A SEARCH FOR H i 21 cm ABSORPTION TOWARD THE HIGHEST REDSHIFT (z \sim 5.2)
RADIO-LOUD OBJECTS

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Received 2006 December 4; accepted 2007 March 25

ABSTRACT

We have searched for H i 21 cm absorption toward the two brightest radio AGNs at high redshift, J0924−2201 at z = 5.20 and J0913+5919 at z = 5.11, using the Giant Metrewave Radio Telescope. These data set a 3 \sigma upper limit to absorption of <30% at 40 km s\(^{-1}\) resolution for the 30 mJy source J0913+5919, and <3% for the 0.55 Jy source J0924−2201 at 20 km s\(^{-1}\) resolution. For J0924−2201, limits to broader lines at the few percent level are set by residual spectral baseline structure. For J0924−2201 the column density limit per 20 km s\(^{-1}\) channel is \(N(\text{H} i) < 2.2 \times 10^{19} T_I \text{ cm}^{-2}\) over a velocity range of \(-700 \text{ to } +1180\) km s\(^{-1}\) centered on the galaxy redshift determined through CO emission, assuming a covering factor of 1. For J0913+5919 the column density limit per 40 km s\(^{-1}\) channel is \(N(\text{H} i) < 2.2 \times 10^{19} T_I \text{ cm}^{-2}\) within \(\pm 2400\) km s\(^{-1}\) of the optical redshift. These data rule out any cool, high column density H i clouds within roughly \(\pm 1000\) km s\(^{-1}\) of the galaxies, as are often seen in compact steep-spectrum radio AGNs, or clouds that might correspond to residual gas left over from cosmic reionization.

Key words: cosmology: observations — galaxies: high-redshift — radio lines: galaxies

1. INTRODUCTION

Observations of H i 21 cm absorption at cosmologically significant redshifts provide important probes into a number of physically interesting problems (Kanekar & Briggs 2004). First, associated systems probe the immediate environment of the AGN and the ISM in the host galaxy. In particular, searches for H i 21 cm absorption toward compact symmetric radio sources (CSOs) show that in the overwhelming majority of sources (\(\geq 80\%\)) absorption is detected at optical depth levels between 4% and 40%, with line widths ranging from about 50 to 500 km s\(^{-1}\) (Peck et al. 2000). CSOs are thought to be young radio jet sources (\(<10^7\) yr), possibly confined by a dense ISM in the host galaxy (Conway 2002). The high H i 21 cm detection rate is thought to be due to the fact that the radio emission is confined to the inner regions of the galaxy (scales \(<10\) kpc), and hence H i 21 cm absorption searches probe the dense gaseous environs in the centers of the host galaxies.

Second, studies of intervening H i 21 cm absorption systems, in concert with observations of damped Lyα absorption, have been used to constrain the evolution of the excitation, or spin temperature, of the neutral gas. Results suggest an increasing fraction of warm neutral gas with increasing redshift for damped Lyα systems (Kanekar & Chengalur 2003; Carilli et al. 1996). This increase might be due to a change in the nature of the parent galaxy of the absorption-line system from large spirals at low z to smaller dwarf and irregular galaxies at higher z (Kanekar & Chengalur 2003), or it could be a cosmological geometry effect, relating to the very slowly changing value of the angular diameter distance for redshifts greater than unity or so (Curran & Webb 2006).

Third are the recent observational constraints on the epoch of reionization (EoR), suggesting that cosmic reionization started around \(\sim 11\), with the last neutral structures being etched away around \(z \sim 6\) (Fan et al. 2006a). It has been pointed out that the existence of radio-loud AGNs within the near edge of cosmic reionization could be used as sensitive probes of intermediate- to small-scale structures in the neutral IGM, through H i 21 cm absorption observations (Carilli et al. 2002; Furlanetto & Loeb 2002), as opposed to the very large scale that can be studied in emission.

In this paper we present a search for H i 21 cm absorption toward two z \(> 5\) radio sources. While not quite extending into the EoR, these sources are the highest redshift bright radio AGNs known, and the redshifts are close enough to the end of reionization (within 200 Myr) that we can explore the possibility of enhanced
residual cool neutral gas content in the vicinity of the host galaxy due to not—fully complete reionization of the densest regions of the universe (Gnedin 2000; Paschos & Norman 2005).

2. THE SOURCES

The source TN J0924−2201 is a radio galaxy with an optical redshift of \( z = 5.19 \pm 0.01 \) (van Breugel et al. 1999). The source was selected from low-frequency radio surveys as an “ultrasteep spectrum” source, with a flux density at 1.4 GHz of 73 mJy and a spectral index between 0.37 and 1.4 GHz of −1.63. Near-IR imaging has revealed a faint, clumpy source, while radio imaging shows a compact double with a separation of \( ~1'' \) (7 kpc), making this source a CSO. The Ly\( \alpha \) emission from this galaxy is clearly weaker than is normal for powerful radio galaxies. Van Breugel et al. (1999) suggest that the likely cause for the abnormally weak Ly\( \alpha \) line is associated Ly\( \alpha \) absorption, thereby indicating the presence of neutral H\( i \) on kiloparsec scales in the host galaxy. The complex near-IR structure, and the associated Ly\( \alpha \) rate in the host galaxy of Venemans et al. (2001). Venemans et al. (2004) estimate a star formation rate has not been corrected for reddenning, which may be substantial. Most recently, Klaer et al. (2005) have detected CO emission from this galaxy, indicating a large reservoir of molecular gas (\( \sim 10^{11} M_\odot \)) and providing a very accurate host galaxy redshift of \( z = 5.202 \pm 0.001 \). The source SDSS J0913+5919 is a luminous quasar at \( z = 5.11 \pm 0.02 \) (Anderson et al. 2001). Radio imaging at 1.4 and 5 GHz reveals a radio source with a flux density of 18 mJy at 1.4 GHz and a spectral index of \( -0.7 \) (Petric et al. 2003). The radio source is compact, but possibly marginally resolved at \( 1'' \) resolution, suggesting this source is a CSO. The optical spectrum of the source shows a relatively narrow Ly\( \alpha \) emission line for a quasar, again likely due to strong associated absorption and again indicating the presence of neutral H\( i \) in the host galaxy (Anderson et al. 2001). The optical luminosity of the QSO implies an Eddington-limited mass to the black hole \( \geq 10^8 M_\odot \), which would imply a massive host galaxy (\( \geq 10^{11} M_\odot \)) based on the black hole mass–bulge velocity dispersion relation (Gebhardt et al. 2000).

3. OBSERVATIONS

Observations were made in the 230 MHz band of the Giant Metrewave Radio Telescope (GMRT). Absolute flux density calibration was done using 3C 48 and 3C 286. The source J0837+001, centered on the expected frequency of the redshifted 21 cm line at a frequency of 232.5 ± 0.8 MHz. For this source we observed two polarizations of 4 MHz bandwidth each, centered on the expected frequency of the redshifted 21 cm line. The 128 spectral channels then yield a spectral resolution of 31.25 kHz, or 40.6 km s\(^{-1}\). 3C 286 was used for bandpass calibration.

For J0924−2201 the source redshift is \( z = 5.202 \pm 0.001 \), placing the 21 cm line at a frequency of 229.0 ± 0.1 MHz. An initial short (2 hr) test observation of this source was made in 2003 September to investigate the radio frequency interference (RFI) environment in the 229 MHz band of the GMRT. Although there was strong interference over much of the 4 MHz band, by careful flagging we were able to generate a spectrum of the spectral region immediately defined by the CO redshift, and interestingly, a potential (3 \( \sigma \) over a few 40 km s\(^{-1}\) channels) absorption line was seen.

We reobserved this source in 2004 February with a longer integration time (three observations of 7 hr each) and a narrower bandwidth (2 MHz) to verify this line. Unfortunately, the interference environment for this second observation was much worse than during the test observations, with only 1 or 2 late-night/early-morning hr per observation being useful. Moreover, the observations of the bandpass calibrators 3C 48 and 3C 286 were completely wiped out, and the phase calibrator 0837−198 had to be used for bandpass and gain calibration, assuming the flux density derived from the test observations. These latter (admittedly marginalized) data did not verify the line seen in the test data.

Given the problems with the second data set, we observed J0924−2201 a third time in 2005 November, separating the observations over three nights but observing only during the 2 hr per night corresponding to the lowest RFI levels and limiting the velocity range to just the 1 MHz band centered on the CO line redshift in order to avoid strong RFI at the edge of the wider band.

All data processing was performed using the wide-field imaging and self-calibration capabilities in AIPS.

4. DATA ANALYSIS

For the 2004 February observations of J0924−2201, all baselines shorter than 2 k\( \lambda \) (~50% of all baselines) were completely corrupted by wide-band RFI, and were therefore flagged. Also, all data were flagged except for roughly 2 hr in the middle of each night. For the 2005 November observations all baselines shorter than 1 k\( \lambda \) were flagged. Flagging of residual channel-by-channel interference removed ~30% of the channels of the remaining data.

For both sources wide-field images were then generated using standard wide-field imaging routines in AIPS, and the data were self-calibrated using the resulting models. For the first (phase-only) self-calibration iteration a model based on the NRAO VLA Sky Survey was used (Condon et al. 1998).

A general issue in low-frequency spectral line imaging is sidelobe confusion from bright sources in the primary beam. In our case this is especially a problem for J0913+5919, where sidelobe confusion is caused by two relatively bright sources (~2.4 and ~1.1Jy) well within the primary beam. In order to overcome this difficulty, proper modeling and subtraction of continuum sources is required. We used a combination of bright source model subtraction from the spectral line data using the AIPS task uvsub, plus spectral baseline fitting in the uv and image plane (uvlin) and in the image plane (imlin).

For the 2004 February observations of J0924−2201, the bandpass calibration using only the phase calibrator resulted in significant residual structure across the band. This was removed using a second-order polynomial fit in imlin, leaving a ~2% residual bandpass ripple across the spectrum. For 2005 November we found that bandpass calibration using 3C 286 was adequate to allow for a simple linear bandpass fit in the image plane using imlin.

In the case of J0913+5919, RFI on short baselines was limited to specific channels, and the data could therefore be edited quite efficiently using the AIPS tasks spflg, uvflg, and flgft, ultimately resulting in the removal of about 35% of all data. A
linear baseline was adequate for residual continuum subtraction with imlin.

5. RESULTS

Figure 1 shows the continuum image of each source. Both sources are unresolved at the resolution of the GMRT (~20′). J0913+5919 was found to have a flux density of 30 ± 3 mJy at 230 MHz, while J0924–2201 had a flux density of 0.55 ± 0.05 Jy. In both cases the errors represent observation-to-observation differences, likely due to residual errors in the flux density bootstrap process.

The continuum-subtracted spectrum of J0913+5919 is shown in Figure 2 (top). The rms noise is 3 mJy per 40.7 km s⁻¹ channel. At this resolution we find no absorption to a 3 σ optical depth limit of 0.3, over a velocity range of ±2400 km s⁻¹ centered on the optical redshift of z = 5.11 ± 0.02.

There is a broad depression in the J0913+5919 spectrum, covering much of the velocity range dictated by the optical redshift plus uncertainty. We have smoothed the spectrum to 164 km s⁻¹, and the result is shown in Figure 2 (bottom). The rms per channel is 2 mJy, and the depression can be seen centered at about 232.3 MHz, or z = 5.114, with a width of about nine channels, or 1500 km s⁻¹. The mean depth of the depression is about 2 mJy, or just 1 σ per channel, although this persists over nine channels. Note that we have used all of the channels shown for linear spectral baseline subtraction. If we exclude the nine line channels from the spectral baseline fit, the mean depression depth increases to almost 3 mJy. We do not consider this a line detection but a potential result that requires further observation.

Figure 3 shows the results for J0924–2201. Figure 3 (top) shows the wide-band spectrum from 2004 February, for which a second-order spectral baseline has been removed using all of the channels shown. We do not detect any absorption over the full band to an rms level of 11 mJy per 20 km s⁻¹ channel, corresponding to a 3 σ optical depth limit of 6%. The frequency range covered corresponds to −700 to +1180 km s⁻¹, centered on the CO redshift for the host galaxy. Figure 3 (middle) shows the spectrum from 2005 November at 20 km s⁻¹ resolution. Again, no absorption is detected to an rms level of 6 mJy per 20 km s⁻¹ channel, corresponding to a 3 σ optical depth limit of 3.3%. The frequency range covered corresponds to ±460 km s⁻¹. We have combined the two spectra, weighting by the rms, and the result is shown in Figure 3 (bottom). The rms per 20 km s⁻¹ channel is now 5 mJy, implying a 3 σ optical depth limit of 2.7%. Residual spectral baseline structure limits any broad (~1000 km s⁻¹) lines to <2%.

6. DISCUSSION

These GMRT observations set 3 σ upper limits to the H i optical depth toward J0924–2201 of 3% at 20 km s⁻¹ resolution within ±460 km s⁻¹ of the host galaxy redshift, and 6% over a wider velocity range of −700 to +1180 km s⁻¹. The column density limit per channel is then N(H i) < 1.1 × 10¹⁸Tₚ cm⁻² over the narrow range and < 2.2 × 10¹⁸Tₚ cm⁻² over the broader range, where Tₚ is the H i spin temperature. Residual broad spectral baseline structure limits any broad absorption line to < 2%. The column density limit is then < 1.8 × 10¹⁸Tₚ cm⁻² for a 500 km s⁻¹ line.

For the weaker radio source, J0913+5919, the optical depth limit is 0.3 at 40 km s⁻¹ resolution, within ±2400 km s⁻¹ of the optical redshift. The column density limit per channel is then N(H i) < 2.2 × 10¹⁸Tₚ cm⁻². There is a broad, weak depression in the center of the spectrum of about 1500 km s⁻¹ width with
a depth of about 7%, although this signal is really only \( \frac{1}{27} \) in nine channels, or roughly \( \frac{3}{27} \) averaged over all of the line channels. If real, the implied column density is \( N(\text{H} \, \text{i}) \sim 10^{20} T_s \, \text{cm}^{-2} \).

We consider this an upper limit to a broad line in this source, although further observations of this source would be very interesting.

We note that both sources in our study show evidence for an extended radio continuum source of \( \sim 10^3 \) in size (\( \sim 6 \) kpc; see § 2). Low \( \text{H} \, \text{i} \) covering factors of the continuum sources could also lead to low apparent optical depths.

For J0924–2201, assuming that the very weak Ly\( \alpha \) emission line from the host galaxy is due to a high column density (damped) associated Ly\( \alpha \) absorption-line system \( [N(\text{H} \, \text{i}) \sim 10^{21} \, \text{cm}^{-2}] \), and using the \( \text{H} \, \text{i} \) 21 cm limits above, suggests that the \( \text{H} \, \text{i} \) spin temperature is relatively high (more than a few hundred kelvins). For comparison, Galactic clouds with \( N(\text{H} \, \text{i}) \sim 10^{21} \, \text{cm}^{-2} \) typically have spin temperature values \( \sim 100 \) K for the absorbing gas (Dwarakanath et al. 2002). For damped Ly\( \alpha \) systems at \( z = 3 \) typical values for \( T_s \) on the order of \( 10^3 \) K are found (Carilli et al. 1996; Kanekar & Chengalur 2003).

These are (by far) the two brightest radio sources known at \( z > 5 \). The redshifts of these two sources place them within 200 Myr of the end of reionization (\( z \sim 6 \)), as determined from,
e.g., the Gunn-Peterson effect toward high-$z$ QSOs (Fan et al. 2006b). Further, these luminous AGNs are likely associated with denser regions of the universe, i.e., protoclusters, at the earliest epochs (Venemans et al. 2004). Given that reionization is likely a process extended in space and time (Fan et al. 2006a), two possibilities exist for the large-scale environments of the systems. There may be a significant residual population of dense H i clouds associated with the denser regions of the universe (Gnedin 2000; Paschos & Norman 2005). In this case, one might expect to see 21 cm absorption not just by gas in the inner kiloparsecs of the radio source host galaxy, but perhaps by the densest residual H i clouds surrounding the host galaxy on scales of tens to hundreds of kiloparsecs, left over from the EoR and still being ionized by the increasing $a$-$e$ background radiation field. Conversely, densest regions may ionize earliest, due to the biased formation of luminous structure and the associated higher ionizing radiation field (Wyithe & Loeb 2006).

Our observations have not detected any absorption by neutral systems in the IGM surrounding the $z \sim 5.2$ quasars, implying that there are no residual neutral hydrogen clouds along their lines of sight. Indeed, we can certainly rule out any large clouds within the lines of sight to either of these sources. This lack of absorption is qualitatively consistent with expectations based both on optical observations of high-redshift ($z \sim 6$) quasars and on theoretical expectations from models of the reionization process. As seen in the SDSS quasars at $z \sim 6$ (White et al. 2003), there should be a proximity zone extending to $\sim 3000$ km s$^{-1}$ blueward of the quasar redshift within which the IGM is sufficiently ionized that Ly$\alpha$ photons are transmitted.

On the theoretical side, we would expect the ionizing background (following reionization) to be much larger than average within 1 MHz of the quasar redshift. For example, the enhancement of the ionizing background as a function of radius from a massive halo has been computed by Dijkstra et al. (2007). When applied to a quasar, they find that the typical enhancement predicted by this model at a distance of 1 Mpc ranges between factors of 10 and 100, depending on the quasar host mass. Much of this enhancement is due to clustering of sources around the quasar, which preferentially form in the overdense infall region (Wyithe & Loeb 2005). This large enhancement in the ionizing background radiation would suppress any absorption signature close to the quasar.

Recent models describe the process of reionization as patchy, meaning in part that overlap is completed at different times in different regions of the IGM. However the time of reionization within a region of IGM is not expected to be random. Rather, galaxy bias will ensure that overdense regions are reionized earlier than the average IGM (e.g., Wyithe & Loeb 2006). Rare objects, such as the massive halos that house quasars at $z \sim 5.2$, formed preferentially in overdense regions. It follows that the distribution of overdensities on 1 Mpc scales surrounding these quasars is significantly skewed toward positive values (Wyithe & Loeb 2006). We therefore expect reionization to occur earlier around such objects. As an example, using the model described in Wyithe & Loeb (2006), we can calculate the time at which the IGM within 1 Mpc of a quasar is reionized relative to the average IGM. Even in a case where the quasar flux is ignored, such a region would only be reionized at a time later than the average IGM in current models of reionization, suggesting that the immediate infall regions around bright quasars ($\sim$ a few megaparsecs) are not the best sites to search for residual cool neutral gas clouds near the end of cosmic reionization. Future searches for such primordial H i clouds toward $z > 6$ radio sources are best done at redshifts a few thousand km s$^{-1}$ below the AGN host galaxy redshift.

Currently, the GMRT is the largest area telescope capable of observing the H i 21 cm line into cosmic reionization, i.e., at frequencies close to, or below, about 200 MHz. The interference environment clearly makes such studies difficult, and any further progress in very high redshift H i 21 cm absorption searches using existing instrumentation will require the discovery of bright ($>100$ mJy) radio sources at redshifts that happen to put the H i line in the ever decreasing RFI-free parts of the low-frequency spectrum. However, within a few years telescopes such as the Mileeura Widefield Array, the Low Frequency Array, the Precision Array for Probing the Epoch of Reionization, and the 21 Centimeter Array, some of which will operate at sites chosen to minimize terrestrial interference, should allow for the study of fainter sources (a few millijanskys), over wider frequency ranges (Carilli 2006).

We acknowledge support from the Max Planck Society and the Alexander von Humboldt Foundation through the Max-Planck Forschungspreise 2005. We thank the referee for useful comments.

References

Anderson, S., et al. 2001, AJ, 122, 503
Carilli, C. L. 2006, NewA Rev., 50, 162
Carilli, C. L., Gnedin, N. Y., & Owen, F. 2002, ApJ, 577, 22
Carilli, C. L., Lane, W., de Bruyn, A. G., Braun, R., & Miley, G. K. 1996, AJ, 111, 1830
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Conway, J. 2002, NewA Rev., 46, 263
Curen, S. J., & Webb, J. K. 2006, MNRAS, 371, 356
Dijkstra, M., Lidz, A., & Wyithe, S. 2007, ApJ, in press (astro-ph/0701667)
Dwarakanath, K., Carilli, C., & Goss, W. M. 2002, ApJ, 567, 940
Fan, X., Carilli, C. L., & Keating, B. 2006a, ARA&A, 44, 415
Fan, X., et al. 2006b, AJ, 132, 117
Furlanetto, S., & Loeb, A. 2002, ApJ, 579, 1
Gebhardt, K., et al. 2000, ApJ, 539, L13
Gnedin, N. Y. 2000, ApJ, 535, 530

Kanekar, N., & Briggs, F. 2004, NewA Rev., 48, 1259
Kanekar, N., & Chengalur, J. 2003, A&A, 399, 857
Kramer, I. J., Eckers, R. D., Sadler, E. M., Weiss, A., Hunstead, R. W., & De Breuck, C. 2005, ApJ, 621, L1
Paschos, P., & Norman, M. 2005, ApJ, 631, 59
Peck, A. B., Taylor, G. B., Fassnacht, C. D., Readhead, A. C. S., & Vermeulen, R. C. 2000, ApJ, 534, 104
Pentericci, L., McCarthy, P., Rottgering, H., Miley, G., van Breugel, W., & Fosbury, R. 2001, ApJS, 135, 63
Petric, A., et al. 2003, AJ, 126, 15
van Breugel, W., et al. 1999, ApJ, 518, L61
Venemans, B. P., et al. 2004, A&A, 424, L17
White, R., Becker, R., Fan, X., &Strauss, M. 2003, AJ, 126, 1
Wyithe, S., & Loeb, A. 2005, ApJ, 625, 1
———. 2006, ApJ, 646, 696

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No. 6, 2007

We acknowledge support from the Max Planck Society and the Alexander von Humboldt Foundation through the Max-Planck Forschungspreise 2005. We thank the referee for useful comments.