ORT observations of the damped Lyman-α system towards PKS 0201+113

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ABSTRACT
We report a deep radio search with the Ooty Radio Telescope (ORT) for the redshifted 21 cm absorption line from the damped Lyman-α system seen at redshift 3.388 against the quasar PKS 0201+113. This is currently the most distant system for which a detection of 21 cm absorption has been claimed. The present observations have a sensitivity comparable to the earlier ones and detect no statistically significant absorption. We use the non-detection to place an upper limit of $\sim 0.011$ on the optical depth of the damped Lyman-α absorber. This corresponds to a lower limit of $\sim 5600$ K to the spin temperature of the system. This is considerably higher than the previous upper limit of $\sim 1380$ K.

Key words: quasars: absorption lines – quasars: individual: PKS 0201+113 – cosmology: observations.

1 INTRODUCTION.
In the highest HI column density systems seen in absorption against distant quasars, the line profile shape is dominated not by motions of the gas but rather by the intrinsic Lorentzian wings. These so-called damped Lyman-α systems are the dominant known repository of neutral gas at high redshifts. Systematic optical studies of such systems have established that $\Omega_{HI}$, the ratio of the density of neutral gas to the critical density, increases rapidly with increasing redshift and, at high redshift, ($z \geq 2$) is similar to $\Omega_{stars}$, (the ratio of the density of luminous material to the critical density), in the local universe (Lanzetta et al. 1991, Rao & Briggs 1995). This is consistent with the idea that the damped Lyman-α systems are the precursors of $z = 0$ disk galaxies.

However, the comoving number density of damped Lyman-α systems is approximately 4 times that of normal spiral galaxies, (Wolfe et al. 1986) , so, if these systems are truly the precursors of spirals, then either there were more precursors than current spirals or the precursors had, on the average, much larger disks. Another significant difference between the observed properties of damped Lyman-α systems and nearby spirals is that the inferred spin temperature, $T_s$, of the gas in damped Lyman-α systems is a factor of $\sim 5$ larger than that observed, for similar HI column densities, either in our galaxy or Andromeda (Wolfe & Davis 1979, Carilli et al. 1996). The spin temperature is inferred from the combination of the optical depth in the 21 cm line and the column density, which is in turn obtained from the equivalent width of the damped profile. This derivation rests on the assumption that the gas seen in absorption against the optical quasars (which have miniscule transverse sizes) completely covers the entire radio continuum emitting region of the quasars (which are often tens of kiloparsecs in size). Direct VLBI observations of 0458-020 (Briggs et al. 1989) have shown that, in this one case at least, the absorbing gas has a transverse extent of at least 8 kpc.

In this paper, we report a deep radio search for the redshifted 21 cm absorption line from the damped Lyman-α system seen at $z = 3.388$ towards the quasar PKS 0201+113. This is the highest redshift system for which a detection of 21 cm HI absorption has been reported (de Bruyn, O’Dea & Baum 1996, Briggs, Brinks & Wolfe 1997). de Bruyn et

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al. used the Westerbork Synthesis Radio Telescope (WSRT) and reported a peak 21 cm optical depth of $\sim 0.085$ with a very narrow velocity width ($\sim 9 \text{ km} \text{ s}^{-1}$). Briggs et al. observed the system with both Arecibo and the VLA. The Arecibo spectrum shows an absorption feature with a peak optical depth of $\sim 0.037$, but with a much larger velocity extent ($\sim 25 \text{ km} \text{ s}^{-1}$) than that seen at the WSRT. The VLA spectrum showed no statistically significant absorption; this is marginally consistent with the Arecibo result, given the sensitivity of the two observations. Our own observations have a noise level which is intermediate between the levels of the Arecibo and VLA spectra and also show no statistically significant absorption feature.

The rest of the paper is divided as follows; section 2 describes the observations, data reduction and results while section 3 contains a discussion of the current and previous observations.

## 2 OBSERVATIONS AND RESULTS.

Ooty Radio Telescope (Swarup et al. 1971) observations of PKS 0201+113 were carried out in two stretches, the first from the 29th of December, 1996 to the 5th of January, 1997 and the second from the 14th to the 17th of January, 1997. The source was observed for about 8 hours (broken up into several 2 to 2.5 hour sessions) each day, with a spectrum being recorded every 2 minutes. The observations were performed using the telescope as a two element interferometer with the northern half of the telescope being correlated with the southern half. The backend bandwidth of 768 kHz was divided into 256 spectral channels, giving a frequency resolution of 6 kHz after a single Hanning smoothing. The centre of the band was at a sky frequency of 323.704 MHz. A strong interference line seen at the edge of the band was traced to various PCs at the observing site and was greatly reduced by switching most of them off during the observations.

The data reduction was carried out using WASP (Chengalur 1996). The system gain was calibrated using the radio source 0710+118, (Bogers et al., 1994) whose declination is similar to that of 0201+113; the ORT gain is a function of declination. A flux density of 11.1 Jy was assumed for the purpose of calibration. The calibrator was observed for 10 minutes at the end of each observing session; the gain was found to be stable to within a few percent over our entire observing run. The raw spectra were corrected for the instrumental gain and bandpass shape using the calibrator data. The corrected spectra were then carefully inspected for any contamination due to interference and a total of ~17 hours of data was discarded on this basis. An iterative procedure was then run, which fitted a third order polynomial to each 2 minute spectrum, identified ‘bad’ channels, and then created a summary spectrum of all good channels. This was done separately for the data from each 2.5 hour session. "Bad" channels were defined as those in which the rms (over time) exceeded 2 times the rms noise for ‘good’ channels. Further, any individual spectral point with an absolute deviation from the median greater than 6 times the average rms of "good" channels was also flagged to remove isolated radio frequency interference (RFI) spikes. This procedure removed most of the RFI; however, some low level interference did persist at channels 163-165 and channels 194-195. These regions were blanked in the final spectrum before applying the final smoothing.

The spectral baseline in an interferometric setup contains contributions from the visibilities of distant continuum sources, our polynomial fitting procedure removes much of this contribution. We also tried fitting first and second order polynomials to the spectra, the results are substantially the same, except for the presence of a low level broad ripple across the spectrum. Since this ripple and our bandwidth are both separately much broader than the width of the absorption line that we are looking for, our baseline fitting procedure should not significantly bias our detection limits. In a small fraction (~5 hours) of the data, extremely strong absorption (60-100 mJy) was seen close to the expected location of the redshifted 21 cm line. This feature was, however, extremely narrow (~1-2 channels wide). The feature was seen for about 1 hour on 4 separate days of observation. Since the data stretches immediately before and after these 1 hour stretches displayed no such absorption, it seems likely that it is caused by some kind of interference, although its nature is not clear. (Note that the ORT is equatorially mounted; hence its beam does not rotate across the sky.) These data stretches were also dropped before creating the final averaged spectrum. The latter was created by the weighted average of the Doppler shifted 2.5 hour summary spectra, where the per channel weights account for both the total integration time in each summary spectrum and the number of spectral points which were flagged. The Doppler shifting was done by linear interpolation; the total shift across the entire observing run was less than one smoothed channel. The final spectrum contains the data from 76 hours of observations.

The final edited spectrum is shown in Fig. 1[A] with the expected line frequency (determined from optical spectroscopy), indicated along with its 1σ error bars. The rms noise level on the final spectrum is ~3.7 mJy, which agrees well with the expected noise level. Gaussians of various widths were then fitted to the data and the most significant feature is found to occur at a depth of ~3.7 mJy with a width of $24 \pm 6$ kHz and a central frequency of 323.758 $\pm 0.006$ MHz. Both the central frequency and the FWHM are similar to the Briggs result ($\nu_c = 323.764 \pm 0.005$ MHz and $\Delta \nu = 25 \pm 5$ kHz); however, the depths of the two features are quite different. Fig. 1[C] shows the ORT spectrum smoothed to a resolution of 24 kHz for the purpose of comparison with the Arecibo result, shown here as a dotted line. de Bruyn et al. detected (albeit at low significance) a very narrow line, their model fit to the line is shown superimposed on the ORT spectrum (smoothed to a resolution of 9
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**Figure 1.** [a] Spectrum of PKS 0201+113. The 21 cm line frequency corresponding to the optical redshift is shown, along with 1σ error bars. [b] shows the spectrum smoothed to a resolution of 9 kHz; the Gaussian fit to the WSRT feature is shown as a dotted line. [c] shows the spectrum smoothed to a resolution of 24 kHz for comparison with the Arecibo absorption line, shown here as a dotted line.

kHz to match the WSRT spectrum) in Fig. 1[B].

3 DISCUSSION.

There are two major issues which need to be addressed, (1) the implications of our observations, taken by themselves, for the physical conditions in the damped Lyman-α absorber and (2) a comparison between the present observations and the earlier ones made with other telescopes. We consider each of these in turn.

As discussed in the introduction, radio observations of the redshifted 21 cm absorption from damped Lyman-α systems have traditionally been used to estimate the spin temperature in these systems. The critical assumptions involved here are that the damped Lyman-α system is homogeneous and completely covers the background radio source. The column density of HI obtained along the narrow line of sight to the background quasar can then be used in conjunction with the observed optical depth in the 21 cm line to estimate the spin temperature of the gas using the standard expression (eg. Rohlfs 1986)

\[
N_{HI} = 1.82 \times 10^{18} \int \tau T_s dV
\]

where \(\tau\) is the optical depth in the 21 cm line; \(N_{HI}\) is in per cm\(^2\), \(T_s\) in K and \(dV\) in km s\(^{-1}\).

In the present case, the HI column density is \(N_{HI} = 2.51 \times 10^{21}\) per cm\(^2\) (White, Kinney & Becker 1993). We use a continuum flux density of 350 mJy (de Bruyn et al. 1996) and obtain an upper limit of \(\tau_{max} = 0.011\) to the optical depth (Briggs et al. quote a continuum flux density of 290 ± 5 mJy; using this value would give \(\tau_{max} = 0.013\)). Since the optical depth is inversely related to \(T_s\), this implies a lower limit of \(\sim 5600\) K to the spin temperature.

0201+113 is a compact GPS source (with angular size < 5 mas at 1.6 GHz, Hodges, Mutel & Phillips 1984), making it likely that the damped Lyman-α absorber completely covers the radio continuum. On the other hand, as noted...
by de Bruyn et al., the 18 cm VLA maps (Stanghellini et al. 1990) show a weak secondary component located ∼ 2" (10 kpc at the redshift of the absorber) south of the optical quasar; however, the flux in this component (at 18 cm) is only a small fraction of the total flux. If the absorbing gas is not at all at the same spin temperature, then, as has been long appreciated, the derived spin temperature is the harmonic mean of the spin temperatures of each of the constituents, weighted by their column densities. Our lower limit to $T_s$ should be regarded as a lower limit to the phase with the highest spin temperature. We note also that our observations have low sensitivity to gas with a very large (∼ a few hundred km s$^{-1}$) velocity dispersion; the spin temperature calculation assumes that there is very little gas with such large dispersion.

Turning now to the second issue, viz. that of a comparison between the present observations and the earlier ones, we begin by noting that our lower limit of ∼ 5600 K to the spin temperature appears to be at odds with the Arecibo and WSRT results of $T_s$ ∼ 1380 K and $T_s$ ∼ 1100 K, respectively. (Although the line profiles obtained from the WSRT and Arecibo observations are vastly different, the integrated optical depth inferred from both these observations are roughly the same; this results in similar values for the spin temperature.) Our results are in excellent agreement with the VLA spectra in Briggs et al. (1997) and are marginally consistent with the Arecibo spectra if one allows the possibility of 3σ deviations from both results. The WSRT detection is in strong disagreement with all the other observations; however, the rms noise level there is much higher than that of the others. Both the Arecibo and the WSRT features were seen to show the expected Doppler shift over the observing period. The ORT observations were carried out ∼ 3 years after the Arecibo detection with the VLA observations 2 years prior to this. This gives rise to the interesting possibility that physical conditions in the source (or, possibly, in the absorbing system) might vary on these time scales, thereby causing the discrepancy in the results. Such an explanation also removes the necessity for fortuitous noise effects which must be otherwise postulated to bring the 3 observations into marginal consistency. We consider this possibility below.

Initially, we note that the depth of the line is a function both of the incident continuum flux density and the optical depth of the absorbing system. This implies that changes in the physical conditions in either the source or the damped Lyman-α cloud can have drastic effects on the line depth. Variability in the absorbing system is unlikely due to the difficulty in co-ordinating the variation in the properties of a cloud of size of the order of a few parsecs. Further, motion of (or within) the cloud itself also seems an implausible explanation as it would require relativistic speeds unless the cloud was extremely inhomogenous. On the other hand, PKS0201+113 is an active galactic nucleus which is extremely compact. Hence, variation of its continuum flux over time scales of ∼ 2 years would not be extremely surprising. Both the ORT and Arecibo observations did not have simultaneous measurements of the continuum flux but rely on earlier results. If the Arecibo observations were carried out at a time when the flux density was significantly higher than the VLA value, a high value of $\tau$ would be estimated which would result in a low estimate of the spin temperature. We note that the VLA and WSRT estimates of the quasar flux differ by ∼ 20 per cent over a period of ∼ 6 months. However, even if this difference is interpreted as being entirely due to variability of the source, it is not quite enough to produce the observed differences in the spectra; a change in the flux density by a factor of ∼ 2 is required, on a time scale of ∼ 2 years. This is, of course, presently in the realm of speculation and the source should probably be monitored to confirm or deny its variability before any firm conclusions can be drawn about the physical conditions in the system.

4 SUMMARY

We report ORT observations of the damped Lyman-α system at $z = 3.388$ towards the quasar PKS0201+113. No absorption feature deeper than 3.7 mJy is seen at or near the expected location of the 21 cm line. This places an upper limit of 0.011 on the optical depth, $\tau$; earlier estimates of HI column density from damped Lyman-α observations are then used to derive a lower bound of ∼ 5600 K on the spin temperature of the absorbing system. This is considerably larger than the previous upper limit of ∼ 1380 K.

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