A survey for the missing hydrogen in high-redshift radio sources

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Accepted 2012 October 8. Received 2012 September 25; in original form 2012 June 29

ABSTRACT
Unlike at lower redshift, where there is a 40 per cent detection rate, surveys for 21-cm absorption arising within the hosts of \( z \gtrsim 1 \) radio galaxies and quasars have been remarkably unsuccessful. Curran et al. (2008) suggest that this is due to the high-redshift selection biasing towards the most optically bright objects [those most luminous in the ultraviolet (UV) in the rest-frame], where the gas is ionized by the active galactic nucleus. They therefore argue that there must be a population of fainter objects in which the hydrogen is not ionized and which exhibit a similar detection rate as at lower redshifts. In order to find this ‘missing’ gas at high redshift, we have therefore undertaken a survey of \( z \gtrsim 2 \) radio sources, selected by optical faintness. Despite having optical magnitudes which indicate that the targets have UV luminosities below the threshold where all of the gas is ionized, there were no detections in any of the eight sources for which usable data were obtained. Upon an analysis of the spectral energy distributions, ionizing photon rates can only be determined for three of these, all of which suggest that the objects are above the highest luminosity of a current 21-cm detection. The possibility that the other five could be located at lower photon rates cannot be ruled out, although zero detections out of five are not statistically significant. Another possible cause of the non-detections is that our selection biases the sample towards sources which are very steep in the radio band, with a mean spectral index of \( \langle \alpha \rangle = -1.0 \), cf. \(-0.3\) for both the 21-cm detections and UV luminous non-detections. This adds the further possibility that the sources have very extended emission, which would have the effect of reducing the coverage by the putative absorbing gas, thus decreasing the sensitivity of the observation.

Key words: galaxies: active – galaxies: high redshift – quasars: absorption lines – galaxies: stellar content – radio lines: galaxies – ultraviolet: galaxies.

1 INTRODUCTION AND SAMPLE SELECTION
Redshifted \( \text{H} \text{i} \) 21 cm provides a probe of the most abundant element in the Universe, through surveys which are not subject to the flux limitations of optical surveys. In absorption, 21 cm probes the cool component of the neutral gas, which is the reservoir of raw material ultimately responsible for all star formation. Furthermore, the strength of the absorption depends only upon the column density of the absorber and the flux of the background source, making the 21-cm transition potentially detectable up to redshifts of \( z \sim 50 \), where the ionosphere begins to affect the \( \lesssim 30 \text{MHz} \) radio waves.

Despite this, redshifted 21-cm absorption is currently rare, with only 78 absorbers known at \( z \gtrsim 0.1 \), 80 per cent of which are detected at \( z \lesssim 1 \). Much of this is due to the past availability of interference free bands at low frequencies, although there are additional selection effects at play.

(i) For absorbers intervening the sight lines to more distant radio sources, the 60 per cent detection rate at \( z \lesssim 1 \), compared to 20 per cent at \( z \gtrsim 1 \), in systems known to have high hydrogen column densities,\(^1\) can be attributed to the geometry effects introduced by an expanding Universe, where the coverage of the background flux is systematically lower at redshifts of \( z \gtrsim 1 \) (Curran & Webb 2006; Curran 2012).

(ii) For absorbers associated with the radio source itself, the detection rate at \( z \lesssim 1 \) is 40 per cent, compared to 17 per cent at \( z \gtrsim 1 \) (Curran & Whiting 2010). This is believed to be due to the higher redshifts biasing towards the most ultraviolet (UV) luminous objects, where the intense flux ionizes the gas. Specifically, associated...
21-cm absorption has never been detected, where the \( \lambda = 1216 \, \text{Å} \) continuum luminosity of the active galactic nucleus (AGN) exceeds \( L_{1216} \approx 10^{23} \, \text{W Hz}^{-1} \) (Curran et al. 2008 and recently confirmed by Grasha & Darling 2011). At these frequencies \( \left( 2.47 \times 10^{15} \, \text{Hz} \right) \) and above, the photons have enough energy to excite the hydrogen beyond the ground state, so that it cannot absorb in 21 cm. Curran & Whiting (2012) have extended this to the ionizing \( (\lambda \lesssim 912 \, \text{Å}) \) radiation and show that a similar \( (L_{912} \approx 10^{23} \, \text{W Hz}^{-1}) \) cut-off also applies. The large fraction of non-detections at high redshift are therefore due to the flux-limited nature of the optical surveys selecting the brightest objects, where the observed-frame optical light is rest-frame UV, in which all of the gas is believed to be ionized (Curran & Whiting 2012).

In order to find the neutral gas missing from high-redshift AGN, we suggest that high-redshift 21-cm surveys should be directed towards the most optically faint sources. We have therefore embarked on an observing campaign of objects selected by faint optical magnitudes. As discussed in Curran et al. (2011c), our usual source catalogue, the Parkes Half-Jansky Flat-spectrum Sample (PHFS; Drinkwater et al. 1997), yielded only two sources with faint blue magnitudes \( B \gtrsim 22 \) in the 90-cm band \( (z = 3.09–3.63) \), both of which have been previously searched for in 21 cm (Curran et al. 2008). We therefore compiled all available radio catalogues, which give both redshifts and magnitudes, and selected those with \( B, V, R, \) or \( I \) magnitudes which indicate that \( L_{1216} \approx 10^{23} \, \text{W Hz}^{-1} \) at the given redshift (Fig. 1). We further shortlisted those in which 21 cm is redshifted into the 290–395 MHz band of the Green Bank Telescope (GBT) or the UHF-low band \( (250–460 \, \text{MHz}) \) of the Westerbork Synthesis Radio Telescope (WSRT) and which reached sufficiently high elevations at these locations, while having flux densities estimated to be \( \gtrsim 0.2 \, \text{Jy at the redshifted 21-cm frequency} \). This gave 11 sources which we observed (Table 1), eight of which were not completely ruined by RFI, and as seen from Fig. 1, all are believed to be below the critical luminosity. For the \( \approx 40 \% \) detection rate at \( L_{1216} \lesssim 10^{23} \, \text{W Hz}^{-1} \), we therefore expect approximately three detections, although there were none. We discuss possible reasons for the exclusive non-detections in this paper.

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2 Applying the \( B - z \) curve (fig. 5 of Curran, Whiting & Webb 2009) gives \( B \gtrsim 22 \) for \( L_{1216} \lesssim 10^{23} \, \text{W Hz}^{-1} \) at these redshifts.

3 Except for J0617+5012 for which no fluxes were available from the NASA/IPAC Extragalactic Database, although we report 1.28 Jy at 342 MHz here.
### 2 OBSERVATIONS AND DATA REDUCTION

#### 2.1 Green Bank observations

Each of the sources targeted with the GBT was observed for a total of 2 h on source, with the aim of reaching an rms noise level of \( \lesssim 5 \text{ mJy per 10 km s}^{-1} \) channel (for \( T_{\text{sys}} = 70 \text{ K} \)). This gives a \( 3\sigma \) optical depth limit of \( \tau \approx 0.03 \) per channel for a flux density of 0.5 Jy, i.e. a sensitivity to \( N_{\text{HI}} \approx 3 \times 10^{18} \) \((T_{\text{spin}}/f) \text{ cm}^{-2} \), the lower limit for most of the published searches (see fig. 4 of Curran et al. 2008).

We used the {	exttt{Rcvr\_342}} receiver backed with the GBT Spectrometer in narrow bandwidth, high-resolution mode in 4 × 12.5 MHz bands, while maintaining a redshift coverage of \( \Delta z \approx \pm 0.06 \) in each band. Each source was observed in two orthogonal linear polarizations, which, after flagging of bad data, were averaged together (using the {	exttt{GBTIDL}} software).

**NVSS J012142+132058** was observed at 314.53 MHz on 2010 June 17, over 4096 channels, giving a spacing of 3.052 kHz (2.92 km s\(^{-1}\)). After flagging of the worst RFI-affected scans, 0.6 h of data remained with an average system temperature of 220 and 241 km s\(^{-1}\), which is from Wall & Peacock 1985), all are ultrasteep spectrum sources (from De Breuck et al. 2002). The second and third columns list the magnitudes and their values. The fourth column gives the source redshift, followed by the observed frequency range (MHz) over which \( \Delta S \), the rms noise (mJy) reached per 10 km s\(^{-1}\) channel, is applicable. \( S \) is the continuum flux density (Jy) and \( r_{\text{obs}} = \ln(1 - 3\Delta S/S_{\text{obs}}) \) gives the \( 3\sigma \) limit to the observed optical depth of the line per 10 km s\(^{-1}\) channel. This is followed by the resulting neutral hydrogen column density, where \( N_{\text{HI}} = 1.823 \times 10^{18} \) \((T_{\text{spin}}/f) \text{ cm}^{-2} \), \( T_{\text{spin}} \) being the spin temperature and \( f \) the covering factor (see Section 3.2). Finally, we list the redshift range over which the limit applies.

| Source       | Mag | Value | \( z \) | \( v_{\text{obs}} \) | \( \Delta S \) | \( S \) | \( r_{\text{obs}} \) | Tel. | \( N_{\text{HI}} \) | \( f/T_{\text{spin}} \) | \( z \) range |
|--------------|-----|-------|--------|------------------|---------------|------|----------------|------|----------------|---------------|------------|
| 0121+1320    | \( r_s \) | >24   | 3.516  | 313.43–316.40 | 23            | 0.455|<0.15 GBT          | 2.7×10\(^{18}\) | 3.4893–3.5318 | <70 K        |
|              | 4   | 3.184 | 312.11–317.06 | 10 | 0.103|<0.29 WSRT        | 5.3×10\(^{18}\) | 3.4799–3.5510 | <70 K        |
| J0205+2242   | \( r_s \) | >24   | 3.506  | 309.93–317.60 | 24            | 0.251|<0.29 GBT          | 5.3×10\(^{18}\) | 3.4723–3.5830 | <70 K        |
|              | 4   | 3.217 | 367.57–372.16 | 77 | 0.574|<0.51 WSRT        | 9.3×10\(^{18}\) | 3.2167–3.2643 | <70 K        |
| J0231+3600   | \( I \) | 25.0 | 3.079  | 342.68–353.46 | 189           |     |<0.15 GBT          | 2.7×10\(^{18}\) | 3.0496–3.1076 | <70 K        |
|              | 4   | 3.193 | 434.80–440.75 | 5.3 | 0.377|<0.042 WSRT       | 7.7×10\(^{18}\) | 3.1391–3.2079 | <70 K        |
| B0300+37A    | \( r_s \) | 23.2 | 2.506  | 400.94–408.65 | –             | –   | –                | –    | –              | –             |
| J0617+5012   | \( R \) | >24   | 3.153  | 337.56–343.17 | 17            | 1.277|<0.040 WSRT       | 7.3×10\(^{18}\) | 2.9593–2.9629 | <70 K        |
|              | 4   | 3.279 | 339.59–344.53 | 22 | 0.874|<0.076 GBT          | 1.4×10\(^{18}\) | 2.5983–2.6298 | <70 K        |
| B0742+10     | \( R \) | 23.7 | 2.630  | 391.32–394.74 | 22            | 0.874|<0.076 WSRT       | 1.4×10\(^{18}\) | 1.4×10\(^{18}\) | <70 K        |
|              | 4   | 3.309 | 388.78–393.61 | – | –   |<0.15 WSRT          | –       | –             | –             |
| J0747+3654   | \( r_s \) | >23   | 2.992  | 355.78–357.15 | 15            | 1.232|<0.037 GBT        | 6.7×10\(^{18}\) | 2.9771–2.9923 | <70 K        |
| J0920+0712   | \( R \) | 22.4 | 2.760  | 436.21–406.21 | 22            | 0.874|<0.076 WSRT       | 1.8×10\(^{18}\) | 2.9638–3.0194 | <70 K        |
| J1115+5016   | \( r_s \) | >24   | 2.540  | 396.21–406.21 | 22            | 0.874|<0.076 WSRT       | 1.8×10\(^{18}\) | 2.9638–3.0194 | <70 K        |
| B1240+39     | \( r_s \) | 23.6 | 2.131  | 451.17–456.15 | 39            | 0.348|<0.41 WSRT        | 7.5×10\(^{18}\) | 2.1139–2.1483 | <70 K        |

\( ^a \) Derived by interpolating \( S_{151 \text{ MHz}} = 1.19 \text{ Jy} \) (Waldram et al. 1996) and \( S_{365 \text{ MHz}} = 0.525 \text{ Jy} \) (Douglas et al. 1996), giving a continuum flux of \( S_{375 \text{ MHz}} \approx 0.57 \text{ Jy} \).
a spacing of 763 kHz (0.61 km s$^{-1}$). The mean system temperature was 65 K and flagging of badly affected data gave a total integration time of 0.63 h. Even so, the bandpass was still dominated by spikes with RFI close to the expected frequency of the redshifted 21-cm line preventing us from assigning a limit.

**B2 1121+31B** was observed at 336.83 MHz in three sessions spanning from 2010 July 6 to August 5. The band was split over 4096 channels, giving a spacing of 3.052 kHz (2.73 km s$^{-1}$). The mean system temperature was 62 K and RFI was minimal, with 0.90 h of data remaining after flagging the worst of this. Despite the absence of severe RFI and the flat bandpasses, like J0205+2242, each scan exhibited a negative flux, in both polarizations, over the whole run. Negative fluxes can often caused by a region of high confusion leading to the off-measurement being stronger than the source. At 337 MHz, the half-power beam width of the GBT is $\sim$40 arcmin, within which the NASA/IPAC Extragalactic Database lists 17 000 sources, 140 of which are classified as radio sources. Therefore, confusion within the beams/sidelobes/off-position leading to a negative flux is a possibility. Although the flux levels may not be properly calibrated, the data themselves are believed to the reliable (Ries 2012), as is apparent from the consistency between scans for both J0205+2242 and 1121+31B.

### 2.2 Westerbork observations

For the WSRT observations we requested 4 h for each source using all 15 antennas (giving 105 baseline pairs), with the aim of reaching an rms noise level of $\lesssim 20$ mJy per 10 km s$^{-1}$ channel. For a flux density of 0.5 Jy, this gives a 3$\sigma$ optical depth limit of $\tau \approx 0.1$ per channel, a sensitivity to $N_{HI} \gtrsim 2 \times 10^{19} (T_{spin}/f)$ cm$^{-2}$. We used the UHF-low receiver backed with the correlator over 2 $\times$ 5 MHz bands, each in two polarizations over 1024 channels, in order to have a channel spacing of $\approx$4 km s$^{-1}$, while maintaining a redshift coverage of $\Delta z \approx \pm 0.04$. For each source the delays were all self-calibrated with 3C 48, 3C 147 and 3C 286 being used for bandpass calibration and the data were reduced using the **MIRIAD** interferometry reduction package, with a spectrum being extracted from each cube. As per the GBT spectra, these are shown in Fig. 2 and summarized in Table 1.

**NVSS J012142+132058** was observed on 2010 January 5 for a total of 5.0 h. Severe RFI meant that extensive flagging of the data was required, leaving 45 baseline pairs. Despite the flagging, a reasonable image could not be produced and so a spectrum was obtained by averaging together the remaining baselines pairs, giving a much reduced flux with two spikes remaining. An rms noise level of 10 mJy per 10 km s$^{-1}$ channel was reached between these spikes, which rises to 134 mJy averaged over the whole bandpass. Each unsmoothed channel was 4.66 km s$^{-1}$ wide and the synthesized beam was 772 $\times$ 83 arcsec.

**NVSS J020510+224250** was observed on 2010 February 19 for a total of 5.0 h. Again severe RFI required extensive flagging, leaving only the XX polarization and 78 baseline pairs which produced a poor-quality image. A spectrum was, however, extracted from the cube, which had an rms noise level of 77 mJy per 10 km s$^{-1}$ channel. 

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3 POSSIBLE REASONS FOR THE NON-DETECTION OF 21 cm

3.1 Sensitivity limits

Despite our deliberate selection of optically faint sources, with continuum luminosities below the threshold of \( L_{1216} = 10^{23} \text{ W Hz}^{-1} \), we have not detected \( \text{H}_\text{I} \) 21 cm in any of the eight sources for which there were useable data. Below this critical value, Curran & Whiting (2010) find a \( \geq 40 \) per cent general detection rate, which consists of \( \approx 50 \) per cent for compact objects\(^4\) and \( \approx 40 \) per cent for others. That is, we may expect approximately three detections out of the eight sources for which the data were not overwhelmed by RFI.

One possible reason for the non-detections is that all of the sources were affected to some degree by RFI, giving some relatively poor sensitivity limits (Table 1), where detections of optical depths of \( \tau_{\text{obs}} \geq 0.1 \) have been documented to be in the minority (Vermeulen et al. 2003; Morganti 2004). In order to investigate this, in Fig. 3 we show the observed optical depths for all the redshifted 21-cm searches. Since many of our sources were observed by both the GBT and WSRT, we use the best limit in each case and smooth these, as well as rebinning the \( 3\sigma \) limits from the literature, to a channel spacing of 167 \( \text{ km s}^{-1} \), the mean full width at half-maximum (FWHM) of the 21-cm detections. This normalizes all of the limits, published at various spectral resolutions, and gives the limit for the detection of putative line of width FWHM = 167 \( \text{ km s}^{-1} \) within a single channel.

This normalization has the effect of moving all of our limits to \( \tau_{\text{obs}} \lesssim 0.1 \), while degrading the column density limits (see Fig. 5) by a factor of \( \approx 4 \) to those quoted in Table 1. From Fig. 3, we see that our limits are located in the densest clustering of the detections and so for the rest of the analysis, since we are attempting to explain

\(^4\) Gigahertz peaked spectrum (GPS), compact steep spectrum sources (CSS) and compact symmetric objects (CSO). Although the 21-cm detection rate is generally believed to be higher for these than the general population, when the \( L_{1216} \geq 10^{23} \text{ W Hz}^{-1} \) sources are removed the rates are similar, indicating that the higher rates may be due to the generally low UV luminosities of the compact objects (Curran & Whiting 2010).
the exclusive non-detections, we assume that (at least some of) the targets have been searched sufficiently deeply.

We note also a weak correlation between the observed optical depth and the profile width (left-hand panel),\(^3\) which may suggest that weak, wide profiles may be missed by 21-cm surveys, despite having similar column densities to the detections (Allison et al., in preparation). For completeness, we also show how the optical depth is distributed with redshift (middle panel) and the rest-frame 1.4 GHz flux density, from which we see the expected anticorrelation.

3.2 Radio properties

A possible effect which could reduce the probability of detecting 21-cm absorption is the non-deliberate selection of these high-redshift radio galaxies having steep radio spectra (all, apart from B0742+10 being ‘ultra-steepest spectrum radio sources’: De Breuck et al. 2002). This may have an effect on the actual optical depth of the line, \(\tau\), which is related to the observed optical depth, \(\tau_{\text{obs}} = \Delta S/S\), through \(\tau = -\ln(1 - \frac{\Lambda}{\tau_{\text{obs}}})\), where \(f\), the covering factor, quantifies how much of the observed flux is intercepted by the absorber. In the optically thin regime (where \(\Delta S \lesssim 0.3 S\)), this expression reduces to \(\tau \approx \Delta S/(Sf) = \tau_{\text{obs}}/f\). Since, by definition, \(f \leq 1\) then the actual optical depth limit is \(\tau \geq \tau_{\text{obs}}\).\(^5\) That is, the limit is affected by how effectively the absorbing gas intercepts the background emission.

Unfortunately, for this sample there is only high-resolution radio imaging available for one source – B0742+10, which subtends 1.2 mas at 15 GHz (Stanghellini et al. 2001). At \(z = 2.630\) this corresponds to a linear extent of 10 pc (using a standard \(\Lambda\) cosmology with \(H_0 = 71\) km s\(^{-1}\)Mpc\(^{-1}\), \(\Omega_{\text{matter}} = 0.27\) and \(\Omega_{\Lambda} = 0.73\)). Of the remaining of the sample, only four are in the area of sky currently covered by the Very Large Array (VLA)’s FIRST (Faint Images of the Radio Sky at Twenty Centimetres) survey, having deconvolved minor axes of 0.91 arcsec (7 kpc) for J0747+3654, 1.02 arcsec (8 kpc) for J0920-0712, 1.58 arcsec (12 kpc) for B1121+31B and 0.75 arcsec (6 kpc) for B1240+39. Since these are typically unresolved by the 5 arcsec synthesized beam, assigning a source size of \(\lesssim 40\) kpc for each component may be more apt. For J0112+1320, J0205+2242, J0231+3600, B0300+37A and J0617+5012, which are all unresolved by the NRAO VLA Sky Survey (NVSS), the typical 17 arcsec minor axis of the beam gives source sizes of \(\lesssim 130\) kpc for these redshifts.

Given the lack of high-resolution radio imaging, information on the source size may be gleaned from the radio spectral energy distributions (SEDs), given that the turnover frequency is anticorrelated with the size of the radio source (Fanti et al. 1990). In order to explore this possibility, in Fig. 4, we show the SEDs of our eight targets, from which the derived turnover frequencies and spectral indices are summarized in Table 2. From this we see that B0742+10 is the only source with an indisputable turnover, consistent with its observed compactness (10 pc at 15 GHz; Stanghellini et al. 2001). Given that none of the other sources exhibits a turnover above the lowest frequency which has been observed in the literature,\(^7\) it is possible that the majority of our targets may have very extended radio morphologies, thus making \(\tau \gg \tau_{\text{obs}}\) in the case of the limits.

In order to verify this through the comparison of the radio SEDs with the rest of the 21-cm searched sources (compiled in Curran & Whiting 2010; Allison et al. 2012), we fit the radio SEDs (see Appendix A) and use the ASURV survival analysis package (Isobe, Feigelson & Nelson 1986) to obtain mean values of the turnover frequency and spectral index for various subsamples (Table 3). From this it is seen that the mean turnover frequency for this sample is indeed lower than for any of the other subsamples, indicating that

\(^{5}\) The observed distribution has a 1.4 per cent probability of occurring by chance, which is significant at 2.4\(\sigma\), assuming Gaussian statistics.

\(^{6}\) Since \(f\) is generally unknown (see Curran 2012), we leave this (as well as the spin temperature) as a free parameter (Table 1). Assuming that \(f\) has its maximum value of unity, as if often the case in the literature, improves the perceived sensitivity of the observation, where in fact \(f < 1\).

\(^{7}\) Whether there are turnovers in the SEDs of J0231+360, J0747+3654, B1121+31B and B1240+39 are disputable (Fig. 4).
Table 2. The radio properties and luminosities of the targets. \( v_{10} \) is the rest-frame turnover frequency (GHz), where the upper limits designate no observed turnover (which is thus assumed to occur below the observed frequencies), followed by the spectral index at the rest-frame 21-cm frequency, \( \alpha \). In the last three columns we list the \( \lambda = 1216 \, \text{Å} \) (as originally estimated and not corrected for extinction) and \( \lambda = 912 \, \text{Å} \) (as derived from the fits in Appendix A) rest-frame continuum luminosities (\( \text{W} \, \text{Hz}^{-1} \)), as well as the ionizing (\( \lambda \leq 912 \, \text{Å} \)) photon rate (s\(^{-1}\)) in logs.

| Source               | \( v_{10} \) | \( \alpha \) | \( L_{1216} \) | \( L_{912} \) | Rate          |
|---------------------|--------------|--------------|--------------|--------------|---------------|
| J0121+1320          | \(<0.331\)   | \(-1.22\)    | 22.50        | –            | –             |
| J0205+2242          | \(<0.331\)   | \(-1.18\)    | 22.15        | –            | –             |
| J0231+360           | \(<0.302\)   | \(-1.18\)    | 21.28        | –            | –             |
| J0617+5012          | \(<1.41\)    | \(-0.89\)    | 22.00        | –            | –             |
| B0742+10            | 6.46         | 0.29         | 22.00        | 22.20        | 55.68         |
| J0747+3654          | 0.17         | \(-1.23\)    | 22.54        | 23.30        | 57.04         |
| B1121+31B           | 0.040        | \(-1.21\)    | 22.98        | 22.97        | 56.03         |
| B1240+39            | 0.012        | \(-1.50\)    | 22.60        | –            | –             |

From the mean values of the turnover frequency (Hz) and the spectral index at the rest-frame 1420 MHz for all of the sources searched in redshifted 21-cm absorption (Curran & Whiting 2010; Allison et al. 2012), \( n_p \) gives the number of data points and \( n_t \) gives the number of which these are limits. Note that the various subsamples in the second to fifth rows exclude the current sources, which are summarized in the first row.

| Subsample          | Turnover frequency (log\(10 \, v_{10} \)) | Spectral index | \( n_p \) | \( n_t \) | \( \langle \alpha \rangle \) | \( n_p \) |
|--------------------|------------------------------------------|----------------|----------|----------|----------------|----------|
| This paper         | 7.91 ± 0.35                             | 8              | 4        | 1.02 ± 0.18 | 8               |
| Detections         | 8.19 ± 0.14                             | 56             | 23       | 0.29 ± 0.08 | 58              |
| Non-detections     | 8.03 ± 0.09                             | 171            | 92       | -0.39 ± 0.04 | 173             |
| Detections + non-detections | 8.07 ± 0.08                          | 227            | 115      | -0.37 ± 0.04 | 231             |
| UV luminous        | 8.14 ± 0.29                             | 19             | 11       | -0.26 ± 0.12 | 19              |

the radio sources are generally larger. However, this is based upon four limits to the turnover frequencies out of eight SEDs and, as warned by \( \text{asurv} \), may be unreliable.\(^8\) In the case of the spectral indices, where there are no limits, we see that the spectra of our sample are significantly steeper than for the other subsamples.\(^9\) Thus, if the spectral index is a reliable tracer of the background source size, the fact that this sample consists almost exclusively of steep spectrum sources, indicating large radio source sizes, means that poor coverage of the background source cannot be ruled out as the cause of the non-detections. Note, however, for the 'UV luminous' sources (the 19 which lie above the \( L_{UV} = 10^{23} \) \( \text{W} \, \text{Hz}^{-1} \) cut-off; Curran et al. 2011b), the mean spectral index is close to that of the 21-cm detections, thus ruling out the same predisposition towards larger radio sources being the cause of the non-detections.

3.3 Ionizing luminosities and photon rates

Although all of our sources were selected to have \( \lambda = 1216 \, \text{Å} \) continuum luminosities below the critical value of \( L_{1216} \sim 10^{23} \) \( \text{W} \, \text{Hz}^{-1} \) (Fig. 1), it is clear that the total ionizing (\( \lambda \leq 912 \, \text{Å} \)) luminosity, \( \int_{\nu_{min}}^{\nu_{max}} (L_{\nu}/\nu) \, d\nu \), provides a much better measure of the ionizing flux than a monochromatic value (be it \( L_{1216} \) or \( L_{912} \); Curran & Whiting 2012). In equilibrium, the total ionizing luminosity is related to the recombination of the atoms via (Osterbrock 1989)

\[
\int_{\nu_{min}}^{\nu_{max}} \frac{L_{\nu}}{\nu} \, d\nu = 4\pi \int_0^{\infty} n_e n_p \alpha R \nu^2 \, d\nu,
\]

where \( h \) is the Planck constant, giving the number of ionizing photons per second. On the right-hand side of the expression, \( n_e \) and \( n_p \) are the proton and electron densities, respectively; \( \alpha \) is the radiative recombination rate coefficient of hydrogen and \( \nu_{min} \) is the extent of the ionization (the 'Strömgren sphere'). For a gas which decreases in density with increasing distance from the ionizing source, Curran & Whiting (2012) show that \( \nu_{min} \rightarrow \infty \) for a finite UV luminosity and that for a large spiral this value is \( L_{912} \sim L_{1216} \sim 10^{23} \) \( \text{W} \, \text{Hz}^{-1} \), thus explaining this critical luminosity above which 21-cm absorption has never been detected.

From the mean SEDs of all of the associated 21-cm searches, the critical ionizing photon rate arising from this luminosity is estimated to be \( \int_{\nu_{min}}^{\nu_{max}} (L_{\nu}/\nu) \, d\nu = 2.9 \times 10^{56} \) \( \text{s}^{-1} \) (Curran & Whiting 2012). From the polynomial fits (see Appendix A), we could determine photon rates for three of the targets presented here (Fig. 4), one of which is above the estimate of the critical value (log_{10}(2.9 \times 10^{56})) = 56.5, cf. Table 2). Applying fits to each of the SEDs, the highest photon rate which could be determined for a 21-cm detection is 5.1 \times 10^{55} \( \text{s}^{-1} \), which is below or close to the photon rate of the three targets (log_{10}(5.1 \times 10^{55}) = 55.7, see Fig. 5).

However, given that we have no estimates of the photon rates for the remaining five sources, from the previous estimates of the \( \lambda = 1216 \, \text{Å} \) continuum luminosities (Table 2), it is possible that several of these have rates lower than for the three for which we do have estimates. For instance, J0121+1320 has been detected in CO emission (De Breuck, Neri & Omont 2003), which may suggest a UV luminosity below the critical value, although further studies are required to find if this applies to the warm emitting molecular gas. While the monochromatic luminosities may not provide a reliable estimate of the photon rates, if, for the sake of argument, the remaining five sources do have ionizing photon rates below the critical value, for a 40 per cent detection rate (Section 3.1), the binomial probability of zero out of five detections is 0.078. This is significant at 1.76\( \sigma \), assuming Gaussian statistics, and so not statistically important. Recalling that a possible reason for the non-detections is that the targets have not been searched sufficiently deeply (Section 3.1), this significance could be lower, thus not requiring us to ‘explain away’ all eight non-detections.

Finally, given that \( \int_{\nu_{min}}^{\nu_{max}} (L_{\nu}/\nu) \, d\nu \sim 3 \times 10^{56} \) \( \text{s}^{-1} \) is sufficient to ionize all of the gas in a large spiral, photon rates lower than this will completely ionize gas discs of correspondingly smaller scale-lengths (Curran & Whiting 2012). The sample presented here is at more than double the look-back time of the majority of 21-cm detections (Fig. 1) and so if there is any evolution in galactic morphology, with a larger fraction of smaller galaxies at higher redshift (Baker et al. 2000; Lanfranchi & Friaça 2003), we may expect the value of the critical photon rate to be lower at the redshifts searched here, making the detection of 21-cm absorption all the more difficult.

Evolution may also play a role in that if the molecular (H\(_2\)) component constitutes a larger fraction of the gas at high redshift (Obreschkow & Rawlings 2009), lower relative column densities will make the H\(_2\) more difficult to detect. However, as seen from Fig. 1, 21 cm has already been detected at \( z \gtrsim 2 \) and, although molecular gas has been detected in emission in over 100.
ultraluminous infrared galaxies (see Curran 2009; Curran et al. 2011a and references therein), searches for molecular absorption within the hosts of millimetre-loud sources have proved unfruitful (Curran et al. 2011d).\footnote{Given that J0121+1320 is detected in CO emission and that a further five of the targets are known exhibit strong FIR emission (Fig. 4), these sources should be searched in the millimetre band to rule out the possibility of a high molecular fraction suppressing the atomic abundance (if not already done so, although there are no published searches for molecular emission in the remaining targets). However, the cool absorbing molecular gas, rather than warm emitting component, may be expected to be the coincident with the cool atomic gas (see Combes & Wiklind 1998; Murphy et al. 2001 and references therein).}

4 SUMMARY

We have undertaken a survey for the hydrogen apparently missing in high-redshift radio galaxies and quasars by selecting targets in which the optical magnitudes indicate that these are below the UV luminosity cut-off, above which all of the gas is ionized (Curran & Whiting 2012). Despite this, there were no detections in the eight $z \gtrsim 2$ objects for which useful data were obtained. Upon an examination of the SEDs of the targets, we suggest two possible reasons for this.
Due to our requirement of optically faint, radio-loud objects, for which their redshift placed them within the GBT and WSRT 90-cm bands, our sample was dominated by the ultrsteep spectrum sources of De Breuck et al. (2002). By fitting radio SEDs to these, we find a mean spectral index of $\alpha = -1.0$, which is significantly higher than $\langle \alpha \rangle = -0.3$ and $-0.4$ for the 21-cm detections and the remaining non-detections, respectively. This suggests that most of our targets may have extended radio emission, thus reducing the coverage of the background flux by the absorbing gas, lowering the effective sensitivity of our survey.

Although it is impossible at this time to determine which reason is main the culprit, note that the mean radio-band SEDs of the 19 sources for which $L_{21}\mathrm{cm} \lesssim 10^{23}$ W Hz$^{-1}$, those for which the ionizing photon rate could be determined are above $5.1 \times 10^{55}$ ionizing photons s$^{-1}$, the highest value which can be determined for a 21-cm detection. However, the photon rate could only be estimated for three of the eight sources and their monochromatic $\lambda = 1216$ Å continuum luminosities may nevertheless suggest that these are below the threshold. Without sufficient blue/UV photometry, this is, however, speculation.

Furthermore, at these redshifts we are probing look-back times more than double that of the $z \lesssim 1$ sources and if there is a larger fraction of smaller galaxies at these epochs, the gas will be ionized at lower luminosities. For instance, the highest photon rate for which there exists a 21-cm detection ($5 \times 10^{55}$ s$^{-1}$) is sufficient to fully ionize a gas distribution of scale-length of 1.6 kpc (50 per cent that of a large spiral; Kalberla & Kerp 2009), for $n_H = 10^{-23}$ cm$^{-3}$ (Curran & Whiting 2012).\textsuperscript{11} If this is the case, objects even fainter than those targeted here are required to find the missing hydrogen at high redshift, a task perhaps best suited for blind surveys with the Square Kilometre Array, where an optical redshift is not a prerequisite.

To conclude, although we cannot rule out the radio structure and other hitherto unforeseen high-redshift effects as the source of the non-detections, the fact remains that $\lambda = 912$ Å photons ionize hydrogen and there exists a $8.32 \times 10^{-4}$ probability (a 5.36σ significance) of the exclusive non-detections above a given ionizing photon rate arising by chance (Curran & Whiting 2012). This is conjunction with the fact that the critical rate observed is just sufficient to ionize all of the gas in a large galaxy, leaves little doubt that photoionization of the gas by the active nucleus is a dominant issue in the search of neutral gas within the hosts of these objects.

\textbf{ACKNOWLEDGMENTS}

We wish to thank Gyula Józsa for coordinating all of the WSRT observations. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has also made use of NASA's Astrophysics Data System Bibliographic Services and ASURV Rev 1.2 (Lavalette, Isobe & Feigelson 1992), which implements the methods presented in Isobe et al. (1986). The Centre for All-sky Astrophysics is an Australian Research Council Centre of Excellence, funded by grant CE110001020.

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APPENDIX A: SED FITTING

In order to estimate the radio spectral indices and turnover frequencies, as well as the $\lambda \leq 912$ Å continuum luminosities and photon rates, we produced an SED for each source by compiling the NED photometries, the Galaxy Evolution Explorer (GALEX) near- and far-UV fluxes as well as the BVRK magnitudes, published elsewhere (compiled in Curran et al. 2008; Curran & Whiting 2010). After correcting for Galactic extinction using the maps of Schlegel, Finkbeiner & Davis (1998), for each of the 241 sources the flux density was converted to a luminosity and the frequency deredshifted to the source rest frame.

Using Vandermonde matrices (Press et al. 1989), three polynomials were fitted to the data points for each source.

(i) The radio SED. A third- or second-order polynomial was fitted to the $v_{\text{rest}} \leq 10^{12}$ Hz points. The turnover frequency was then obtained from $\frac{dL_v}{dv} = 0$ (with a maximum being tested using $\frac{d^2L_v}{dv^2} < 0$) and the spectral index from the value of $\alpha = \frac{dL_v}{dv}$ at $v_{\text{rest}} = 1.42 \times 10^9$ Hz, thus being defined as $S \propto \nu^{\alpha}$. Fig. A1 shows an example of a possible turnover (at 40 MHz) and a spectral index of $\alpha = -1.21$. In the case where no radio turnover is apparent, providing $\frac{dL_v}{dv} < 0$ (e.g. as in Fig. A1), the UV SED was used to derive the luminosities and photon rate.

(ii) The full SED. A third-order polynomial was fitted to the all of the data points at $v_{\text{rest}} \leq 10^{17}$ Hz. This fit provides a visual guide only.

(iii) The UV SED. A first-order polynomial (power law) was fitted to the $10^{14.5} \leq v_{\text{rest}} \leq 10^{17}$ Hz data. This upper cut-off is applied since, although relevant and used to derive the composite SEDs (Curran & Whiting 2012), the, usually sparsely sampled, X-ray points can have a strong influence on the fit, although these may be arising from other mechanisms than those producing the UV SED.

(a) Provided that $dL_v/dv < 0$ (e.g. as in Fig. A1), the UV SED was used to derive the luminosities and photon rate.

(b) Should the gradient exceed $dL_v/dv = 0$ at $v_{\text{rest}} = 3.29 \times 10^{15}$ Hz, usually from a concentration of data points, the luminosity is estimated from the mean of any neighbouring data points (at $v_{\text{rest}} = 10^{15.52 \pm 0.50}$ Hz).

Only in the first case (a), where a reliable fit is obtained over the range specified, is the ionizing photon rate derived from

$$\int_{v_{\text{rest}}}^{\infty} \frac{L_v}{h\nu} d\nu, \quad \text{where} \quad \log_{10} L_v = \alpha \log_{10} \nu + C \Rightarrow L_v = 10^C \nu^\alpha$$

for a power-law fit, where $\alpha$ is the spectral index and $C$ is the intercept. This gives

$$\frac{10^C}{h} \int_{v_{\text{rest}}}^{\infty} \nu^{\alpha-1} d\nu = \frac{10^C}{a h} [\nu^\alpha]_{v_{\text{rest}}}^{\infty} = -10^C \frac{a}{h} \nu^\alpha \quad \text{where} \quad \alpha < 0,$$

otherwise the ionizing photon rate is flagged as indeterminable.

Finally, in Fig. A3 we show the SED fits to the UV luminous sources (those which lie above the $L_{\text{UV}} = 10^{23}$ W Hz$^{-1}$ cut-off, the last row in Table 3).

As seen from this, the UV luminosities may be estimated and photon rates derived for all of these (see Curran & Whiting 2012).
Figure A3. As per Fig. 4, but for the 19 UV luminous sources (Curran et al. 2011b).

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