Probing Galaxies through Quasar Absorption Lines
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HI 21cm absorption studies of damped Lyman-α systems

Nissim Kanekar[1]
and Jayaram N. Chengalur[2]

[1]National Radio Astronomy Observatory, Socorro, USA
email: nkanekar@aoc.nrao.edu

[2]National Centre for Radio Astrophysics (TIFR), Pune, India
email: chengalu@ncra.tifr.res.in

Abstract. HI 21cm absorption spectroscopy provides an independent probe of the nature of damped Lyman-α systems (DLAs), yielding information on their ISM conditions, kinematics, and spatial extent. We find that the majority of DLAs have significantly higher spin temperatures than seen in the Milky Way and local spirals, indicating larger fractions of the warm phase of HI, especially at high redshifts. Present data suggests that the spin temperature might be used as a secondary indicator of the nature of the absorbing galaxy. We have succeeded in spatially resolving the 21cm absorption in two $z \sim 0.4$ DLAs, thus obtaining lower limits on the transverse extent of these absorbers.

1. Introduction

Damped Lyman-α systems (DLAs), the highest HI column density absorbers seen in QSO spectra, are expected to arise in the precursors of present-day galaxies (e.g. Wolfe *et al.* 1986). Despite their importance in the context of galactic evolution, the typical size and structure of DLAs, and physical conditions in them, have long been issues of controversy. Redshifted HI 21cm absorption studies of DLAs toward radio-loud background sources provide an entirely independent means of probing the nature of these systems, notably the kinematics, temperature, and distribution of the absorbing gas (see Kanekar & Briggs 2004 for a recent review). In this article, we describe our recent results from such radio studies, primarily based on work with the Giant Metre-wave Radio Telescope (GMRT) and the Green Bank Telescope (GBT).

2. Physical conditions in DLAs : the spin temperature

The information that can be derived from 21cm absorption studies depends critically on the compactness of the background radio source and whether the lines of sight to the radio and optical/UV continua are the same. In such cases, one can combine the 21cm optical depth τ_{21} with the HI column density (obtained from the Lyman-α line) to obtain the spin temperature $T_{\rm s}$ of the absorbing gas, through the equation (e.g. Rohlfs 1986),

$$N_{\rm HI} = 1.823 \times 10^{18} \; [T_{\rm s}/f] \int \tau_{21} \, {\rm d}V \ , \tag{2.1}$$

where $N_{\rm HI}$ is in cm^{-2}, $T_{\rm s}$ in K, and dV in km s^{-1}. The covering factor f gives the fraction of radio flux covered by the absorbing gas; this can be estimated from VLBI observations at the redshifted 21cm line frequency. We note that the spin temperature obtained from the above equation is *not* necessarily a physical temperature but, for a

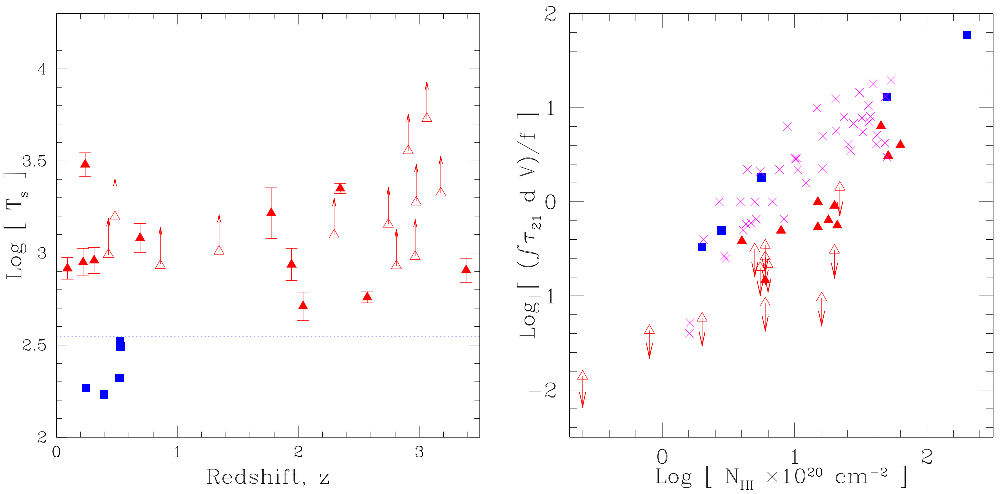

Figure 1. [A] Left panel : the spin temperature T_s as a function of redshift for the 28 DLAs of the sample. DLAs identified with spiral galaxies are shown with filled squares. [B] Right panel : the "true" equivalent width ($\mathrm{Log}[(\int \tau dV)/f]$) plotted as a function of HI column density (Log $[N_{\mathrm{HI}}]$), for the 28 DLAs of the sample. The crosses show measurements in The Galaxy by Colgan *et al.* (1988) and Payne *et al.* (1982), using 21cm emission/absorption studies.

multi-phase medium, is the column-density-weighted harmonic mean of T_s values of different HI phases along the line of sight. T_s thus contains information about the relative fractions of gas in the cold and warm phases, besides their actual temperatures. Furthermore, T_s is biased toward cold gas; for example, a line of sight with half of the HI at 100 K and the other half at 10^4 K would have $T_s \sim 200$ K, while T_s is only ~ 1000 K even if 90% of the HI is at 10^4 K and the rest at ~ 100 K.

Redshifted 21cm lines arise at frequencies where strong terrestrial radio-frequency interference (RFI) is common, due to, for example, TV stations, cellular phones, ham radios, etc. Furthermore, 21cm optical depths in DLAs are usually very small ($\tau \lesssim 0.1$), due to the weak strength of the transition. Detecting such lines thus requires radio telescopes with large collecting area and good frequency coverage, as well as locations in a relatively clean RFI environment. The recently commissioned GMRT and GBT are the best current telescopes for such observations. Despite this, observations at some frequencies (e.g. ~ 475 MHz, corresponding to $z \sim 2$) appear near-impossible due to strong terrestrial transmissions and may have to await next generation instrumentation like the SKA, with modern RFI-suppression techniques (e.g. Briggs, Bell & Kesteven 2000).

Earlier 21cm studies have found T_s values in DLAs to be significantly higher than those seen in the Milky Way or local spirals (e.g. Wolfe, Briggs & Jauncey 1981; Carilli *et al.* 1996; Briggs, Brinks & Wolfe 1997; Lane *et al.* 1998); however, the small size of the sample made it very difficult to detect any clear trends. Furthermore, hardly any DLAs were known at low redshifts, $z \lesssim 1.6$, as detection of the Lyman-α line here requires space-based observing, making blind surveys impossible with current instrumentation. In recent times, however, the size of the low z sample has been significantly increased by the MgII-selected DLA surveys of Rao & Turnshek (2000). Similarly, the CORALS survey (Ellison *et al.* 2001) has resulted in a sizable sample of DLAs toward radio-loud QSOs at higher redshifts ($z \gtrsim 2.2$). And, as mentioned above, the commissioning of the

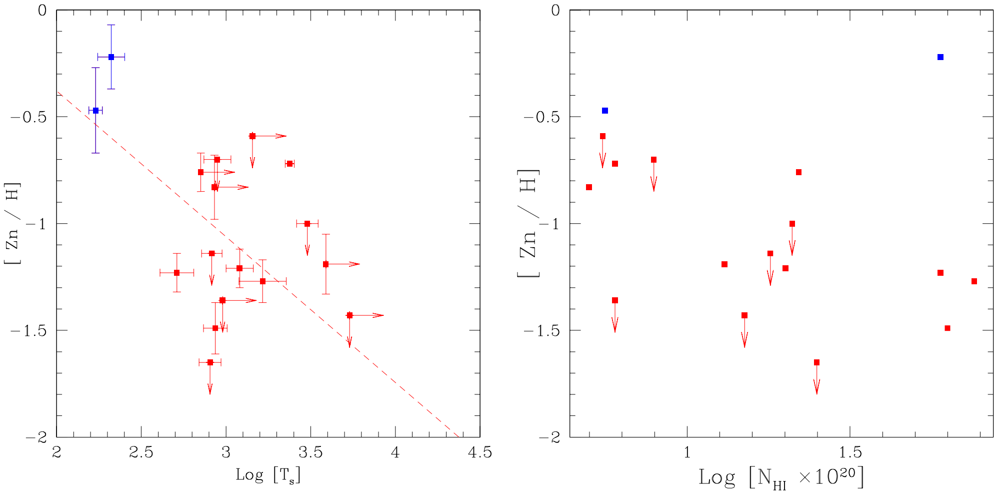

Figure 2. [A] Left panel : Metallicity ([Zn/H]) plotted as a function of T_s. A clear anti-correlation can be seen between metallicity and spin temperature. [B] Right panel : Metallicity ([Zn/H]) plotted as a function of HI column density for the 17 absorbers of the left panel. No trend can be identified between the two quantities.

GMRT and the GBT has allowed access to a significantly wider frequency range than before, with high sensitivity.

We have used the GMRT and the GBT to carry out deep searches for 21cm absorption in thirty-one DLAs, with $0.09 \lesssim z \lesssim 3.4$ (e.g. Chengalur & Kanekar 1999; Chengalur & Kanekar 2000; Kanekar & Chengalur 2003; Kanekar & Chengalur 2005a; Kanekar *et al.* 2005). This has resulted in the detection of HI absorption in 12 DLAs, with stringent upper limits on the 21cm optical depth in most other cases. Eight of the new detections are at $z < 0.6$, one at $z \sim 1.4$, two at $z \sim 2.4$, and one at $z \sim 3.4$. We have also used VLBI observations at either the redshifted 21cm line frequency or at two frequencies bracketing the line frequency to estimate the covering factor f for most of the absorbers in the sample. The sample of DLAs with 21cm absorption searches now consists of 35 systems, of which 28 have fairly reliable estimates of the spin temperature.

Fig. 1[A] shows a plot of spin temperature against redshift for the above 28 absorbers. The dotted horizontal line in the figure is at 350 K — more than 80% of spin temperature measurements in the Milky Way and M31 have values < 350 K (Braun & Walterbos 1992). It can be seen that the spin temperatures of the majority of DLAs are considerably higher than those typical of lines of sight through the Milky Way or nearby spiral disks. The only exceptions are five absorbers at low z, shown as solid squares; interestingly enough, all of these have been identified with $L \sim L_\star$ galaxies (e.g. Le Brun *et al.* 1997; Rao *et al.* 2003). Conversely, $z < 1$ DLAs with $T_s \gtrsim 1000$ K have been found to be associated with low luminosity systems, such as dwarfs or low surface brightness galaxies, with no bright spirals close to the line of sight (e.g. Rao *et al.* 2003).

Fig. 1[B] shows a direct comparison between DLAs and Galactic HI clouds, through a plot of the “true” HI 21cm equivalent width (i.e. $(1/f)\int \tau \mathrm{d}V$) against the HI column density (Kanekar & Chengalur 2003). The triangles and squares show the DLAs of our sample, with the squares again indicating absorbers identified with bright galaxies. The crosses represent Galactic HI clouds (Colgan, Salpeter & Terzian 1988; Payne, Salpeter & Terzian 1982), with the equivalent width and HI column density measured using 21cm absorption/emission studies. At a given HI column density, it is clear that most DLAs have significantly smaller 21cm equivalent widths than those found for lines of sight through The Galaxy. The only exceptions are DLAs associated with spiral galaxies, which do indeed lie within the range of Galactic values.

The very different $T_{\rm s}$ values in low z DLAs identified as dwarfs and spirals can be understood as arising due to the different fractions of warm and cold phases of neutral gas (WNM and CNM respectively) in these galaxies. Higher $T_{\rm s}$ values are to be expected in smaller systems like dwarfs, whose low metallicities and pressures are not conducive to the formation of the CNM (Wolfire *et al.* 1995). Such systems hence have a substantially higher fraction of warm HI as compared to normal spirals, and, therefore, a higher $T_{\rm s}$ on an average line of sight. On the other hand, spirals like the Milky Way have roughly equal fractions of warm and cold HI; the above bias of $T_{\rm s}$ toward colder temperatures implies that lines of sight through such systems would, on average, yield lower $T_{\rm s}$ values. The conclusion would thus appear to be that the majority of DLAs contain larger fractions of the warm (and thus weakly absorbing) phase of neutral hydrogen than typical in nearby spirals, as earlier pointed out by Carilli *et al.* (1996) and Kanekar & Chengalur (2001). This is especially true at high redshifts, with only one detection of 21cm absorption at $z \gtrsim 3$; all eight $z \gtrsim 3$ DLAs show $T_{\rm s} \gtrsim 1000$ K, indicating that these systems contain small fractions of the CNM ($\lesssim 20\%$).

The low z results of Fig. 1[A] suggest that $T_{\rm s}$ might be used as a secondary indicator of the nature of an absorbing galaxy, to “distinguish” between dwarfs and large spirals. If true, this would be very interesting, as one might then use $T_{\rm s}$ measurements to verify whether galaxies at high z are small or large systems, in a statistical sense. An obvious first test of the above hypothesis is to directly measure the fractions of cold and warm HI in specific DLAs to verify that the WNM fraction is indeed higher in systems with a high $T_{\rm s}$. This has so far been carried out for two low z DLAs, toward the quasar OI363, where high spectral resolution 21cm studies have succeeded in separating the contributions of the cold and warm phases to the 21cm optical depth (Lane, Briggs & Smette 2000; Kanekar, Ghosh & Chengalur 2001). These observations have shown that the WNM fraction is $\gtrsim 70\%$ in the $z \sim 0.0912$ absorber and $\gtrsim 75\%$ in the $z \sim 0.2212$ system. Thus, the high $T_{\rm s}$ values obtained in at least these two DLAs are indeed the result of a higher WNM fraction.

Next, if high $T_{\rm s}$ values arise because the ISM in small galaxies is inefficiently cooled due to the lack of metals (and hence a lack of radiation pathways), one would expect an anti-correlation to exist between spin temperature and metallicity (Kanekar & Chengalur 2001). We have recently used VLT-UVES to measure the metallicity (i.e. [Zn/H]) in a sample of DLAs with $T_{\rm s}$ measurements. Fig. 2[A] shows a plot of [Zn/H] vs. $T_{\rm s}$ for the 17 absorbers of the present sample; the predicted anti-correlation is indeed seen to be present, at $> 3\sigma$ significance from the Kendall Tau test. Fig. 2[B] plots [Zn/H] vs. HI column density for the same 17 absorbers, to test whether the anti-correlation in Fig. 2[A] might arise due to a dependence on $N_{\rm HI}$, which is used in estimating both [Zn/H] and $T_{\rm s}$. No trend can be identified here, with the data consistent with a scatter plot; this suggests that the trend between metallicity and spin temperature is a genuine one. Note that this sample contains DLAs from both high and low redshifts.

The above results suggest that the spin temperature is indeed a possible indicator of the nature of the absorbing galaxy. Fig. 1[A] then indicates that the majority of damped systems of the present 21cm sample arise in dwarf or LSB galaxies, with only a few systems (at low redshifts) being luminous disks.

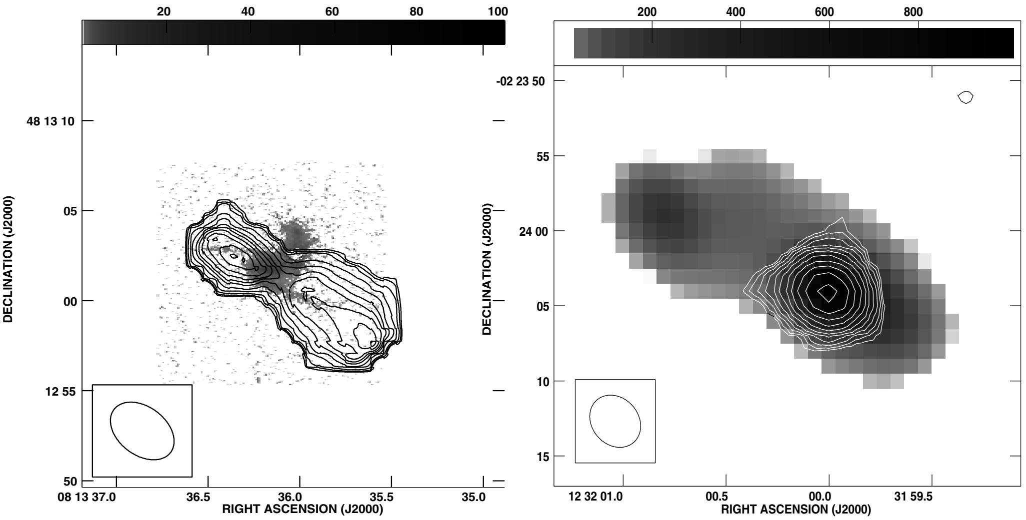

Figure 3. [A] Left panel : the integrated 21 cm optical depth toward 3C196 (contours; Kanekar & Chengalur 2005b), overlaid on an HST image (greyscale; Cohen *et al.* 1996; Ridgway & Stockton 1997). [B] Right panel : the integrated 21 cm optical depth toward PKS 1229−021 (contours), overlaid on a GMRT continuum image of the source at the redshifted 21cm frequency (greyscale).

3. The spatial extent of DLAs : HI 21cm mapping studies

While the results of section 2 suggest that $T_{\rm s}$ might be used to differentiate between large and small galaxies, it would be even more exciting to actually measure the physical sizes of the absorbers, their kinematics, and gas distributions. The most direct way of doing this is through 21cm emission observations; unfortunately, the sensitivity of today's radio telescopes limits such studies to fairly low redshifts. However, information about the size and gas kinematics of DLAs can also be obtained from 21cm absorption studies, in cases where the background radio continuum is extended on scales larger than the synthesised telescope beam (see discussion in Kanekar & Briggs 2004). Note that such information cannot be obtained through optical or ultraviolet spectroscopy, as the background continuum is unresolved at these wavelengths; even cases of multiple images, if the background quasar is lensed by a foreground galaxy, provide only a few lines of sight through the absorbing system.

We have used the GMRT to obtain such spatially resolved 21cm absorption images at $z \sim 0.437$ toward the radio galaxy 3C196 (Kanekar & Chengalur 2005b). Fig. 3[A] shows the zeroth velocity moment of the integrated absorption, in contours, overlaid on an HST image, in grey-scale (Cohen *et al.* 1996). The two main components of the 21cm profile were found to arise from absorption in two arms of a large barred spiral, against the S-W hot-spot and the Eastern lobe of 3C196, as originally argued by Briggs, de Bruyn & Vermeulen (2001). No absorption was detected from the N-E hot-spot. HI absorption was detected out to a radius of $\sim$ 35 kpc, far beyond the extent of the optical galaxy. Similarly, we have also detected extended 21cm absorption from the $z \sim 0.395$ DLA toward PKS 1229−021 (Brown & Spencer 1979), showing that the absorber has a physical size larger than $\sim$ 30 kpc. Fig. 3[B] shows the zeroth velocity moment of the integrated absorption toward PKS 1229−021, in contours, overlaid on a GMRT continuum image of the background source at the 21cm line frequency. These observations have only now become possible, due to the combination of high sensitivity, excellent frequency coverage, and long interferometric baselines at the GMRT.

In summary, 21cm absorption studies of DLAs provide an excellent complement to information on these systems obtained from other wavebands. The recent commissioning or upgrade of telescopes such as the GMRT, the GBT, and the WSRT has resulted in a dramatic improvement in radio spectroscopic instrumentation, making this an exciting time for studies of galactic evolution using redshifted radio lines.

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