High Redshift HI 21cm Absorption toward Red Quasars

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Abstract.
We have searched for redshifted absorption in the 21 cm line of neutral hydrogen toward ‘red quasars’, which are extragalactic radio sources with a steep spectral drop between optical and infrared wavelengths. The success rate for detecting HI 21cm absorption toward a representative sample of such sources is 80%. This compares to the much lower success rate of 11% for detecting HI 21cm absorption associated with optically selected Mg II absorption line systems. The large neutral hydrogen column densities seen toward red quasars supports the hypothesis that these sources are reddened by dust, as opposed to having an intrinsically red spectrum due to the AGN emission mechanism. The lower limits to the spin temperatures for the neutral hydrogen are between 50 K and 1000 K, assuming a Galactic dust-to-gas ratio.

We consider the question of biases in optically selected samples of quasars due to dust obscuration. The data on the red quasar sub-sample support the models of Fall & Pei for dust obscuration by damped Lyα absorption line systems, and suggest that: (i) there may be a significant, but not dominant, population of quasars missing from optically selected samples due to dust obscuration, perhaps as high as 20% at the POSS limit for an optical sample with a redshift distribution similar to the 1 Jy, flat spectrum quasar sample, and (ii) optically selected samples may miss about half the high column density quasar absorption line systems.

1. Introduction

Quasar absorption line systems provide a distance-independent means of studying baryonic matter cosmologically distributed throughout the universe. The neutral hydrogen column density distribution function for these systems can be characterized roughly by a single power-law between 10^{13} cm^{-2} and 10^{22} cm^{-2}, with an index of −1.5. (Tytler 1987). The implication is that absorption line systems with neutral hydrogen column densities greater than 10^{21} cm^{-2} are very
rare: for every 1000 absorption line systems with $N(\text{HI}) < 10^{14}$ cm$^{-2}$ there is one system with $N(\text{HI}) > 10^{21}$ cm$^{-2}$. Although the highest column density systems are rare, study of these systems is critical to our understanding of the high redshift universe for a number of reasons, including:

- Most of the neutral baryonic material at high redshift may reside in the highest column density systems (Lanzetta et al. 1995).

- The very high column systems are thought to be absorption by gas associated with the pre-cursors of present day disk galaxies (Wolfe et al. 1986).

- Obscuration by dust associated with the high column density systems may affect the observed statistics of quasar populations at high redshifts, and perhaps more significantly, the observed statistics of the cosmic evolution of the neutral baryon density (Fall & Pei 1995).

- Perhaps most importantly in the cases of radio loud background sources, the high column density systems allow studies of the HI 21cm line in absorption, and in the more extreme cases, of associated molecular absorption at high redshift.

Spectroscopic imaging at radio wavelengths of molecular and HI 21cm absorption line systems opens a new window into the physics of these systems, including detailed studies of astrochemistry at high redshift, and new methods for determining basic cosmological parameters such as the evolution of the temperature of the microwave background radiation and the deuterium abundance. These systems probe the dense, pre-star-forming interstellar medium (ISM) in galaxies at substantial look-back times. Background radio continuum sources typically show spatial structure on scales ranging from parsecs to kilo-parsecs. Radio interferometers allow for direct spectroscopic imaging of the spatial structure in the absorbing gas over this entire range of spatial scales. Also, radio spectroscopy allows for study of the velocity structure in the absorption lines down to 10 m s$^{-1}$.

2. Red Quasars

Over the last few years we have developed an effective technique for discovering very high column density quasar absorption line systems by searching for redshifted HI 21cm absorption toward flat spectrum radio sources with faint, red optical counterparts. The physical basis for selecting these ‘red quasars’ for radio absorption searches is the hypothesis that these sources are red due to dust obscuration. Dust obscuration leads to a natural bias against finding the highest column density absorbers using optical techniques in two ways: (i) sources may drop out of optical magnitude limited samples due to dust obscuration, and (ii) follow-up optical spectroscopy typically requires fairly bright, blue objects (Heisler & Ostriker 1988, Fall & Pei 1993, Webster et al. 1995, Shaver et al. 1996). Hence, radio spectroscopy may provide the only method for studying the very highest column density quasar absorption line systems, as has long been the
case for studies of the early stages of star formation in Galactic dark molecular clouds.

In this paper we present a summary of recent detections of redshifted neutral hydrogen 21cm absorption toward red quasars using the new UHF system at the Westerbork Synthesis Radio Telescope (WSRT), and the NRAO 140ft telescope in Green Bank WV (see Carilli et al. 1997, 1998). These observations are intended to address a number of issues. First, we want to address the question whether some AGNs have intrinsically red, rather than dust-reddened, spectra. Second is the question of the fraction of quasars missing from optical samples due to dust obscuration, as well as the fraction of missing high column density quasar absorption line systems. Third, we wish to enlarge the sample of dusty, high column density absorption line systems in order to study the dense ISM in galaxies at significant look-back times. An earlier review of redshifted HI 21cm absorption line systems can be found in Carilli (1995). More recent results using the new UHF system at the WSRT can be found in Vermeulen et al. and Lane et al. (this volume).

The resulting sample of very high column density absorption line systems detected in the radio via HI 21cm absorption and/or molecular absorption, falls into two classes: (i) associated absorbers, ie. absorption by gas in the host galaxy of the quasar, and (ii) cosmologically intervening absorbers. For the associated absorbers the gas can be either ‘circumnuclear material’ directly associated with the active galactic nucleus (AGN), or gas in the general ISM of the AGN host galaxy. For the cosmologically intervening systems the interesting trend has arisen that many of these systems are gravitational lenses. In retrospect the association of lensing with very high column density absorbers may not be surprising, since high column density absorption requires a fairly small impact parameter on the intervening galaxy. The surprise has been that many gravitational lenses are gas rich systems, as opposed to the original naive hypothesis that most lenses would be gas poor elliptical galaxies.

Parameters for the radio continuum sources, and for Gaussian models fit to the HI absorption lines, are given in Table 1. The reference redshift corresponding to zero velocity is given in each figure, and in the table, as \( z_0 \).

3. Individual Sources

3.1. 0108+388

The radio source 0108+388 is located at the center of a narrow emission line galaxy at \( z = 0.670 \) (Stickel et al. 1996a, Stanghellini et al. 1993). The radio source shows twin-jets on 3 mas scales, plus extended structure on large scales (Taylor, Readhead, & Pearson 1996). This source also shows an inverted spectrum at low frequency, perhaps indicating free-free absorption. Optical images of the field show a very red, ‘slightly asymmetric’ galaxy, perhaps a face-on spiral (Stanghellini et al. 1993). The lack of a point source in R band images, and the presence of a compact I band source, have led Stanghellini et al. (1993) to propose ‘the existence of nuclear obscuration’ toward 0108+388.

A strong HI 21cm absorption line is detected at \( z = 0.66847 \) with a width of 100 km s\(^{-1}\) and a peak optical depth of 0.44 (Carilli et al. 1998). The integrated
HI column density for this system is $81 \times 10^{18} \times (T_s f) \text{ cm}^{-2}$, where $T_s$ is the spin temperature of the gas and $f$ is the HI covering factor (Figure 1). Using the VLBI structure of the radio source, and the high opacity of the HI line, Carilli et al. (1998) estimate a lower limit to the absorbing cloud size of about 6 mas, or 36 pc ($H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$).

The velocity width for the HI 21 cm absorption line toward 0108+388 is comparable to linewidths seen for systems associated with nearby Seyfert galaxies and other low redshift AGN (Pedlar et al., this volume; Conway, this volume). High resolution imaging of the absorption toward a number of nearby AGN indicates that the high velocity dispersion gas is local to the AGN, perhaps in a circumnuclear torus or ring with size of order 10 pc, and that the velocity width reflects the torus dynamics (Pedlar et al., and Conway this volume).

3.2. 0218+357
The radio source 0218+357 is the ‘smallest Einstein ring’, with a radio ring with diameter of 0.′′37 plus two point sources, one at the center of the ring and the second on the ring. Differential reddening in the optical toward the two compact sources has led to the hypothesis of a dusty gravitational lens (O’Dea et al. 1992, Patnaik et al. 1993). HI 21 cm absorption has been detected toward 0218+357 by the lensing galaxy at $z = 0.6847$ (Carilli, Rupen, & Yanny 1993), with $N(\text{HI}) = 3 \times 10^{18} \times (T_s f) \text{ cm}^{-2}$ (Figure 2). Subsequent imaging spectroscopy has revealed molecular absorption at $z = 0.6847$ toward the redder of the two compact radio components (Wiklind & Combes 1995 and this volume; Menten & Reid 1996). Lens models predict a velocity dispersion for the lensing galaxy of 100 km s$^{-1}$, suggesting lensing by the bulge of a spiral galaxy. The HI 21 cm line has a FWHM = 43 km s$^{-1}$, suggesting that the disk of the lensing galaxy may be fairly close to the sky plane (Carilli et al. 1993).

3.3. 0414+055
The radio source 0414+055 is an ‘Einstein quad’ with a maximum component separation of 1′. Optical and near IR imaging by Lawrence et al. (1995) indicates that the optical components are heavily reddened by dust. The source redshift is 2.636. The redshift of the lens remains unknown. Moore, Carilli, & Menten (1999) have detected HI 21 cm absorption at $z = 2.636$ toward 0414+055 with $N(\text{HI}) = 7.5 \times 10^{18} \times (T_s f) \text{ cm}^{-2}$ (Figure 3). The large velocity dispersion of this gas (FWHM $\approx 300$ km s$^{-1}$) suggests absorption by circumnuclear material. The observed HI 21 cm absorption implies that much of the reddening is by gas in the AGN host galaxy. However, differential colors for the optical components may require additional reddening by dust in the lens (McLeod et al. 1998).

3.4. 0500+019
The radio source 0500+019 is unresolved at cm wavelengths at resolutions ranging from a few mas to a few arcseconds (Taylor & Perley 1996). A 2.2 μm image of this source reveals a point source with faint emission extending 3′′ to the south, while an R band image shows an inclined disk galaxy with a major axis of about 4′′ (Stickel et al. 1996b). There is no evidence for a point source in the R band image, although the galaxy brightness profile is asymmetric, peaking about 1′′
Figure 1. Spectra of redshifted HI 21cm absorption toward three red quasars. These three systems are likely to be absorption by gas associated with the host galaxy of the AGN. The sources and redshifts are listed in each frame. The redshifts listed correspond to zero velocity. The parameters for the radio source and the Gaussian model fit, are given in Table 1.
to the north of center along the major axis of the galaxy, coincident within the
ers with the position of the K band point source. The galaxy redshift is \( z = 0.5834 \pm 0.0014 \), but there is a narrow emission line at 0.6354 \( \mu \text{m} \) which cannot
be reasonably identified with the galaxy (Stickel et al. 1996b). This unidenti-
fied emission line, the off-center location of the 2.2 \( \mu \text{m} \) point source relative to the
galaxy center, and the asymmetric galaxy profile in the R band image,
lead Stickel et al. to suggest that the quasar may be a background source at \( z > 0.5834 \), and that the red color of the quasar is due to dust in the foreground
galaxy.

HI 21cm absorption has been detected toward 0500+019 at \( z = 0.58472 \),
with \( \text{N(HI)} = 7 \times 10^{18} \times (T_s^{-2}) \text{ cm}^{-2} \) (Carilli et al. 1998). The observed spectrum
is fit reasonably well by two Gaussians (Figure 3). The total HI linewidth is
about 140 km s\(^{-1}\). This broad profile toward 0500+019 could be used to argue
for absorption by circumnuclear material. However, there are the additional
puzzles that the HI redshift is offset from the optical redshift by 240 km s\(^{-1}\),
plus the offset between the K band point source and the galaxy center and the
 unidentified optical emission line. A possible model to explain all these data
is that the quasar is a background source which projects off-center from the z
= 0.5834 galaxy. The large velocity offset of the HI line relative to the galaxy,
and the large velocity dispersion, would then be explained by galactic rotation.
For instance, assuming a galaxy rotation velocity of 200 km sec\(^{-1}\), and the fact
that the line-of-sight to the quasar cut through the edge-on disk halfway out
along the major axis, the expected linewidth due to differential rotation would
be about 100 km s\(^{-1}\).

3.5. 1413+135

The flat spectrum radio source 1413+135 is located at the center of an edge
on spiral galaxy at \( z = 0.247 \) (Perlman et al. 1996), and the radio AGN is
situated behind the galaxy’s dust lane (McHardy et al. 1994). Carilli, Perlman,
& Stocke (1992) have detected HI 21cm absorption at \( z = 0.247 \) with \( \text{N(HI)} = 17 \times 10^{18} \times (T_s^{-2}) \text{ cm}^{-2} \) (Figure 1). The HI 21cm absorption line is fairly narrow
(FWHM \( \approx 20 \text{ km s}^{-1} \)), and very narrow molecular absorption (FWHM \( \approx 1 \text{ km s}^{-1} \)) has been detected at the redshift of the HI line (Wiklind & Combes 1994
and this volume). The narrow velocity width of the absorption toward 1413+135
suggests that it does not occur in circumnuclear gas, but in the general ISM of
the AGN host galaxy. Perlman et al. propose that 1413+135 is a young radio
loud AGN (age \( \leq 10^4 \) years) behind a giant molecular cloud in the disk of the
host galaxy.

3.6. 1504+377

The flat spectrum radio source 1504+377 is located at the center of an inclined
disk galaxy with a moderate-excitation narrow emission line spectrum at \( z = 0.674 \pm 0.001 \). The source shows evidence for flaring of its near IR intensity,
although optical images of 1504+377 show no indication of a bright AGN (Stickel
et al. 1996a). Radio spectroscopic observations of 1504+377 have revealed
strong HI 21cm absorption (Figure 1), and absorption by a number of molecular
species, at the redshift of the parent galaxy (Wiklind & Combes 1996a, Carilli et
Figure 2. Spectra of redshifted HI 21cm absorption toward the Einstein ring radio sources 1830-211 and 0218+357. The redshifts listed correspond to zero velocity. These systems are due to cosmologically intervening gas. The parameters for the Gaussian model fit, and the source continuum flux densities, are given in Table 1. Note that the spectrum of 1830-211 is corrupted by terrestrial interference velocity $= +100$ km s$^{-1}$ in this spectrum. A second peak in HI 21cm absorption has been detected at this velocity (see Chengalur, de Bruyn, & Narasimha, this volume).
The HI profile is reasonably fit by three Gaussians, with a total $N(\text{HI}) = 45 \times 10^{18} \times (T_s f) \text{ cm}^{-2}$. The broad absorption line in this case again argues for absorption by circumnuclear material (Wiklind & Combes 1996a, Carilli et al. 1997, 1998).

The molecular absorption toward 1504+377 also shows a narrow feature at $z = 0.67150$ (linewidth $\leq 10 \text{ km s}^{-1}$), or 330 km s$^{-1}$ relative to the broad line. No HI 21cm absorption is detected at the redshift of this narrow molecular feature. This and the velocity difference between the broad and narrow absorption components in 1504+377 is discussed by Carilli et al. (1997, 1998).

### 3.7. 1830−211

The radio source 1830−211 is the ‘brightest Einstein ring’, with a ring of 1″ diameter and two point sources located on opposite sides of the ring. The source remains unidentified in the optical, but there is a possible detection in the near IR (Frye et al. this volume). Strong molecular and HI 21cm absorption has been detected toward 1830−211 at $z = 0.886$ (Wiklind & Combes 1996b and this volume; Frye et al. 1997 and this volume; Menten, Carilli, & Reid, this volume; Chengalur et al., this volume). The HI 21cm absorption is broad, with two components separated by 146 km s$^{-1}$. Spectroscopic imaging of the molecular absorption shows strong absorption toward the SW radio component at $z = 0.88582$, and weaker absorption toward the NE component at $-146 \text{ km s}^{-1}$ relative to the strong lines. This velocity separation is consistent with the dynamics for the lensing galaxy predicted by lens models (Wiklind & Combes 1998 and this volume; Menten et al. this volume).

A second HI 21cm absorption system has been discovered toward 1830−211 at $z = 0.1926$ with $N(\text{HI}) = 1.2 \times 10^{18} \times (T_s f) \text{ cm}^{-2}$. No molecular absorption has been detected at this redshift (Wiklind & Combes this volume). This second absorption component complicates the lens models for 1830−211, implying that this source is a compound gravitational lens (Lovell et al. 1997).

#### Table 1. Gaussian Model Parameters

| $S_\nu$ | $z_0$ | Velocity | Int. Opt. Depth | Opt. Depth | FWHM | $N(\text{HI})$ |
|---------|------|----------|----------------|------------|------|----------------|
| Jy      | km s$^{-1}$ | km s$^{-1}$ | km s$^{-1}$ | km s$^{-1}$ | cm$^{-2}$ |
| 0108+388 | 0.18 | 0.66847 | 0±4 | 46±7 | 0.44±0.04 | 94±10 | 81±12 |
| 0218+357 | 1.8  | 0.68466 | -13±7 | 1.7±0.3 | 0.034±0.005 | 45±4 | 3.0±0.5 |
| 0414+055 | 3.3  | 2.63647 | 93±12 | 1.6±0.4 | 0.011±0.001 | 140±33 | 3.0±0.8 |
| 0414+055 | -94±12 | 2.4±0.5 | 0.015±0.001 | 154±28 | 4.5±0.9 |
| 0500+019 | 1.6  | 0.58457 | 43±3 | 2.5±0.3 | 0.036±0.003 | 62±7 | 4.5±0.5 |
| 0500+019 | -27±5 | 1.4±0.3 | 0.027±0.003 | 45±9 | 2.5±0.4 |
| 1413+135 | 1.1  | 0.24671 | 0±2 | 9.6±0.6 | 0.41±0.02 | 21±1 | 17±1 |
| 1504+377 | 1.0  | 0.67150 | 325±19 | 7.0±4.3 | 0.073±0.045 | 85±22 | 12.8±8 |
| 1504+377 | 313±1 | 4.0±0.6 | 0.22±0.03 | 16±2 | 7.3±1 |
| 1504+377 | 347±1 | 13.4±4 | 0.34±0.08 | 34±5 | 24±7 |
| 1830−211 | 11   | 0.88536 | -141±3 | 5.8±0.4 | 0.041±0.002 | 127±6 | 10.1±0.7 |
| 1830−211 | 12   | 0.19260 | -28±2 | 0.28±0.05 | 0.009±0.001 | 30±5 | 0.53±0.1 |
| 1830−211 | 12   | 0.19260 | 15±2 | 0.36±0.05 | 0.010±0.001 | 35±5 | 0.68±0.1 |
Figure 3. Spectra of redshifted HI 21cm absorption toward the ‘Einstein Quad’ radio source 0414+055, and toward 0500+019. The redshifts listed correspond to zero velocity. The absorption toward 0414+055 is by gas associated with the AGN. For 0500+019 it is unclear whether the gas is associated with the AGN, or cosmologically intervening. Note the different velocity scales for the two frames. The parameters for the Gaussian model fit, and the source continuum flux densities, are given in Table 1.
4. Discussion

4.1. The Statistics of Red Quasars

We have searched for HI 21cm absorption toward a representative sub-sample of five red quasars from the complete sample of Stickel et al. (1996a). (Note that 1830−211, 1413−135, and 0414+055 are not in the Stickel et al. red quasar sub-sample due to various selection criteria.) We have detected high column density absorption systems in four of five sources (Carilli et al. 1998). This 80% detection rate is significantly higher than in optically selected samples: searches for HI 21cm absorption associated with optically selected MgII absorption line systems result in two detections out of 18 systems (Lane et al. this volume).

The average value of the radio-to-optical spectral index, $\alpha_{rad}^{opt}$, for optically identified, flat spectrum radio loud quasars is: $\alpha_{rad}^{opt} = -0.6$ (Condon et al. 1983), while the values for the Stickel et al. (1996a) red quasar sub-sample are: $\alpha_{rad}^{opt} < -0.9$. On the other hand, the radio-to-near IR spectral indices for most of the red quasar sub-sample are: $\alpha_{rad}^{IR} \geq -0.8$, implying significant steepening of the spectra between the near IR and the optical: $\alpha_{IR}^{opt} \ll -1$ (Stickel et al. 1996a). A rough lower limit to the required extinction can be derived by comparing the observed optical flux density with that predicted by extrapolating the radio-to-IR spectrum into the optical. This is a lower limit due to confusion by emission from stars in the galaxy with which the absorbing gas is associated. Values of the rest frame visual extinction, $A_V$, range from: $A_V \geq 2$ for 0108+388 and 0500+019, to $A_V \geq 3$ for 0218+357, and $A_V \geq 7$ for 1504+377. Using the observed value of N(HI) derived from the HI 21cm absorption lines leads to lower limits to the spin temperatures of about 50 K for 0108+388, 300 K for 1504+377, 500 K for 0500+019, and 1000 K for 0218+357, assuming a Galactic dust-to-gas ratio, and $f = 1$.

Carilli et al. (1998) consider in detail the question of biases in optically selected samples of quasars due to dust obscuration, using the statistics of red quasars and the high detection rate of HI 21cm absorption toward red quasars. They find that the fraction of quasars ‘missing’ from optically selected samples due to dust obscuration is between 6% and 20%, and that the fraction of high column density absorption systems missing from optically selected samples of quasars is between 40% and 70%, where ‘optically selected sample’ means a sample of quasars selected from a moderately deep optical survey such as the POSS, with a redshift distribution comparable to the 1 Jy quasar sample.

Fall and Pei (1993) have presented detailed models of the numbers of quasars missing from optically selected samples due to obscuration by dust associated with high column density quasar absorption line systems as a function of redshift. Using the redshift distribution for the 1 Jy sample, the models of Fall and Pei predict that between 2% and 12% of the sources would be missing from such a sample due to dust obscuration. The comparative numbers for the fraction of missing high column density quasar absorption line systems from the models of Fall and Pei (1993) are between 30% and 60%. In both cases (missing quasar fraction and missing high column absorber fraction), the models of Fall and Pei agree reasonably well with the data on the 1 Jy sample.
We should emphasize that there are a number of significant uncertainties in the statistics presented above. First is simply the small number of red quasars searched thus far for redshifted HI 21cm absorption. Second are the possible biases introduced by the fact that, due to practical observational limitations, our absorption searches were limited to the specific redshifts of the parent galaxies of the absorbing clouds, as determined from emission lines seen in deep optical spectra (Stickel et al. 1996a). It is possible that we have under-estimated the number of high column density systems by not searching over the full redshift range in each case. Conversely, this selection criterion might skew the results toward absorbers at the redshift of the quasar host galaxy, which perhaps could bias the statistics in the opposite sense. And third is the fact that the fairly high radio flux density limit of the 1 Jy sample biases the sample toward lower redshift quasars. The redshift distribution of the 1 Jy quasar sample peaks at $z \approx 1$, while quasar samples derived from radio surveys with lower flux density limits peak at $z \approx 2$, close to the redshift peak found for optically selected quasar samples (Shaver et al. 1996). While the redshift distribution is used explicitly in the calculations above, unbiased searches for redshifted HI 21cm absorption toward a sample of red quasars selected from fainter radio catalogs would make for a fairer comparison with the optical data.

Overall, the statistics presented above should not be considered rigorous, but only representative. Still, the red quasar data support the basic conclusions of Fall and Pei (1993): (i) there may be a significant, but not dominant, population of quasars missing from optically selected samples due to obscuration, perhaps as high as 20% at the POSS limit for an optical sample with a redshift distribution similar to the 1 Jy, flat spectrum quasar sample, and (ii) optically selected samples may miss about half the high column density quasar absorption line systems. A final point made by Fall and Pei is that the strongest bias in optical samples may be against the high column density systems with high metallicities and dust-to-gas ratios. Such systems might be the most interesting from the perspective of follow-up radio studies of the dense, pre-star forming ISM in galaxies at significant look-back times. The data presented herein suggests that searching for redshifted HI 21cm absorption toward radio-loud red quasars may be an effective method for circumventing this bias.

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