers, we do not detect Si \( \Pi \lambda 1808\) (with \( W \leq 0.3 \) Å) and Zn \( \Pi \lambda 2026\) lines (with \( W \leq 0.2 \) Å) in the SDSS spectrum.

2.3. \( \zeta_{\text{abs}} = 1.1726\) System toward J2358−1020

Relatively weak 21 cm absorption is clearly detected and the profile can be well fitted with a single Gaussian component with \( \tau_{\text{peak}} = 0.035 \pm 0.004\) and FWHM = 6.0 ± 0.8 km s\(^{-1}\) (Fig. 2). This implies \( T_K \leq 800 \) K and \( \log [f_c N(H\ i)] \leq 20.5\) in the 21 cm absorbing component. If the absorbing gas happens to be a CNM, then \( \log [f_c N(H\ i)] = 19.6\). The value of \( f_c \) could be close to unity as VLBA observations at 5 GHz by Fomalont et al. (2000) show the source to be ≤0.5 mas, which corresponds to a projected size of ≤54 pc at \( \zeta_{\text{abs}} = 1.1726\). Thus, the inferred range in \( N(H\ i) \) is consistent with the 21 cm absorbing gas being a sub-DLA. Like the previous system, the 21 cm absorption is shifted by 70 km s\(^{-1}\) with respect to the optical redshift based on the SDSS data. The Zn \( \Pi + \) Cr \( \Pi \) blend at \( \lambda = 2062 \) Å is clearly detected in the SDSS spectrum. The compactness of the background radio source and the simplicity...
of the 21 cm absorption profile make this system an ideal case for probing the variation of fundamental constants.

3. DISCUSSION

In this Letter we have reported the detection of 21 cm absorption in three systems. This has substantially increased the number of 21 cm absorption systems at $z > 1.0$, as prior to this only four systems were known. In two of our systems ($z_{\text{abs}} = 1.1908$ toward J0804+3012 and $z_{\text{abs}} = 1.1726$ toward J2358/H11002) and different line ratios. Solid and dotted histograms are, respectively, for our GMRT sample and the sample of DLAs (downscaled by a factor of 2) studied by Rao & Turnshek (2000). Light and dark histograms are for the systems observed for 21 cm absorption so far and the systems with detections, respectively. [See the electronic edition of the Journal for a color version of this figure.]

As the energy of the 21 cm transition depends on the electron-to-proton mass ratio ($\mu$), the fine-structure constant ($\alpha$), and the proton G-factor ($G_p$), high-resolution optical spectra in conjunction with high-resolution 21 cm spectra can be used to probe the variation of these constants (Tzanavaris et al. 2005). However, it is important first to understand the origin of the relative shifts that we observe between the redshifts of the atomic heavy element lines and the 21 cm absorption. This needs detailed modeling of the absorption systems taking into account all transitions simultaneously. This is what we plan to do in the near future.

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