COMPLETE IONIZATION OF THE NEUTRAL GAS: WHY THERE ARE SO FEW DETECTIONS OF 21 cm HYDROGEN IN HIGH-REDSHIFT RADIO GALAXIES AND QUASARS

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ABSTRACT

From the first published $z \gtrsim 3$ survey of 21 cm absorption within the hosts of radio galaxies and quasars, Curran et al. found an apparent dearth of cool neutral gas at high redshift. From a detailed analysis of the photometry, each object is found to have a $\lambda = 1216$ Å continuum luminosity in excess of $L_{1216} \sim 10^{23}$ W Hz$^{-1}$, a critical value above which 21 cm has never been detected at any redshift. At these wavelengths, and below, hydrogen is excited above the ground state so that it cannot absorb in 21 cm. In order to apply the equation of photoionization equilibrium, we demonstrate that this critical value also applies to the ionizing ($\lambda \lesssim 912$ Å) radiation. We use this to show, for a variety of gas density distributions, that upon placing a quasar within a galaxy of gas, there is always an ultraviolet luminosity above which all of the large-scale atomic gas is ionized. While in this state, the hydrogen cannot be detected or engage in star formation. Applying the mean ionizing photon rate of all of the sources searched, we find, using canonical values for the gas density and recombination rate coefficient, that the non-detection of 21 cm absorption is not due to the sensitivity limits of current radio telescopes, but rather that the lines of sight to the quasars, and probably the bulk of the host galaxies, are devoid of neutral gas.

Key words: early Universe – galaxies: active – galaxies: high-redshift – galaxies: ISM – radio lines: galaxies – ultraviolet: galaxies

Online-only material: color figures

1. INTRODUCTION

Hydrogen gas accounts for 75% of all the baryonic matter in the universe, of which the cool component, the reservoir for star formation, is traced by the radio-band 21 cm spin-flip transition. Due to the low probability of the transition, compounded by the inverse square law, this is essentially undetectable at $z \gtrsim 0.2$ (see Catinella et al. 2008), although in absorption the line strength is dependent only upon the column density of the absorbing gas and the radio flux of the background source.

Hydrogen has been detected in the ultraviolet band Ly$\alpha$ transition, which traces all of the neutral gas, in 1500 high-redshift galaxies intervening the sight lines to more distant quasi-stellar objects (QSOs; see Curran et al. 2002; Noterdaeme et al. 2009). However, despite four decades of searches, knowledge of the cool component of this gas in the distant ($z \gtrsim 0.1$) universe remains very scarce, with only 42 cases reported in these absorbers, intervening radio-loud QSOs (quasars), in addition to 35 associated with the quasar host galaxy itself.

In both cases, the majority of detections occur at redshifts of $z \lesssim 1$ (look-back times $\lesssim 7.7$ Gyr). In the case of the intervening absorbing galaxies, the apparent lack of cool gas at high redshift may be accounted for by geometry effects. In an expanding universe, absorbers at redshifts of $z \gtrsim 1$ are always disadvantaged, in comparison to the low-redshift ($z \lesssim 1$) absorbing galaxies, in how effectively the absorber can cover the higher redshift background source (Curran & Webb 2006; Curran 2012).

Since for the associated systems the absorbing gas is located within the quasar host galaxy, such geometry effects cannot account for the fact that the 21 cm detection rate at $z \lesssim 1$ is double that at $z \gtrsim 1$. Furthermore, only one associated 21 cm absorber has ever been found at $z > 3$ (Uson et al. 1991). This runs contrary to the expectation that at these redshifts (look-back times $\gtrsim 11.5$ Gyr), much of the gas has yet to be consumed by star formation, meaning that we would expect the abundance of hydrogen to be many times higher than in the present-day universe (e.g., Péroux et al. 2001).

In addition to these covering factor effects, for a given column density, the optical depth of the 21 cm absorption is dependent upon the spin temperature of the gas (Wolfe & Burbidge 1975). Since only atoms populating the lower hyperfine level can absorb in 21 cm, the spin temperature may be elevated through collisions.

4 Compiled in Curran (2010), with the addition of those recently reported by Srianand et al. (2010) and Curran et al. (2011c).
5 Compiled in Curran & Whiting (2010), with the addition of three new associated absorbers, two reported in Curran et al. (2011b) and one in Curran et al. (2011d). See also Allison et al. (2012).
6 We employ a standard $\Lambda$ cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\text{matter}} = 0.27$, and $\Omega_{\Lambda} = 0.73$. 
find no dependence of the 21 cm detection rate on the rest-frame 1420 MHz continuum luminosity of the active galactic nucleus (AGN), thus at least ruling out excitation through this radiative process.

Curran et al. (2008b) do, however, find a strong dependence on the rest-frame $\lambda = 1216 \AA$ ($\nu = 2.47 \times 10^{15}$ Hz) continuum luminosity. Specifically, that 21 cm absorption has never been detected above an apparent critical luminosity of $L_{1216} \approx 10^{23}$ W Hz$^{-1}$. For a $\approx 50\%$ detection rate at $L_{1216} < 10^{23}$ W Hz$^{-1}$ (Curran et al. 2008b), the probability of 0 detections out of 19 searches occurring by chance is $1.9 \times 10^{-6}$ (significant at 4.76$r$ assuming Gaussian statistics; Curran et al. 2011b). So although the gas may be excited through other processes (collisions and the cosmic microwave background), this correlation strongly suggests that excitation above the ground states (and possibly ionization) by $\lambda \leq 1216 \AA$ photons is the dominant cause of the non-detections.

Given that 17 of the 19 $L_{1216} \geq 10^{23}$ W Hz$^{-1}$ sources are type-1 AGNs, it is also possible that the absorption, by cool gas in the circumnuclear obscuring torus invoked by unified schemes, simply does not occur along our line of sight to the continuum source (e.g., Morganti et al. 2001; Pihlström et al. 2003; Gupta et al. 2006). However, at $L_{1216} \leq 10^{23}$ W Hz$^{-1}$, both type-1 and type-2 AGNs exhibit a 50% detection rate (Curran et al. 2008b, 2011b), indicating that the absorption must primarily arise in the main galactic disk, which is randomly oriented with respect to the torus. Therefore, the bias toward type-1 objects at $L_{1216} \geq 10^{23}$ W Hz$^{-1}$ is due to these tending to arise in the more luminous quasars, as opposed to radio galaxies, which tend to be associated with type-2 objects, and is therefore not an orientation effect (Curran & Whiting 2010).

Thus, Curran et al. (2008b) interpreted their exclusive non-detections at $z \geq 3$ to the traditional optical selection of targets, in conjunction with the high redshifts, introducing a bias toward the sources more luminous in rest-frame ultraviolet. The same critical ultraviolet continuum luminosity is also evident in the lower redshift surveys (see Allison et al. 2012), and attributing the lack of cold gas in the hosts of powerful AGNs to the high ultraviolet luminosities exciting the gas beyond detection which we dub “the UV interpretation”) can explain why this effect is seen at all redshifts. The UV interpretation may also account for several other issues in extragalactic radio astronomy, such as the elevated detection rate in compact objects and the preference for 21 cm detection in radio galaxies over quasars (Curran & Whiting 2010).

Given the low probability of zero detections occurring by chance above a given 1216 Å continuum luminosity, in conjunction the fact that $\lambda < 1216 \AA$ photons excite (and possibly ionize) the gas so that it cannot absorb in 21 cm, there is little doubt that the UV interpretation is the correct physical description. This has been confirmed by an independent survey for 21 cm in 143 radio sources at redshifts $0.02 < z < 3.8$, where the lack of detections is correlated with the UV luminosity (Grasha & Darling 2011), as well as by Page et al. (2012), who find a critical X-ray luminosity, above which sources are not detected in 250 $\mu$m continuum emission, a tracer of star formation.

However, one question remains unanswered. Why is there a hard limit to the UV luminosity, above which the gas is excited beyond detection by the most sensitive radio telescopes, rather than a continuum where the detections gradually become fewer and fewer as the ultraviolet luminosity increases? We address this issue here.

2. PHOTOIONIZATION EQUILIBRIUM

For a cloud of hydrogen containing an ionizing source, the equilibrium between photoionization and recombination of protons and electrons in a nebula can be written as (Osterbrock 1989)

$$\int_{\nu_{\text{min}}}^{\infty} \frac{L_{\nu}}{h \nu} d\nu = 4\pi \int_{0}^{r_{\text{cm}}} n_p n_e \alpha_{A,B} F^2 dr,$$

(1)

where $L_{\nu}$ is the specific luminosity at frequency $\nu$ and $h$ is the Planck constant, giving the number of ionizing photons per second. On the right-hand side, $r_{\text{cm}}$ is the extent of the ionization, $n_p$ and $n_e$ are the proton and electron densities, respectively, and $\alpha_{A,B}$ is the radiative recombination rate coefficient of hydrogen (see Section 2.2).

Since, after excitation to the upper hyperfine level, the next excitation is to $n = 2$ by Ly$\alpha$ photons, our proxy has been the $\lambda = 1216 \AA$ continuum luminosity. However, since excitation to the $n = 2$ level and ionization of the hydrogen atom are so close in energy (both events being $\approx 2 \times 10^6$ times as energetic as the spin-flip transition), this critical luminosity should also apply in the case of ionization. In order to verify this, in Figure 1 we show the $\lambda = 912 \AA$ continuum luminosity distribution. The luminosities have been derived from the photometries as described in Curran et al. (2008b), but with the inclusion of data from the Galaxy Evolution Explorer (GALEX; Martin et al. 2003). These, in conjunction with the $BV/RK$ magnitudes from the literature, allow reliable power-law fits to the rest-frame UV data (corrected for Galactic extinction using the maps of Schlegel et al. 1998) over a range of redshifts, from which the $\lambda = 912 \AA$ continuum luminosities were derived (see Curran et al. 2012).

From Figure 1, we see that the same approximate critical value applies in the case of ionizing photons. That is, 21 cm absorption has never been detected above a luminosity close to $L_{912} \approx 10^{23}$ W Hz$^{-1}$. The largest measured 912 Å luminosity for which there is a detection is $L_{912} = 1.1 \times 10^{23}$ W Hz$^{-1}$, above which there are 20 non-detections. Of the sources for which we could reliably determine $L_{912}$, there are 38 detections and 60 non-detections (i.e., a 39% detection rate) below this luminosity. Applying this probability of $p = 0.61$ for a non-detection to the $L_{912} > 1.1 \times 10^{23}$ W Hz$^{-1}$ sources, there is a binomial probability of $5.09 \times 10^{-5}$ of the 20 non-detections occurring by chance, a 4.05$\sigma$ significance.

Thus, although only excitation above the ground state is required to explain the dearth of 21 cm absorption in UV luminous sources, it is possible that ionization of the gas is the primary cause of the non-detections. Given that the lifetime in the $n = 2$ state is only $\approx 10^{-6}$ s, this is the more likely situation and so we are justified in applying Equation (1) to this problem. Thus, in Section 2.1, we derive the value of the left-hand side of the equation, for the sources searched in 21 cm, and in Section 2.2, we apply various recombination models to the right-hand side of the equation.

2.1. Photoionization Rates

In addition to determining the UV fluxes from the GALEX photometries and the $BV/RK$ magnitudes, in order to investigate differences between the 21 cm detected and UV luminous non-detected samples, we obtained multi-wavelength data from

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7 Despite shortlisting the faintest objects (with blue magnitudes of $B \geq 19$, see Figure 5 of Curran et al. 2009).
all of the relevant photometries given by the NASA/IPAC Extragalactic Database (NED), again correcting for Galactic extinction using the maps of Schlegel et al. (1998). As per the λ = 912 Å continuum luminosities, above, we used the redshifts of the targets to blueshift the observed frequencies back to the source rest-frame values and converted the observed fluxes to luminosities. We then averaged all of the luminosities within a specified frequency range to obtain a composite spectral energy distribution (SED) for all of the redshifted sources searched in 21 cm absorption.

Performing a Kolmogorov–Smirnov test between the binned luminosities of the various sub-samples (shown in each panel of Figure 2), we find no evidence that the 21 cm detected and $L_{\text{UV}} \lesssim 10^{23}$ W Hz$^{-1}$ non-detected samples are drawn from different populations, with a probability of $\gtrsim 0.2$ (for all bin widths) that they are drawn from the same population. However, comparing the 21 cm detected sample with either the $L_{\text{UV}} \lesssim 10^{23}$ W Hz$^{-1}$ non-detected samples or the $L_{\text{UV}} \gtrsim 10^{23}$ W Hz$^{-1}$ sample, it is seen that, for sufficiently high-resolution bins, the probability can get as low as $1 \times 10^{-6}$, although this is due to the extra high frequency points in the $L_{\text{UV}} \lesssim 10^{23}$ W Hz$^{-1}$ non-detected sample, with a probability of $\approx 0.004$ being more likely. This still suggests, however, that the UV luminous sources are drawn from a different sample than those with $L_{\text{UV}} \lesssim 10^{23}$ W Hz$^{-1}$.

In order to obtain the rate of ionizing photons, we are interested in frequencies above $v = 3.29 \times 10^{15}$ Hz. However, as seen from Figure 2, there is a large gap in the SEDs between $\sim 10^{16}$ and $\sim 10^{17}$ Hz, the range of spaced-based ultraviolet observations between the optical and X-ray bands. Although the X-ray observations are also space based, these generally have more sky coverage than the ultraviolet observations and are thus more likely to have observed one of our sources. So, in order to obtain an estimate of $\int_{v_{\text{ion}}}^{\infty} (L_{\nu}/v) \, dv$, where $v_{\text{ion}} = 3.29 \times 10^{15}$ Hz, we smooth the SEDs (Figure 3) and interpolate a power-law fit between $\sim 10^{16}$ and $\sim 10^{20}$ Hz to obtain the mean dependence of $L_{\nu}$ on $v$. The photon rate is given by

$$\int_{v_{\text{ion}}}^{\infty} \frac{L_{\nu}}{h v} \, dv, \quad \text{where} \quad \log_{10} L_{\nu} = \alpha \log_{10} v + C \Rightarrow L_{\nu} = 10^C v^\alpha$$

for a power law, where $\alpha$ is the spectral index and $C$ is the intercept. Solving this,

$$\frac{10^C}{h} \int_{v_{\text{ion}}}^{\infty} v^{\alpha-1} \, dv = \frac{10^C}{ah} \left[ \frac{v^{\alpha}}{\alpha} \right]_{v_{\text{ion}}}^{\infty} = \frac{10^C}{ah} v_{\text{ion}}^{\alpha-1},$$

where $\alpha < 0$.

From the composite SEDs, for the non-UV luminous sample, we find $L_{\nu} \approx 10^{37.3} \, v^{-0.95} \text{ W Hz}^{-1}$, giving $5.5 \times 10^{55}$ ionizing photons s$^{-1}$ and for the UV luminous sample, $L_{\nu} \approx 10^{34.6} \, v^{-0.68} \text{ W Hz}^{-1}$, giving $2.9 \times 10^{57}$ ionizing photons s$^{-1}$. This is $\approx 50$ times the luminosity of the 21 cm detected sample, which is consistent with the factor of $\approx 7$ in the luminosity distances between the $z \gtrsim 3$ sample and the cluster of 21 cm detections at $z \lesssim 0.9$ (Figure 1).

2.1.1. The Critical Photoionization Rate

Since we are interested in the ionizing photon rate resulting from a critical luminosity of $L_{\text{UV}} \sim 10^{23}$ W Hz$^{-1}$ (Figure 1), we use the highest 21 cm detected luminosity of $L_{\nu 12} = 1.1 \times 10^{23}$ W Hz$^{-1}$ at $3.29 \times 10^{15}$ Hz, together with the above spectral index of $\alpha = -0.68$, to obtain $L_{\nu} \approx 10^{33.6} \, v^{-0.68} \text{ W Hz}^{-1}$, which gives $2.9 \times 10^{56}$ s$^{-1}$ for the critical ionizing photon rate. Referring to the literature, from the spectra of several hundred QSOs, Telfer et al. (2002) find a mean optical–X-ray slope of $\alpha = -1.5$. This is significantly steeper than the mean spectral index derived for our sample, which consists exclusively of powerful radio sources, although applying a critical luminosity of $L_{\nu 12} = 1.1 \times 10^{23}$ W Hz$^{-1}$ gives $L_{\nu} \approx 10^{35.3} \, v^{-1.3} \text{ W Hz}^{-1} \approx 1.1 \times 10^{56}$ s$^{-1}$, which is in the ballpark of the value derived for our sample. This is a consequence of the steeper spectral index being compensated by a larger constant (intercept) and the fact that the lower frequency end of the UV SED ($v \sim 3.3 \times 10^{15}$ Hz) contains most of the energy. We are therefore confident in applying $\int_{v_{\text{ion}}}^{\infty} (L_{\nu}/h v) \, dv = 2.9 \times 10^{56}$ photons s$^{-1}$ to the left-hand side of Equation (1).$\footnote{Other studies of the UV continuum slope in quasars and AGNs indicate their spectral indices to be in the range $\alpha = -1.4$ to $-0.56$, although with considerable scatter. These give critical photon rates of $\sim 5 \times 10^{55}$ and $\sim 2 \times 10^{54}$–$2 \times 10^{55}$ s$^{-1}$ (Scott et al. 2004; Shull et al. 2012, respectively).}
Lastly, it is clear that while the specific continuum luminosity ($L_{1216}$ or $L_{912}$) may provide an indicator of the amount ionizing radiation from the AGN, the integrated ionizing luminosity (i.e., the ionizing photon rate) is the correct measure. By fitting polynomials to the photometry of the individual sources (Curran et al. 2012), in Figure 4 we re-plot Figure 1 in terms of $\int_{\nu_{\text{ion}}}^{\infty} (L_{\nu} / h\nu) \, d\nu$. For those for which accurate polynomial fits could be obtained, we see that above $\sim 10^{56}$ ionizing photons s$^{-1}$, 21 cm searches have resulted in exclusive non-detections. The highest photon rate for a detection that could be reliably determined is $1.7 \times 10^{55}$ s$^{-1}$, a value above which there are 29 non-detections. Below this rate, there are 38 detections and 51 non-detections, giving a $p = 0.57$ probability of a non-detection. Using this proxy, the binomial probability of 29 out of 29 non-detections occurring by chance is just $8.32 \times 10^{-8}$. This 5.36σ result therefore strongly suggests that ionization of
the gas by $\lambda \leq 912$ Å photons from the AGN is responsible for the non-detection of 21 cm absorption in high-redshift sources.

2.2. Recombination Models

We now parameterize the right-hand side of the photoionization equilibrium expression (Equation (1)). Since we are concerned with the ionization of neutral gas and its subsequent recombination, $n_p = n_e = n$. Also, in optical band observations of an optically thick plasma, where direct capture onto the ground state is excluded, $\alpha_B$ is used. However, since we are concerned with the ground state, $\alpha_A$ is the relevant total recombination rate coefficient (Osterbrock & Ferland 2006). We choose this value at 2000 K, $\alpha_A = 1.27 \times 10^{-12}$ cm$^3$ s$^{-1}$, the typical upper limit to the spin temperature found in intervening absorbers (when the Ly$\alpha$ line is also detected and an upper limit to the spin temperature can be determined; Curran et al. 2010). Naively assuming a constant particle density of $n = 10$ cm$^{-3}$ (typical of the cool neutral 21 cm absorbing interstellar medium) throughout the nebula, we find $r_{\text{ion}} = 3$ and $13$ kpc for the mean radii of the “Strömgren spheres” of the UV non-luminous and

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Figure 3. As Figure 2, but for a bin width $\pm 2$ (i.e., each bin is $10^{2\pm 2} = 10,000$ times the frequency of the previous). In this and Figure 2, the symbol shows the mean luminosity at the center of the frequency bin (e.g., at $10^8, 10^{10}, \ldots, 10^{20}$ Hz here) with the errors bars showing the standard deviation in both luminosity and frequency. (A color version of this figure is available in the online journal.)
UV luminous samples, respectively. Although the latter value is of the same order of magnitude as the extent of neutral gas in a large galaxy, this model represents a gradual increase in ionized radius with luminosity, with no critical value.

2.2.1. Exponential Gas Density Distribution

Unlike the idealized ionized region around a star, we do not expect the gas density to remain constant on galactic scales. A more realistic model of the density of the cold neutral medium (CNM) within a galaxy is that of an exponential decrease in the gas density with distance from the nucleus (Begeman et al. 1991; Kalberla et al. 2007). Thus, for \( n = n_0 e^{-r/R} \), where \( n_0 \) is the gas density at \( r = 0 \) and \( R \) is a scale length describing the rate of decay of this with the radius, Equation (1) becomes

\[
\int_{r_{ion}}^{\infty} \frac{L_{\nu}}{h \nu} d\nu = 4\pi \alpha A n_0^2 \int_{0}^{r_{ion}} e^{-2r/R} r^2 dr = \pi \alpha A n_0^2 (R^3 - R e^{-2r_{ion}/R} (2 r_{ion}^2 + 2 r_{ion} R + R^2)).
\]

Unlike the constant density distribution, this becomes independent of \( r \) at sufficiently large radii, i.e., \( \int_{0}^{\infty} (L_{\nu}/h \nu) d\nu \rightarrow \pi \alpha A n_0^2 R^3 \). Conversely, for a given scale length, \( R \), there always exists a “ceiling luminosity” (the number of ionizing photons \( \times h \)) for which all of the gas is ionized (Figure 5).

Using the above values of \( \alpha_A = 1.27 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1} \) and \( n_0 = 10 \text{ cm}^{-3} \), the critical ionizing photon rate of \( 2.9 \times 10^{44} \text{ s}^{-1} \) gives a scale length of \( R = 2.9 \text{ kpc} \). We can compare this to the H i in the Milky Way, where Kalberla & Kerp (2009) fit an exponential profile to the mid-plane volume density distribution to find \( R = 3.15 \text{ kpc} \) and \( n_0 = 0.9 e^{R_0/R} = 13.4 \text{ cm}^{-3} \). This is in close agreement with our values, demonstrating that the mean SED normalized by a \( \lambda = 912 \text{ Å} \) continuum luminosity of \( 10^{33} \text{ W Hz}^{-1} \) is sufficient to ionize all of the atomic gas in a large spiral galaxy, rendering it undetectable in 21 cm.

It is therefore clear that an exponential decrease in gas density with distance from the nucleus can naturally yield a critical value in the UV luminosity which is close to that found observationally. This does, however, rely on a simple model of the CNM, within which various structures and phases will be embedded, such as the warm neutral medium, as well as localized regions of ionized gas and dense molecular clouds. However, here we are modeling the large-scale CNM, for which an exponential density distribution is a realistic model (Begeman et al. 1991; Kalberla et al. 2007).

Although using the canonical values for \( \alpha \) and \( n_0 \) gives the correct scale length for the observed photon rate, a further physical (sanity) check can be obtained by deriving the total gas mass from the gas density and volume via \( M_{\text{gas}} = \int_0^R \rho dV \). In this case, where the particle density of \( n \) protons cm\(^{-3} \) corresponds to \( \rho = 1.67 \times 10^{-21} \times n \text{ kg m}^{-3} \), exponentially decaying with \( r \) across a disk of thickness, \( t \), we have

\[
M_{\text{gas}} = 2\pi n_0 \int_0^r e^{-r/R} r t dr = 2\pi n_0 \int_0^r e^{-r/R} r^2 = 2\pi n_0 R^3 \left[ 2 - e^{-r/R} \left( \frac{r^2}{R^2} + \frac{r}{R} + 1 \right) \right].
\]

where the flare factor, \( f_{\text{FL}} \), describes the flaring of the H i gas scale height with galactocentric radius. Applying the mean Milky Way value of \( f_{\text{FL}} \approx 20 \) (Kalberla et al. 2007), a scale length of \( R = 2.9 \text{ kpc} \) gives a total gas mass of \( M_{\text{gas}} = 7.5 \times 10^8 M_\odot \) (Figure 5, bottom panel). This is close to the mean value found from a low-redshift survey of 21 cm emission from the 1000 H i brightest galaxies in the southern sky (Koribalski et al. 2004), giving us further confidence in the exponential decay model and choice of gas density.

2.2.2. Alternative Temperatures and Disk Profiles

Although spin temperatures in the intervening 21 cm absorbers may be, on average, \( \lesssim 2000 \text{ K} \), without the total neutral hydrogen column density from the Ly\( \alpha \) transition, as is the case for the associated absorbers, an upper limit to the spin temperature cannot be computed. Traditionally, in the discussion of gas ionization, temperatures of \( \sim 10^5 \text{ K} \) are bracketed (e.g., Osterbrock 1989; Haiman & Rees 2001), although these are in the case of Ly\( \alpha \) emission, rather than the much less energetic 21 cm absorption. Given that the gas is most likely ionized however, in Figure 6 (top panel) we show the ionizing luminosity versus the extent of the ionized gas for
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Figure 5. Number of ionizing (λ < 912 Å) photons per second (top), particle density (middle) and gas mass in solar masses (bottom) vs. the galactocentric radius for an exponential gas distribution at a temperature of 2000 K (α_A = 1.27 x 10^{-12} cm^3 s^{-1}). The different line styles represent the various scale lengths, R, in parsecs, applied to the gas density distribution, n = n_0 e^{-r/R}, with the top panel showing the radius of ionized gas for each value of R. (A color version of this figure is available in the online journal.)

Figure 6. As Figure 5 but for a gas temperature of 10,000 K (α_A = 4.19 x 10^{-13} cm^3 s^{-1}) and a spherical gas distribution. (A color version of this figure is available in the online journal.)

α_A = 4.19 x 10^{-13} cm^3 s^{-1} (i.e., at 10^4 K). From the observed critical rate of 2.9 x 10^{56} photons s^{-1}, we see that the scale length increases to R = 4.2 kpc, which is larger than that of the Milky Way. Thus, for this temperature, the photon rate is more than that required to ionize all of the neutral gas, while demonstrating that our main result is not overly sensitive to the choice of temperature.10

Although having no effect on the extent of the ionization, in order to investigate the effect of a different disk profile on the mass, in Figure 6 we show the distribution of gas mass for a sphere, rather than a disk (i.e., dV = 4π r^2 dr). For R = 4.2 kpc, this gives a total gas mass of M_gas = 4.6 x 10^{11} M_☉, which is close to the total (dynamical) mass expected in a galaxy and is thus too high11 and, applying a temperature of 2000 K (i.e., R = 2.9 kpc), lowers this only slightly to M_gas = 1.5 x 10^{11} M_☉. This confirms that the disk model, which reproduces a gas mass close to the typically observed value, is the more physically accurate distribution. Furthermore, although the most luminous quasars may reside in elliptical galaxies (Taylor et al. 1996), this shape traces the stellar distribution and not necessarily that of the neutral gas. For instance, “superdisks” of gas and dust in the elliptical hosts of powerful radio galaxies have been proposed (Athreya et al. 1998; Gopal-Krishna & Wiita 2000), with diameters of >75 kpc (Gopal-Krishna & Wiita 2000), perhaps up to ≈300 kpc (Curran et al. 2011d).

2.2.3. Alternative Gas Distributions

For completeness, we investigate several alternative density distributions for the gas. These are typically profiles that arise from dynamical models, often applied to the dark matter content

10 Since α ∝ √T (http://amdpp.phys.strath.ac.uk/tamoc/DATA/RR/).

11 See Curran et al. (2008a) for an inventory of the various masses in a nearby active galaxy.
of a galaxy, although we are interested in their effects when applied to the distribution of the CNM. The Jaffe profile (Jaffe 1983) models the distribution of light in a spherical galaxy as $n = n_0 (r_c/r)^2 / 4\pi (1 + r/r_c)^2$, where $r_c$ is the radius which contains half the total emitted light. In this case Equation (1) becomes

\[ \int_0^{\infty} \frac{L_v}{hV} \, dv = 4\pi \alpha_A n_0^2 \int_0^{r_{\text{ion}}} \frac{r^2 (r_c/r)^4}{(4\pi)^2 (1 + r/r_c)^4} \, dr \]

\[ = -\frac{4}{3} \pi \alpha_A n_0^2 r_c^3 \left[ r_c \left( 3r_c^2 + 22r^2 r_c + 30r_c r^2 + 12r^3 \right) \right] \]

\[ - 12 \ln(r_c + r) + 12 \ln(r_c) \left. \right|_0^{r_{\text{ion}}}. \]  

(4)

However, due to the "cuspy" nature of the distribution, solving this over these limits yields infinities, and between any reasonable limits yields unreasonably large numbers, even when the approximation $n = n_0 (r_c/r)^2 / 4\pi (1 + r/r_c)^2 \approx n_0 (r_c/r)^2 / 4\pi (r/r_c)^2 = (n_0/4\pi)(r_c/r)^4$ is used.

A similarly asymptotic density distribution is given by the Navarro–Frenk–White (NFW) profile (Navarro et al. 1996), which models the density as the distribution of dark matter in the halo, via $n = n_0 (r_c/r)/(1 + r/r_c)^2$, where $n_0$ and $r_c$ are the core density and radius of the halo, respectively. Here, the right-hand side of Equation (1) becomes

\[ 4\pi \alpha_A \int_0^{r_{\text{ion}}} n^2 r^2 \, dr = 4\pi \alpha_A n_0^2 \int_0^{r_{\text{ion}}} \frac{r^2 (r_c/r)^2}{(1 + r/r_c)^4} \, dr \]

\[ = \frac{4}{3} \pi \alpha_A n_0^2 r_c^3 \left[ 1 - \frac{r_c^3}{r_c^3 + r_{\text{ion}}^3} \right]. \]  

(5)

Unlike the Jaffe profile, the photoionization equilibrium equation can be solved, again giving a ceiling luminosity, albeit less pronounced than for the exponential gas distribution (Figure 7, top panel). The $L_{UV} = 10^{43}$ W Hz$^{-1}$ threshold of 2.9 x 10$^{56}$ $\lambda < 912$ Å photons s$^{-1}$ gives $r_c \approx 2.6$ kpc, which is very close to the scale length of the exponential disk and typical of that found for nearby galaxies (de Blok et al. 2008; Oh et al. 2011).

For a spherical mass distribution, the NFW profile gives

\[ M_{\text{gas}} = 4\pi n_0 \int_0^{r_c} \frac{r_c/r}{(1 + r/r_c)^2} \, r^2 \, dr \]

\[ = 4\pi n_0 r_c^3 \left[ \frac{r_c}{r_c + r} - 1 + \ln(r_c + r) - \ln(r_c) \right], \]  

(6)

from which $r_c \approx 2.6$ kpc gives a total gas mass of $M_{\text{gas}} = 7.1 \times 10^{11} M_\odot$, which, not surprisingly given the distribution used, is close to the expected value for the dynamical mass.

The asymptotic density distribution of the NFW profile can be avoided by employing the halo density distribution of an isothermal sphere (Begeman et al. 1991), i.e., $n = n_0/(1 + r/r_c)^2$, Figure 8 (middle panel). For this, the right-hand side of Equation (1) gives

\[ 4\pi \alpha_A \int_0^{r_{\text{ion}}} n^2 r^2 \, dr = 4\pi \alpha_A n_0^2 \int_0^{r_{\text{ion}}} \frac{r^2}{(1 + r/r_c)^4} \, dr \]

\[ = \frac{4}{3} \pi \alpha_A n_0^2 r_c^3 \left[ 1 - \frac{r_c^3}{r_c^3 + 3r_c r + 3r^2} \right]. \]  

(7)

which yields $r_c \approx 3.7$ kpc for 2.9 x 10$^{56}$ $\lambda < 912$ Å photons s$^{-1}$. Note that the ceiling luminosities are more pronounced than for the NFW profile, due to the steeper power-law rise at $r < r_c$, similar to that of the exponential gas distribution (Figure 8, top panel). For a spherical mass distribution, the profile gives

\[ M_{\text{gas}} = 4\pi n_0 \int_0^{r_c} \frac{r^2}{(1 + r/r_c)^2} \, dr \]

\[ = 4\pi n_0 r_c^3 \left[ \frac{3}{1 + r_c + r} - 2 \ln(r_c + r) + 2 \ln(r_c) \right], \]  

(8)

which again gives a physically unrealistic total gas mass, $M_{\text{gas}} \approx 9 \times 10^{10} M_\odot$.

Based on the derived gas masses, we therefore conclude that the exponential distribution is the most relevant to the density profile of the CNM within the host galaxy, although the alternative models do reproduce the observed critical $\lambda \approx 912$ Å luminosity for a similar scale length (all of which, at $\approx 3$ kpc, are close to that of the Milky Way). Although the exponential
21 cm absorption has never been detected in a source in which the luminosity exceeds $L_{1216} \sim 10^{23}$ W Hz$^{-1}$. Although other factors may contribute to the raising of the spin temperature of the gas, the fact that 21 cm cannot be detected above the ground state, in conjunction with the lack of detections above this critical luminosity (significant at 4.76σ), strongly suggests that excitation by $\lambda \lesssim 1216$ Å photons is the dominant cause of the dearth of 21 cm in optically bright radio sources.

Here, we demonstrate that this critical luminosity is also applicable to ionizing ($\lambda \lesssim 912$ Å) photons, showing that associated 21 cm is not detected for any source where $L_{912} \gtrsim 10^{23}$ W Hz$^{-1}$ or, more precisely, when there are $\gtrsim 2.9 \times 10^{56}$ ionizing photons s$^{-1}$. We apply this photoionization rate, together with various gas density distribution models, to the equation of photoionization equilibrium, from canonical values for the gas density ($n_0 = 10$ cm$^{-3}$) and the recombination rate coefficient ($\alpha_A = 1.27 \times 10^{-12}$ cm$^3$ s$^{-1}$) and obtain the following.

1. We obtain the observed critical photon rate for a scale length of $\approx 3$ kpc for all of the tested profiles (exponential, NFW and isothermal sphere). This scale length is the same as that for the HI in the Milky Way, thus suggesting that the observed critical value is just sufficient to ionize all of the neutral gas within a large spiral galaxy.

2. This scale length grows as follows.

   (a) For an exponential distribution within a disk, a total gas mass of $M_{gas} = 7.5 \times 10^9$ $M_\odot$ typical of that found from 21 cm emission studies of low-redshift galaxies.

   (b) For the NFW and isothermal sphere density distributions, a total gas mass which exceeds the total expected dynamical mass of the galaxy.

This leads us to conclude that the exponential profile is the more applicable to the distribution of the CNM (see Kalberla & Kerp 2009), although all of the models give a critical UV luminosity. That is, for a gas profile in which the density decreases with distance from the nucleus, the Str"{o}mgren sphere has an infinite radius for a finite luminosity. This suggests that a balance is maintained between the decreasing number of photons and the number of particles with increasing distance from the ionizing source.

For the sources under consideration here, the critical photon rate (where $L_{912} \sim L_{1216} \sim 10^{23}$ W Hz$^{-1}$) is consistent with the dearth of 21 cm detections in all searched high-redshift sources (Curran et al. 2008b). A “proximity effect” for highly ionized Lyα forest clouds has previously been noted (Weymann et al. 1981; Bajtlik et al. 1988), where in these intervening systems the high ionizing flux from the QSO is believed to be responsible for the decrease in the number density of the Lyα lines as the redshift of the absorbing galaxy approaches that of the QSO ($z_{abs} \rightarrow z_{QSO}$).12

However, until our high-redshift survey of radio galaxies and quasars, no such effect was known for the 21 cm transition.13 Furthermore, the 21 cm effect is striking in that, rather than a gradual decrease in associated 21 cm absorption with increasing ultraviolet luminosity, there is an abrupt cutoff in the 21 cm absorption.

12 Bahcall & Ekers (1969) also show that both the 21 cm and the Lyα flux can contribute to higher spin temperatures at absorber–quasar separations of less than a few tens of kpc.

13 From a study of absorber clustering around QSOs in the SDSS DR3, Wild et al. (2008) suggest that the QSO destroys the Mg ii clouds out to beyond 800 kpc. Mg ii has an ionization potential of 15.04 eV, close that of H i (13.60 eV) and so a similar critical $\lambda \lesssim 827$ Å luminosity could perhaps account for this.
provides the fuel for star formation, and our result suggests that the AGN could therefore suppress star formation in the large-scale disk. Note also that although the 250 µm fluxes are also subject to a sensitivity limit, the deficit of 250 µm above a critical luminosity is further evidence of a suppression of star formation (Page et al. 2012). Here, we show that this is not a sensitivity issue, but that the neutral gas, and most likely, appreciable star formation activity is simply not present.

Therefore, even the SKA will be unlikely to find this cool gas in the objects currently known. Where it will excel, however, is in blind surveys of radio sources from which the visible light is too faint to be detected by optical instruments (Curran et al. 2009). Although unseen, these sources must exist in order to have had star formation within the host galaxies of early AGNs. As such, the traditional optical selection of targets must be abandoned in order to find the missing star-forming material within high-redshift radio sources.

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